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 (t-C\textsubscript{4}F\textsubscript{11}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 μm.

The conceptual design of a 50 kW directly solar-pumped iodine laser (DSPIL) module was developed for a space-based power station which transmits its coherent-beam power to users such as the moon, Martian rovers, or other satellites with large (>25 kW) electric power requirements. Integration of multiple modules would provide an amount of power that exceeds the power of a single module by combining and directing the coherent beams to the user’s receiver. The model developed for the DSPIL system conservatively predicts the laser output power (50 kW) that appears much less than the laser output (93 kW) obtained from the gain volume ratio extrapolation of experimental data. The difference in laser outputs may be attributed to reflector configurations adopted in both design and experiment.

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 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 moment gyroscope (CMG). The LST are 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.
system. Each loop has its own pump and flow controller. Thus, if one of the six circulation loops malfunctions, the functioning loops take over and still maintain a proper circulation of the lasant or coolant. The flow rates of lasant and coolant are generally determined by the amounts of thermal loading to the laser tube and lasant, respectively.

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

**Nomenclature**

- $g_0$: unsaturated energy gain
- $W_n N_l \sigma_T$: Einstein coefficient of emission transition probability
- $h$: 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
- $N_l$: 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
- $P_A$: amplified power output
- $P_o$: unsaturated power
- $P_{PreAmp}$: injected laser beam power into PreAmp or power amplifier
- $P_s$: saturated power
- $P_{LASER}$: power required for DSPIL system
- $P_e$: solar power absorbed by cooling water
- $R$: radicals of perfluoroalkyl-iodides
- $Re$: Reynolds number
- $S$: solar constant $= 1.353 \text{ kW/m}^2$ at air-mass zero
- $S_r$: solar concentrator rate
- $S_n$: thermal power removal by convection
- $S_{re}$: radiative exchange with the solar concentrator
- $S_{sl}$: radiative loss from laser cavity to space
- $S_m$: power remaining in the lasant medium after lasing
- $S_{sq}$: solar flux absorbed by quartz tube
- $S_{ref}$: solar flux reflected from concentrator surface
- $S_c$: solar flux absorbed by cooling water
- $T_r$: solar concentrator temperature
- $T_q$: quartz tube temperature
- $\Delta T$: laser medium temperature between inlet and outlet of laser cavity
- $\Delta T_r$: water temperature difference between inlet and outlet
- $V$: active volume of laser cavity
- $v_m$: medium flow velocity in the laser cavity
- $v_c$: cooling water flow velocity through annular space of laser cavity
- $W_p$: pumping rate per molecule

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the input power to PreAmp or PA, $W_p$ 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

$$P_i = \frac{h\nu A_i}{\sigma_i \tau}$$

where $A_i$ is the cross-sectional area of a laser tube, $\sigma_i$ the cross section of stimulated emission, and $\tau$ the life time of an excited iodine atom and determined by

$$\frac{1}{\tau} = A + Q_1 N_i + Q_2 N_b$$

where $A$ is the Einstein coefficient, $Q_1$ and $Q_2$ are the rate coefficients defined, respectively, for $t-C_4F_8I$ molecules and buffer gas, and $N_b$ the molecular number density of buffer gas argon. The cross section of stimulated emission ($\sigma_i$) is largely dependent on the partial pressure of the lasant ($t-C_4F_8I$) (Bredlerow et al., 1983, p10) and determined by

$$\sigma_i = \frac{7 A_{34} \lambda^2}{48 \pi^2 \Delta \nu}$$

where $A_{34}$ is the Einstein coefficient (5.1 for $t-C_4F_8I$) defined at a specific quantum level (in this case, 3 to 4) transition probability, and $\lambda$ the lasing wavelength ($1.3152 \times 10^{-6}$ meter). The collisional frequency of pressure-broadened iodine laser spectrum is derived as a pressure dependent:

$$\Delta \nu = 0.15 \cdot P_g \cdot 1.333 \times 10^8 \text{ Hz}.$$ (5)

