A 50-kW Module Power Station of Directly Solar-Pumped Iodine Laser

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Introduction

Lasers permit efficient long-range transmission of electromagnetic wave energy because of their small beam divergence. Accordingly, numerous conceptual and experimental studies have been performed to explore laser systems for power transmission in space (DeYoung et al., 1988). Among them is the direct solar-pumped iodine laser (DSPIL) (Lee et al., 1988; Hwang and Tabibi, 1990). An early design study of DSPIL showed that a megawatt power output is feasible in space (DeYoung et al., 1987).

In the present study, a 50-kW DSPIL power module was considered since (a) the development of such a small unit is technologically and economically feasible, (b) the combination of several modules, as shown in Fig. 1, can be adopted for higher power demand, and (c) each module could be designed to provide power according to a user's need. The power level of the module is suitable for powering a lunar or Martian surface rover which requires a roughly 25-kW power for operation, and for powering other spacecraft. Power availability can be multiplied by directing the beams from many modules (Fig. 1).

The laser within a module is based on the master oscillator power amplifier (MOPA) principle and is composed of a master oscillator (MO), a pre-amplifier (PreAmp), a power amplifier (PA) (Fig. 2). An output of 10 W from the MO is amplified to 4 kW at the PreAmp, then this 4-kW laser beam is amplified to 50 kW at the PA for transmission. The lasant chosen for this MOPA is perfluoro-t-butyl iodide ($\text{t-C}_4\text{F}_7\text{I}$) which is the most promising lasant for solar pumping (Lee et al., 1988). The pumping wavelength for this lasant ranges of 250 nm to 350 nm with its peak at 290 nm (Fig. 3). Laser emission is at 1.315 $\mu$m.

The results of our 50-kW module study were the conceptual design, the sizes, and masses of subsystems, and an energy budget, including thermal, mechanical, electrical, and laser energy. A key element of the conceptual design of the module is that lasant and coolant pipes also provide much of the structure of the system.

General Layout of the Module

This laser power module consists of a three-stage iodine MOPA with solar concentrators, a set of resonator mirrors, beam-steering optics, a lasant circulation loop with a pump, and a radiator. The overall configuration is shown in Fig. 2. Other elements include lasant storage tanks (LST) and a control momentum gyroscope (CMG). The LST is designed to hold sufficient amount of lasant for sustaining the operation over five years. The CMG is used to keep the power station oriented with the solar concentrator axis pointed directly at the sun.

The main solar concentrator has a hexagonal frame for easy integration with other modules (see Fig. 1). The area between the aperture of concentrator and hexagonal frame is covered by a photovoltaic cell panel that provides the power required for DSPIL module operation. The solar concentrator focuses solar flux into the power amplifier (PA). The iodine master oscillator (MO) and preamplifier (PreAmp) use their own solar concentrators for laser pumping.

The amplifier is composed of a double-layered quartz tube (Fig. 4). The annular space between tubes is used for active cooling of the quartz laser cavity. The lasant material that passes through the PA is also heated and thus requires heat dissipation to maintain the lasant temperature below 500 K for laser kinetics of the returning lasant. The MO and PreAmp are designed to use a low solar concentration, so that they do not require any active cooling of laser cavity. The PA tube has 12 branches of circulation outlets and inlets, respectively. The six circulation loops are for lasant cooling and the other six loops for cooling the quartz tubes. The pipes, which comprise both lasant and coolant loops, also provide mechanical supports to the MOPA.
The laser system is designed to operate with six circulation loops, each equipped with its own pump and flow controller. If one of these loops malfunctions, the system continues to function properly, ensuring a stable heat load distribution to the laser cavity and coolant.