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

$$W_p = \frac{A_t}{N_i V} \int_0^\infty F(\lambda) \eta(\lambda) [1 - e^{-\sigma(\lambda) N_b \lambda}] d\lambda$$

where $A_t$ is the area of side wall, $N_b$ the lasant number density, $V$ the volume of the laser tube, $F(\lambda)$ the solar spectral photon fluence, $\eta(\lambda)$ the spectral quantum yield, $\sigma(\lambda)$ the absorption cross section of lasant molecules, and $D_s$ 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

<table>
<thead>
<tr>
<th>Nomenclature (cont.)</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>angle subtended by the sun's diameter = $9.305 \times 10^{-3}$ radian</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>density of medium</td>
</tr>
<tr>
<td>$\epsilon_i$</td>
<td>total emissivity of concentrator</td>
</tr>
<tr>
<td>$\epsilon_q$</td>
<td>total emissivity of quartz</td>
</tr>
<tr>
<td>$\eta_a$</td>
<td>absorption efficiency of solar spectrum through medium</td>
</tr>
<tr>
<td>$\eta_e$</td>
<td>extraction efficiency of laser cavity</td>
</tr>
<tr>
<td>$\eta_f$</td>
<td>effectiveness due to geometrical form factor of laser cavity</td>
</tr>
<tr>
<td>$\eta_l$</td>
<td>Laser quantum efficiency</td>
</tr>
<tr>
<td>$\eta_s$</td>
<td>reflectance of solar flux at quartz tube surface</td>
</tr>
<tr>
<td>$\eta_a$</td>
<td>reflectance of solar flux at quartz tube surface</td>
</tr>
<tr>
<td>$\eta_i$</td>
<td>absorption percentage of solar spectrum by lasant</td>
</tr>
<tr>
<td>$\eta_{t1}$</td>
<td>transmittances of inner and outer quartz tubes</td>
</tr>
<tr>
<td>$\eta_{t2}$</td>
<td>transmittance between water and quartz wall</td>
</tr>
<tr>
<td>$\theta$</td>
<td>angle between impinging and reflected solar fluxes on concentrator</td>
</tr>
<tr>
<td>$\theta_{\text{opt}}$</td>
<td>angle between the optical axis and the rim of center hole of concentrator</td>
</tr>
<tr>
<td>$\theta_p$</td>
<td>angle between the optical axis and the aperture rim of concentrator</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>thermal conductivity</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>wavelength of iodine laser = 1.3152 $\mu$m</td>
</tr>
<tr>
<td>$\mu$</td>
<td>viscosity</td>
</tr>
<tr>
<td>$\nu$</td>
<td>frequency of light wave</td>
</tr>
<tr>
<td>$\Delta \nu$</td>
<td>collisional frequency of pressure-broadened iodine laser spectrum</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Stefan-Boltzmann constant</td>
</tr>
<tr>
<td>$\sigma_s(\lambda)$</td>
<td>absorption cross section of lasant molecule</td>
</tr>
<tr>
<td>$\sigma_i$</td>
<td>cross section of stimulated emission</td>
</tr>
<tr>
<td>$\tau$</td>
<td>upper level lifetime of excited lasant molecules</td>
</tr>
</tbody>
</table>
The medium is quite high. To dissipate such a high thermal load, a moderate the solar image into it. Thus, the thermal load to the
these parameters for MO, the 11 W of power output is obtained.

\[ P_o \text{ (W)} = \frac{1.5 \times 10^{-3}}{(160)} = 1.307 \text{ sec}^{-1} \]

From MO is selected as 10 W, then the extraction efficiency, \( \eta_r \), becomes
\[ \eta_r = \frac{P_o}{P_{\text{in}}} = 4.51 \times 10^{-3}. \]

The second term of Eq. (1), \( P_{\text{in}} \), becomes 7.54 kW. The input power, \( P_{\text{in}} \), from MO is selected as 10 W, then the extraction efficiency, \( \eta_r \), is
\[ \eta_r = \frac{P_o}{P_{\text{in}}} = 0.98. \]

System Efficiencies. The laser tube is designed to accommodate
the medium of the solar image. Thus, the thermal load to the
medium is quite high. To dissipate such a high thermal load, a
double-layered quartz tube was adopted (Fig. 4). Pure water is
used as the coolant because the absorption band of water lies
at a shorter wavelength than the pumping band of the laser.
For reasonable values of the water attenuation coefficient (Dris-
coll and Vaughan, 1978) at the pump-band wavelength and for
a 0.025-m thickness of the water jacket, the transmittance (\( \eta_w \))
is greater than 99 percent. Thus, the water pocket attenuates
the pumping power by only an insignificant amount. The same
cooling method was used in the laboratory-scale DSPIL experi-
ments, and there was no measurable amount of attenuation
observed.