The MO produces continuous wave (CW) power. This CW laser beam could be modulated at a frequency of 1 kHz by an acousto-optics modulator. Whether CW or pulsed, the beam is expanded, collimated, and injected into the PreAmp for initial power amplification. Since a small low-power laser cavity with a spatial filter produces a single transverse mode to yield Gaussian beam profile, the master oscillator is designed as a small low-power system. If a high quality beam from the PreAmp is injected into the PA, then the amplifier can produce a high quality beam suitable for long distance transmission. The beam amplified by PA enters the beam-steering optics (BSO) where the beam is expanded to the size of the steering reflector and aimed toward a user. The PA equation was derived for the estimations of power requirements of PreAmp and PA:

\[ P = P_o + W_p N L V_{hv} \ln \left( \frac{P}{P_o} \right) \]  

where \( P \) is the amplified power output from PreAmp or PA, \( P_o \) is the saturated power, \( W_p \) is the power remaining in the lasant medium after lasing, \( N_L \) is the lasant molecule number density, \( V_{hv} \) is the photon energy, and \( \ln \) is the natural logarithm.

**Nomenclature**

- \( A \) = Einstein coefficient of emission transition probability
- \( A_{full} \) = Einstein coefficient \((5.1 \text{ for } t-C_4F_9I)\) defined at a specific quantum level transition probability
- \( A_a \) = aperture area of solar concentrator
- \( A_b \) = side wall area of a frustum-like solar concentrator
- \( A_{ref} \) = reflective surface area of concentrator
- \( A_e \) = area of laser cavity side wall
- \( A_t \) = cross section area of laser cavity
- \( c_p \) = specific heat of medium
- \( c_w \) = specific heat of water
- \( C_a \) = geometric correction constant
- \( C_b \) = absorption constant of solar energy through quartz tube wall
- \( C_m \) = absorption constant solar energy by medium
- \( d \) = one absorption length for \( N_\sigma \)
- \( D \) = diameter of laser cavity
- \( D_h \) = hydraulic diameter of a circular tube annulus
- \( D_p \) = path distance of photon in the medium
- \( f \) = focal length of parabolic solar concentrator
- \( F(\lambda) \) = solar spectral photon fluence
- \( F_{nt} \) = view factor between laser cavity and concentrator
- \( g_a \) = unsaturated energy gain
- \( h \) = Planck's constant
- \( I \) = atomic iodine
- \( I^* \) = excited atomic iodine
- \( k_2 \) = rate coefficient for \( R+I \rightarrow RI \)
- \( K \) = attenuation coefficient of solar flux in water
- \( L \) = length of laser cavity
- \( M \) = geometric magnification parameter
- \( N_b \) = number density of buffer gas (argon)
- \( N_L \) = molecular number density of lasant \((t-C_4F_9I)\)
- \( p_B \) = pressure of buffer gas
- \( p_I \) = pressure of lasant
- \( P \) = solar power required for DSPIL system
- \( P_m \) = power remaining in the lasant medium after lasing
- \( P_n \) = solar flux absorbed by cooling water
- \( P_o \) = injected laser beam power into PreAmp or power amplifier
- \( P_s \) = saturated power
- \( R \) = radicals of perfluoroalkyl-iodides
- \( Re \) = Reynolds number
- \( S \) = solar constant \(= 1.353 \text{ kW/m}^2 \) at air-mass zero
- \( S_c \) = solar concentrator rate
- \( S_t \) = thermal power removal by convection
- \( S_e \) = radiative exchange with the solar concentrator
- \( S_r \) = radiative loss from laser cavity to space
- \( S_m \) = power remaining in the lasant medium after lasing
- \( S_{q} \) = solar flux absorbed by quartz tube
- \( S_{ref} \) = solar flux reflected from concentrator surface
- \( T_e \) = solar cavity temperature
- \( T_q \) = quartz tube temperature
- \( \Delta T \) = laser medium temperature between inlet and outlet of laser cavity
- \( \Delta T_e \) = water temperature difference between inlet and outlet
- \( V \) = active volume of laser cavity
- \( v_m \) = medium flow velocity in the laser cavity
- \( v_w \) = cooling water flow velocity through annular space of laser cavity
- \( W_p \) = pumping rate per molecule.
the input power to PreAmp or PA, \( P_i \), the pumping rate, \( N_i \) the molecular number density of lasant, \( V \) the active volume, \( h \) the Planck's constant, \( \nu \) the frequency of light wave, and \( P_i \) the saturation power which is described by

\[
P_i = \frac{h v A_v}{\sigma_v \tau} \tag{2}
\]

where \( A_v \) is the cross-sectional area of a laser tube, \( \sigma_v \) the cross section of stimulated emission, and \( \tau \) the life time of an excited iodine atom and determined by

\[
\frac{1}{\tau} = A + Q_1 N_i + Q_2 N_b
\tag{3}
\]

where \( A \) is the Einstein coefficient, \( Q_1 \) and \( Q_2 \) are the rate coefficients defined, respectively, for \( t-C_4F_1 \) molecules and buffer gas, and \( N_b \) the molecular number density of buffer gas argon. The cross section of stimulated emission \( (\sigma_v) \) is largely dependent on the partial pressure of the lasant \( (t-C_4F_1) \) (Brederlow et al., 1983, p10) and determined by

\[
\sigma_v = \frac{7 A_{b4} \lambda^2}{4 \pi \nu^2 \Delta \nu} \tag{4}
\]

where \( A_{b4} \) is the Einstein coefficient (5.1 for \( t-C_4F_1 \)) defined at a specific quantum level (in this case, 3 to 4) transition probability, and \( \lambda \) the lasing wavelength \( (1.315 \times 10^{-6} \text{ meter}) \). The collisional frequency of pressure-broadened iodine laser spectrum is derived as a pressure dependent:

\[
\Delta \nu = 0.15 \cdot p \cdot 1.333 \times 10^8 \text{ Hz}. \tag{5}
\]

The pumping rate per molecule, \( W_p \) (\# of photons absorbed/sec/molecule), is determined by (Lee and Conway, 1991)

\[
W_p = \frac{A_V}{N_i V} \int_0^{\infty} F(\lambda) \eta(\lambda) \left[ 1 - e^{-n(\lambda) N_i \sigma} \right] d\lambda \tag{6}
\]

where \( A_V \) is the area of side wall, \( N_i \) (cm\(^{-3}\)) the lasant number density, \( V \) (cm\(^3\)) the volume of the laser tube, \( F(\lambda) \) the solar spectral photon fluence, \( \eta(\lambda) \) (1) the spectral quantum yield, \( \sigma(\lambda) \) (cm\(^2\)) the absorption cross section of lasant molecules, and \( D_s \) (cm) the path length of a photon in the medium.

Components Design

Power Requirements. The power level required for lunar and Martian surface rovers is in the range from 15 kW to 25 kW (Petri et al., 1990). Considering the conversion efficiency (43 percent, from beam power to electrical power) (Walker and Heinbockel, 1988), the power output of the module to be considered in the design has to be at least 50 kW.

The design parameters for the PA to produce 50 kW are selected or determined as follows: the average temperature of

**Nomenclature (cont.)**

- \( \alpha \) = angle subtended by the sun's diameter = 9.305 \times 10^{-3} \text{ radian} 
- \( \gamma \) = density of medium 
- \( \epsilon_r \) = total emissivity of concentrator 
- \( \epsilon_q \) = total emissivity of quartz 
- \( \eta_a \) = absorption efficiency of solar spectrum through medium 
- \( \eta_e \) = extraction efficiency of laser cavity 
- \( \eta_f \) = effectiveness due to geometrical form factor of laser cavity 
- \( \eta_r \) = Laser quantum efficiency 
- \( \eta_{r a} \) = reflectance of solar flux at quartz tube surface 
- \( \eta_s \) = absorption percentage of solar spectrum by lasant 
- \( \eta_{r a 1, 2} \) = transmittances of inner and outer quartz tubes 
- \( \eta_{r 5} \) = transmittance between water and quartz wall 
- \( \theta \) = angle between impinging and reflected solar fluxes on concentrator 
- \( \theta_{a b} \) = angle between the optical axis and the rim of center hole of concentrator 
- \( \theta_{a b m} \) = angle between the optical axis and the aperture rim of concentrator 
- \( \kappa \) = thermal conductivity 
- \( \lambda \) = wavelength of iodine laser = 1.3152 \mu \text{m} 
- \( \mu \) = viscosity 
- \( \nu \) = frequency of light wave 
- \( \Delta \nu \) = collisional frequency of pressure-broadened iodine laser spectrum 
- \( \sigma \) = Stefan-Boltzmann constant 
- \( \sigma_s(\lambda) \) = absorption cross section of lasant molecule 
- \( \sigma_s \) = cross section of stimulated emission 
- \( \tau \) = upper level lifetime of excited lasant molecules 