A 90 percent reflectance (\( \eta_{1r} \)) is used for the concentrator
at the pumping wavelength. The reflection of solar flux at a vacuum-
quartz surface is five percent. Thus, the rest (\( \eta_{2r} = 95 \)) enters
the concentrator. The transmittance (\( \eta_{3r} \) and \( \eta_{4r} \)) of quartz tubes
is 0.98. The transmittance (\( \eta_{4r} \)) between water and quartz is
unity since the refractive indices of water and quartz are almost
the same. The laser quantum efficiency (\( \eta_q = 0.2205 \)) is defined
as the ratio of the photon energy (\( h\nu \)) at the stimulated emission
wavelength (1315 nm) to the average photon energy at the
absorption band (250 ~ 350 nm). This efficiency signifies that
a portion of solar spectrum absorbed along the ray path length
(\( \eta_{5r} \)) by the medium is converted into laser output. The absorption
band of \( t-C_4_\text{F}_8 \) is 250 nm to 350 nm as shown in Fig. 3. The solar spectral irradiance within this bandwidth is
approximately four percent (\( \eta_{5r} \)). This portion of the solar spectrum
passes through the lasant medium and is partially absorbed
during passage. The lasant, \( t-C_4_\text{F}_8 \), is transparent to the rest
of the solar spectrum.

The absorption length, \( d \), is defined as
\[ d = \frac{1}{\eta_q N_s \sigma_s} \]

The effective absorption cross section per molecule and \( N_s \)
the molecular number density. The effective absorption cross
section, \( \sigma_s \), of \( t-C_4_\text{F}_8 \) is roughly estimated as 2.0 \( \times 10^{-23} \text{ } \text{m}^2\)
using the maximum absorption cross section from Krug and
Witte (p. 3, 1982). The partial pressure of the \( t-C_4_\text{F}_8 \) is 3.6
torr over an average path length (\( D_p \)) of 0.593 m. The number
density at this pressure is 1.18 \( \times 10^{24} \text{ } \text{m}^{-3}\). Hence, the absorption
length, \( d \), equals 0.424 m. Therefore, the absorption, \( \alpha =
1 - e^{-\alpha d} \), along the path becomes 0.753. The geometrical
form factor, \( \eta_q = 0.8488 \), is determined for the geometrical
arrangement between concentrator and laser tube (see Appendix).
The extraction efficiency, \( \eta_r \), becomes nearly 100 percent for
long pulse extraction (Hwang and Han, 1984).

The total system efficiency is
\[ \eta_s = \frac{\eta_{1r}\eta_{2r}\eta_{3r}\eta_{4r}\eta_{5r} P_4}{P_3} \]
\[ = 4.594 \times 10^{-3}. \]

Therefore, the solar energy required for a 50-kW module system
is \( P_3 = P_4/\eta_s = 10,884 \text{ } \text{kw} \). The solar concentration within
the focal volume formed inside the laser cavity is represented by
\( S = \eta_s P_4 / (S \cdot A_t) \) which is equivalent to 1178 times AM0 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, \( A_t \), 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 outlet
tubes are extended to the pump station which also supports a transmission mirror (Fig. 2). The aperture diameter of the
concentrator is 102 m.