306 / Vol. 119, November 1997 Transactions of the ASME
The concentrator for the 50-kW module system is \( P_S = P/\eta_{sys} = 10,884 \) kW. The solar concentration within the focal volume formed inside the laser cavity is represented by \( S_0 \), which is equivalent to 1178 times AMo solar constant (\( S \)) per focal volume of laser cavity (0.3 m in diameter and 5 m long).

Solar Concentrator. The concentrator for the 50-kW module requires an aperture area, \( A_c \), of 8044 m². The concentrator is a parabolic dish with a central hole which is framed by the six branched-circulation outlet tubes from the PA. The diameter of the central hole is 14.3 m. The six branched-circulation outlets from the PA. The diameter of the central hole is 14.3 m. The six branched-circulation outlets from the PA.

The concentrator is a pseudo-parabolic dish which is increased outward from a true parabolic surface. The focal length of the true parabolic concentrator is 44.4 m. The six branched-circulation outlets from the PA.

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plus the rim area of hexagon, which is 14.687 m². The rim area is used for solar photovoltaic cells which will provide 250 kW electric power for system operation.

The weight of the concentrator without supporting frames is estimated as approximately 1469 kg by using the mass density of 0.1 kg/m² (Canady and Allen, 1982). The frame structure is formed by a set of radiator and circulation loops. This structure serves not only as circulation loops, but also as a strong frame for concentrator. The weight of circulation loops will be discussed below.

**Laser Tube.** In this design, 5 m and 0.30-m are chosen for the length and diameter of the laser tube, respectively. The path length of each ray through the laser medium in the tube varies with its orientation within the angle subtended by the sun’s diameter, α, and with the angle of reflection, θ. The size of the image of solar disk on a focal plane varies along the length of laser tube as a function of the angle θ given in the Appendix. The pseudo-parabolic concentrator forms a frustum-like focal volume. Hence, the size of laser tube is matched to the frustum-like focal volume. The intensity of impinging ray onto the focal plane may also vary with ray’s propagation depth through the lasant medium. It also varies with density profile of the lasant (1−C₄F₁₀) molecules in the cavity if the density profile is not uniform. The path length D can be geometrically approximated by assuming that it is the same as the tube diameter. However, taking the oblique angle of the impinging rays into account, an average ray travels a longer distance than the tube diameter.

The pumping rates were computed by considering the geometrical and spectral aspects and the density profile together. Table 1 shows the pumping rates with respect to the path length. The rays impinge on the cavity with angles from 12 deg to 75 deg. Thus, the path lengths are greater than the diameter of laser cavity. Figure 5 shows the profile of pumping rate along the radial direction. The absorption through lasant is exponentially decayed across the cavity. However, the rays impinge on the cavity by all directions. The pair of rays that impinge on the cavity by all directions. The pair of rays that are opposite each other is superposed along the path. The result of superposed pair is given in Fig. 5. The results also contribute to the formation of Gaussian profile of laser output beam.

**Thermal Loads.** The thermal load on the outer quartz tube of laser cavity by impinging solar flux is estimated by the equation given in the Appendix,

\[ S_q = C_v C_q \frac{S_f L}{a L} = 15,768 \text{ W/m}^2 \]  

where \( C_v = 1.082 \), \( C_q = \eta_1 \eta_2 \eta_3 (1 - \eta_1) \), \( S = 1.353 \text{ kW/m}^2 \), \( f \) the focal length (33.6 m), \( \alpha \) the angle subtended by the sun’s diameter (9.3048 × 10⁻³ radian), and \( L \) the length of laser tube. For the inner quartz tube, \( C_v = \eta_1 \eta_2 \eta_3 (1 - \eta_1) \) and \( S_{q2} = 15,298 \text{ W/m}^2 \). The absorbed energy, \( S_q = S_{q1} + S_{q2} \), dissipates through radiation and convection. Thus

\[ S_q = S_{q1} + S_{q2} + S_n \]

\[ = (1 - F_{ru}) \epsilon \sigma T_q^4 + F_{ru} \sigma (\epsilon_s T_s^4 - \epsilon T_q^4) + S_n \]  

where \( S_n \) is the radiative loss to space, \( S_q \) the radiative exchange with concentrator, \( S_{q1} \) the convective heat removal, \( F_{ru} \) the view factor which is approximately 40 percent due to the geometrical formation selected in this design, \( \epsilon \) the total emissivity of quartz (=0.932), \( T_q \) the quartz tube temperature, and \( T_r \) the concentrator temperature. Without considering the heat removal by convection \( S_n \), the radiatively cooled quartz temperature would be 877 K. When 92 percent of the heat is removed from the quartz by the coolant, the quartz temperature is reduced to 471 K.

The power to be dissipated by the lasant medium (per unit wall area) after lasing may be estimated using Eq. (9) with a slight modification.

\[ S_m = C_v C_m \frac{S_f L}{a L} = 17,602 \text{ W/m}^2 \]  

The coefficient, \( C_m = \eta_1 \eta_2 \eta_3 (1 - \eta_1) \), determines the fraction of the absorbed power density to be removed from the medium after lasing. In term of power, \( P_m = S_m A_i \). For stable operations, this amount of power has to be removed also from radiator to return the laser medium to its appropriate inlet temperature. The designed inlet and outlet temperatures of medium in the laser tube are 280 K and 480 K, respectively. Flow of the lasant medium carries away some of the absorbed energy from the active volume. The medium velocity in the tube may be expressed by

\[ V_m = \frac{S_m A_i}{\gamma A_i c_p \Delta T} \]  

where \( A_i \) is the area of the tube side-wall, \( \gamma \) is the density of the fluid in kg/m³, \( A_i \) is the cross-sectional area of the tube, and \( c_p \) is the specific heat of the fluid. Table 2 lists the parameters of the lasant and buffer gases. For \( A_i = 4.7124 \text{ m}^2 \), \( A = 0.0707 \text{ m}^2 \), \( \gamma = 1.776 \text{ kg/m}^3 \), \( c_p = 526.09 \text{ J/kgK} \), and the 200 K temperature difference allowed between the inlet and outlet of the laser cavity maintain the medium temperature at the exit below the pyrolytic point (500 K) of the lasant, the medium velocity is 6.28 m/sec.

In this design, the medium velocity is increased to 10 m/sec to keep the medium temperature well below the pyrolytic temperature of \( t-C_4F_{10}I \). With this velocity, the temperature difference between the inlet and outlet of laser tube becomes 137 K.

The distilled water has a broad absorption band beyond 0.4 µm of solar spectrum (Driscoll and Vaughan, 1978, p. 15-28 and p. 15-29) and the absorption by water accounts for
approximately 5.88 percent of impinging solar power. For a 5-
cm thick water in an annular channel and 1180 AM0 solar
constant, the total absorbed solar flux by water \((S_w)\) is 62,173
W/m\(^2\). This coolant water needs to remove the solar fluxes
absorbed by both the quartz tubes and cooling water \((S_q + S_w =
93,239 \text{ W/m}^2\)). The design sets the maximum outlet tempera-
ture of water in the laser cavity to be 350 K by allowing 70 K raise
from 280 K inlet temperature of water. To keep the water
under boiling point, the maximum 17 K difference between
quartz walls and water at the outlet of a laser cavity is allowed.
These design tolerances require 1.75 m/sec \((\text{Re} = 10^5)\) flow
velocity of cooling water \((Pr = 4.86)\) in the annular channel
\((D_a = 0.1 \text{ m})\). The heat transfer rates estimated for the annular
channel \((\text{Kays, 1966})\) to remove this amount of heat flux \((S_q +
S_w)\) are 3154 W/m\(^2\)K and 3382 W/m\(^2\)K, respectively,
for the outer and inner quartz tubes. The temperature differences
are 14.7 K and 13.9 K which are within the design tolerances.
The water flow velocity determined above is adequate for opera-
tion, but increased to 2.0 m/sec for safety.