The concentrator is a pseudo-parabolic dish which is increas-
ingly opened outward from a true parabolic surface. The focal
length of the true parabolic concentrator is 33.6 m. The surface
area of the concentrator (approximated by a parabolic dish) is
13,687 m². The hexagonal frame has 118-m diagonals, and the
rim area of the hexagon after subtracting the aperture area is 1,000
m². The total area of the concentrator is the area of concentrator

<table>
<thead>
<tr>
<th>Table 1 Path lengths and pumping rates</th>
</tr>
</thead>
<tbody>
<tr>
<td>( D_p ) &amp; ( \beta_0 \cdot D_p ) &amp; ( W_\nu \times 10^{-7} \text{ sec}^{-1} \text{ per } 1 \text{ sec} )</td>
</tr>
<tr>
<td>cm &amp; torr · cm &amp;</td>
</tr>
<tr>
<td>72.9 &amp; 262.4 &amp; 0.8939</td>
</tr>
<tr>
<td>72.8 &amp; 262.1 &amp; 0.8939</td>
</tr>
<tr>
<td>72.7 &amp; 261.7 &amp; 0.8939</td>
</tr>
<tr>
<td>72.0 &amp; 260.4 &amp; 0.8937</td>
</tr>
<tr>
<td>72.5 &amp; 259.2 &amp; 0.8230</td>
</tr>
<tr>
<td>70.9 &amp; 259.2 &amp; 0.8230</td>
</tr>
<tr>
<td>70.2 &amp; 259.2 &amp; 0.8230</td>
</tr>
<tr>
<td>69.3 &amp; 246.5 &amp; 0.8167</td>
</tr>
<tr>
<td>68.3 &amp; 246.5 &amp; 0.8167</td>
</tr>
<tr>
<td>67.4 &amp; 246.5 &amp; 0.8019</td>
</tr>
<tr>
<td>65.8 &amp; 236.9 &amp; 0.7959</td>
</tr>
<tr>
<td>64.3 &amp; 231.5 &amp; 0.7877</td>
</tr>
<tr>
<td>62.6 &amp; 225.4 &amp; 0.7778</td>
</tr>
<tr>
<td>60.7 &amp; 218.3 &amp; 0.7664</td>
</tr>
<tr>
<td>58.7 &amp; 211.3 &amp; 0.7577</td>
</tr>
<tr>
<td>56.8 &amp; 203.8 &amp; 0.7438</td>
</tr>
<tr>
<td>54.0 &amp; 194.4 &amp; 0.7372</td>
</tr>
<tr>
<td>51.3 &amp; 184.7 &amp; 0.7282</td>
</tr>
<tr>
<td>48.0 &amp; 172.8 &amp; 0.7170</td>
</tr>
<tr>
<td>44.4 &amp; 158.8 &amp; 0.7053</td>
</tr>
<tr>
<td>40.5 &amp; 145.8 &amp; 0.6944</td>
</tr>
<tr>
<td>36.4 &amp; 131.0 &amp; 0.6789</td>
</tr>
<tr>
<td>31.9 &amp; 114.8 &amp; 0.6685</td>
</tr>
<tr>
<td>27.0 &amp; 97.2 &amp; 0.6553</td>
</tr>
</tbody>
</table>

\( * \): The average path length is 59.3 cm.
\( * \): The average pumping rate is 0.7864 \times 10^{-2} \).
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, θ, 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-C_F/4L) 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 to the laser 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 are opposite each other is superposed along the path. The result of superposed pair is given in Fig. 5. The results also contribute 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,

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

where \( C_y = 1.082 \), \( C_q = \eta_l \eta_c (1 - \eta_l) \), \( S = 1.353 \text{ kW/m}^2 \), \( f \) the focal length (33.6 m), \( a \) the angle subtended by the sun's diameter \( (9.3048 \times 10^{-3} \text{ radian}) \), and \( L \) the length of laser tube. For the inner quartz tube, \( C_y = \eta_l \eta_c \eta_l \eta_r (1 - \eta_l) \) and \( S_{q2} = 15,298 \text{ W/m}^2 \). The absorbed energy, \( S_a = S_{q1} + S_{q2} \), dissipates through radiation and convection. Thus

\[
S_q = S_{q1} + S_{q2} + S_n = (1 - F_0) \epsilon_0 \sigma_4 T_q^4 + F_0 \epsilon_0 \sigma_4 (\epsilon_0 T_q^4 - \epsilon_0 T_q^4) + S_n
\]

where \( S_n \) is the radiative loss to space, \( S_e \), the radiative exchange with concentrator, \( S_c \), the convective heat removal, \( F_0 \), the view factor which is approximately 40 percent due to the geometrical formation selected in this design, \( \epsilon_0 \), 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 \( (S_e) \), 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.