The heat removal system includes the coolant pumping sta-
tion, the lasant circulation loop with radiators, and the water
loop with radiators. This system removes heat from the lasant
medium and quartz tubes. The estimated weight of this system
is 4212 kgs.

**Lasant Medium.** The formation of \(I_2\) molecules has a
quenching effect on excited iodine atoms \(I^*\). The high quench-
ing rate of \(I^*\) reduces laser power output and efficiency.
The quenching rate coefficient, \(Q_i\), for \(t-C_4F_8I\) molecules is not
well defined yet. The rate coefficients used in the calculation
may be found from Brederlow et al. \(1983\). Since \(t-C_4F_8I\)
molecules exhibit little or no irreversible radical dimerization
\((\text{Zalesskii, 1983})\), \(t-C_4F_8I\) molecules circulating with the 10
m/sec velocity in the DSPIL cavity leave no steady-state con-
centration of \(I_2\), except a low initial concentration of iodine
molecules. The dwell time of medium in the cavity is slightly
less than a second.

The quenching effect of the excited iodine molecules by argon
at one atmospheric partial pressure is negligible as com-
pared to the quenching effects by other molecules. For instance,
using the parameters illustrated on Tables 2.5 and 2.6 of Breder-
low et al. \(1983\), argon, at 760 torr pressure, allows approxi-
mately five kinetic reactions \((I^* + Ar \rightarrow I + Ar)\) within
the dwell time. With \(t-C_4F_8I\) \((RI)\) at 3.6 torr, 90 kinetic reac-
tions \((I^* + RI \rightarrow I + RI)\) take place within the cavity. On
the other hand, the atomic iodine \((I)\) after laser action recombines
with radical \((R)\). This regenerative kinetic process \((R+I \rightarrow
RI)\) is the most favorable and dominant feature of the lasant
\(t-C_4F_8I\). Within the dwell time, \(7.64 \times 10^5\) regenerative kinetics
are expected.

At low temperature, the pyrolytic production of \(I_2\) is negligi-
ble. Zalesskii \(1983\) reported that at below 400 K no trace of
\(I_2\) appeared. And a recent laboratory test \((\text{Miner, 1991})\) shows
no trace at 523 K, indicating a higher pyrolytic temperature. In
space, the leakage control \((\text{Zalesskii, 1986})\) reduces \(t-C_4F_8I\)
molecules to prevent any service life of the laser is not a significant
issue as reported by Zalesskii \(1986)\). In space, the leakage control
could be a major issue.

**Master Oscillator (MO).** The minimum output power re-
quired from MO for the preamplifier is 10 W. The solar energy
required for pumping at 10-W MO power is 6.34 kW. The low
solar concentration \((S_c = 50 \text{ times AM0})\) on the MO laser tube
\((0.05 \text{ m dia. and } 1 \text{ m long})\) does not require any active cooling
system. From Eq. \((10)\) without convective cooling, the tempera-
ture of laser tube is obtained as 434 K. However, the circulation
of lasant in the tube is required to avoid \(I_2\) formation by pyro-
lytic. The velocity has to be 0.041 m/sec. The rest of the par-
ameters are illustrated in the first column of Table 3.

**Pre-amplifier.** The laser tube is stretched to 15 m to
achieve both a reduction of solar concentration and exponen-
tial gain saturation. Since low solar concentration \((S_c = 160\times
\text{AM0})\) onto the PreAmp tube is employed, no active
cooling of the laser tube is necessary. From Eq. \((10)\), the
temperature of the laser tube is 353 K. The thermal load
medium is 46 kW. Thus, the flow velocity to remove 46 kW
becomes 2.2 m/sec when constrained by a 200 K temperature
increase for medium. The rest of parameters are listed in the
second column of Table 3.

**Results of Laboratory Work**

The laboratory-scale DSPIL experiments have been the main
thrust of the effort to prove and validate the concept and to find
better lasant materials \((\text{Lee, 1984})\). The experimental setup
consists of a solar simulator \((40-kW \text{ optical power output})\),
an elliptical reflector enclosure, a lasant circulation loop, and a
laser cavity. The laser cavity for experiments has the same
annular quartz tube of which annular space is used for coolant
passage. The results are chronologically tabulated in Table 4.
Experiments could have been the basis for establishing the
design of the DSPIL system. A scaling-up estimation of laser
power based on experimental results is possible. The laser out-
put is proportional to the active volume of the laser cavity and
the input solar intensity \((S)\). Extrapolation of the experimental
data to the active volume \((V)\) of the 50-kW DSPIL system
gives approximately 110-kW output. Considering the form fac-
tor correction \((\eta_f = 0.8488)\) because of the frustum-like for-
mation of focal volume, the laser output power becomes 93 kW.
This is approximately 1.8 times more than the design value, 50
kW. Thus, the 50-kW DSPIL system may be able to generate
more power than designed. On the other hand, for a 50-kW
operation the loads \((\text{thermal, mass, optical power})\) can be re-
laxed and the overall weight estimated in this design study can
be drastically reduced. Even though the theoretical modeling
significantly underestimate the laser output power, the differ-
ce does not indicate a problem with the theoretical model.
This difference may also be attributed to the difference in con-
figurations that were used in the design and experiments \((i.e.,
a parabolic reflector versus an elliptic reflector)."

**Concluding Remarks**

A method of design for a 50-kW direct solar pumped iodine
laser was conceptualized. Concentration of solar energy to a
size of laser tube is essential for maximizing the use of solar
energy. Therefore, modification of a true parabolic dish reflector
to the pseudo-parabolic dish enables a formation of a frustum-

<table>
<thead>
<tr>
<th>Table 3 Parameters for MO, PreAmp, and PA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>-----------</td>
</tr>
<tr>
<td>Output Power</td>
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<tr>
<td>(n_{\text{PrA}}\times[10^{-2}])</td>
</tr>
<tr>
<td>Solar Power</td>
</tr>
<tr>
<td>Aperture Dia.</td>
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<tr>
<td>(A_{\text{PrA}})</td>
</tr>
<tr>
<td>Laser Tube Dia.</td>
</tr>
<tr>
<td>Solar Concentration, (S_c)</td>
</tr>
<tr>
<td>Tube Length</td>
</tr>
<tr>
<td>Lasant, torr</td>
</tr>
<tr>
<td>Buffer, torr</td>
</tr>
<tr>
<td>(W_{\text{PrA}}\times[10^{-2}])</td>
</tr>
<tr>
<td>Path Length</td>
</tr>
<tr>
<td>Medium Velocity</td>
</tr>
<tr>
<td>Radiator Power</td>
</tr>
<tr>
<td>Radiator Area</td>
</tr>
<tr>
<td>Weight</td>
</tr>
</tbody>
</table>
like focal volume. The thermal loads have been estimated for design of components. The design provides some details of the DSPIL system and defines many system requirements.

The 50-kW DSPIL system is a simple and easily achievable concept. Currently, technology and knowledge base required for most of the system components are available. The laboratory efforts were confined to the use of an available source, 40-kW optical power for a laboratory-scale DSPIL experiment. Further development of a theoretical model for the DSPIL is necessary and eventually provide a scaling law so that experimental results can be interpreted for a full-scale DSPIL system.

The weight estimation in Table 3 is made for the five-year operational system. The weight could be reduced by intelligent selection of materials and tight design. The overall design weight of a 50-kW DSPIL is 10,725 kg and the specific power of 4.7 W/kg.

References


Tabibi, Bagher M., 1990, private communications (from laboratory notes).


APPENDIX

The aperture area, A_r, of a concentrator is determined by the requirement of a solar concentration rate (1180 AMO) into a laser cavity to generate a 50-kW net laser beam power. The aperture diameter is

\[ D_r = \sqrt[4]{\frac{4}{\pi} A_r + D^2} \]

where \( D_r \) is the center hole diameter of a pseudo-parabolic dish. Using the maximum aperture angle, \( \theta_{\text{max}} \), which is determined by the angle between the optical axis of the concentrator and the radius, \( \rho' \), that connects the focal point to the periphery of concentrator, the maximum radius of the aperture is determined by

\[ \rho'_{\text{max}} = \frac{D_r}{2 \sin \theta_{\text{max}}} \]

The pseudo-parabolic dish that generates a frustum-like focal volume is created by opening up the aperture diameter of a true parabolic dish and subsequently deflecting a true parabolic dish backward by a few degrees of angle as shown in Fig. 6. The deflection angle will be determined according to the desired length of laser cavity. The radius of a true parabolic dish from its focal point is determined by

\[ \rho = \frac{2f}{1 - \cos (\pi - \theta)} \]

The radius of the deflected parabolic dish is

\[ \rho' = \rho + L \cos \theta' \]

where \( \theta' = \theta - \beta \) and \( L \) is the length of the laser cavity. For a small deflected angle (\( \beta \)) and \( L \ll \rho \),

\[ \beta_{\text{max}} = \cos^{-1} \left( \frac{\rho^2 + \rho'^2 - L^2}{2\rho \rho'} \right) \]

The radius of a laser cavity is also determined by the forma-

![Fig. 6 A pseudo-parabolic reflector concept for a formation of frustum-like focal volume](image-url)
Fig. 7 A geometry for determining a geometric factor that compensates the geometrical deviation of laser cavity from the frustum-like focal volume.

The $c$ in Fig. 7 is defined as

$$c = \frac{\rho' \alpha}{2 \cos \left(\frac{\pi}{2} - \theta\right)}$$

and

$$\rho'' = \rho' - c \sin \left(\frac{\pi}{2} - \theta\right).$$

The $d$ in Fig. 7 is

$$d = \rho' \alpha \left[1 - \frac{\alpha}{2} \cot \theta\right].$$

The radius of the laser cavity is determined by

$$r_\phi = \frac{\rho' \alpha}{2} \left[1 - \frac{\alpha}{2} \cot \theta\right] \cos \theta.$$

The surface area of the concentrator, without including a hexagonal frame, is obtained by integrating the infinitesimal area over the angle from $\theta_s$ to $\theta_{\text{max}}$.

$$A_{\text{eff}} = \frac{2\pi \int_{\theta_s}^{\theta_{\text{max}}} \rho' \cos \theta \, d\theta}{\rho' \cos \theta}.$$

The side-wall area of a frustum-like focal volume is

$$A_\phi = \pi (r_q + r_q') L.$$

where

$$r_q = \frac{\rho \alpha}{2} \left[1 - \frac{\alpha}{2} \cot \theta\right] \cos \theta$$

and

$$r_q' = \frac{\rho' \alpha}{2} \left[1 - \frac{\alpha}{2} \cot \theta\right] \cos \theta'.$$

For $\alpha \ll 1$, $[1 - (\alpha/2) \cot \theta] = 1$. Therefore,

$$A_\phi = \frac{\pi a L}{2} \{ \rho \cos \theta + \rho \cos (\theta - \beta) + L \cos (\theta - \beta)^2 \}.$$

The solar flux that reaches to the surface of a laser cavity is defined by

$$dS_s = \alpha_s \sin \theta \, d\theta = \alpha_s \sin \theta \frac{dS_{\text{eff}}}{A_\phi},$$

in which $dS_{\text{eff}} = 2\pi \eta_s S_{p3} \rho^2 \, d\theta$. Eventually,

$$dS_s = 8\alpha_s \eta_s \eta_l \eta_r \eta_3 \frac{S_f}{\alpha L} \int_{\theta_s}^{\theta_{\text{max}}} \sin \theta \, d\theta \frac{\sin \theta \, d\theta}{(1 + \cos \theta) \left[\cos \theta + \cos (\theta - \beta) + \frac{L}{2f} (1 + \cos \theta) \cos (\theta - \beta)^2\right]}.$$