\[
S_n = C_y C_m \frac{S_F L}{a L} = 17,602 \text{ W/m}^2
\]

The coefficient, \( C_m = \eta_l \eta_c \eta_l \eta_r \eta_l \eta_r (1 - \eta_l) \), determines the fraction of the absorbed power density to be removed from the medium after lasing. In term of power, \( P_w = S_m A_s = 83 \text{ kW} \). 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

\[
V_n = \frac{S_m A_s}{\gamma A_c c_p \Delta T}
\]

where \( A_s \) is the area of the tube side-wall, \( \gamma \) is the density of the fluid in kg/m³, \( A_c \) 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 \( A_c = 4.7124 \text{ m}^2 \), \( A_s = 0.0707 \text{ m}^2 \), \( \gamma = 1.776 \text{ kg/m}^3 \), \( c_p = 526.09 \text{ J/kgK} \), and the 200 K temperature difference allowed between the inlet and outlet of the laser cavity to 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 \( t - C_F/4L \). 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 constants, the total absorbed solar flux by water \((S_w)\) is 62,173 \(\text{W/m}^2\). This coolant water needs to remove the solar fluxes absorbed by both the quartz tubes and cooling water \((S_p + S_w = 93,239 \text{ W/m}^2)\). The design sets the maximum outlet temperature 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 \(\text{m/s} (Re = 10^5)\) flow velocity of cooling water \((Pr = 4.85)\) in the annular channel \((D_o = 0.1 \text{ m})\). The heat transfer rates estimated for the annular channel \((Kays, 1966)\) to remove this amount of heat flux \((S_p, \text{ and } S_w)\) are 3154 \(\text{W/m}^2\cdot\text{K}\) and 3382 \(\text{W/m}^2\cdot\text{K}\) 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 operation, but increased to 2.0 \(\text{m/sec}\) for safety.

The heat removal system includes the coolant pumping station, 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 quenching rate of \(I^*\) reduces laser power output and efficiency. The quenching rate coefficient, \(Q_q\), for \(t-C_4F_9I\) molecules is not well defined yet. The rate coefficients used in the calculation may be found from Bröderlow et al. (1983). Since \(t-C_4F_9I\) molecules exhibit little or no irreversible radical dimerization (Zaleskii, 1983), \(t-C_4F_9I\) molecules circulating with the 10 \(\text{m/sec}\) velocity in the DSPIL cavity leave no steady-state concentration 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 compared to the quenching effects by other molecules. For instance, using the parameters illustrated on Tables 2.5 and 2.6 of Bröderlow et al. (1983), argon, at 760 torr pressure, allows approximately five kinetic reactions \((I^* + Ar \rightarrow I + Ar)\) within the dwell time. With \(t-C_4F_9I\) \((RI)\) at 3.6 torr, 90 kinetic reactions \((I^* + RI \rightarrow I + RI)\) 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 \(t-C_4F_9I\). Within the dwell time, \(7.64 \times 10^3\) regenerative kinetics are expected.

At low temperature, the pyrolytic production of \(I_2\) is negligible. Zalesskii (1983) reported that at below 400 K no trace of \(I_2\) appeared. And a recent laboratory test (Miner, 1991) shows no trace at 523 K, indicating a higher pyrolytic temperature. In the design, the medium temperature becomes 443 K in the safe range from pyrolytic. Since this lasant temperature is at an outlet, the active region of medium remains below this temperature.

The lasant consumption due to chemical kinetics and pyrolytic for 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 required 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 \((S_o = 50 \text{ times AM0})\) 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 temperature of laser tube is obtained as 434 K. However, the circulation of lasant in the tube is required to avoid \(I_2\) formation by pyrolytic. The velocity has to be 0.041 \(\text{m/sec}\). The rest of the parameters 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 exponential gain saturation. Since low solar concentration \((S_o = 160 \text{ times AM0})\) 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 to medium is 46 kW. Thus, the flow velocity to remove 46 kW becomes 2.2 \(\text{m/sec}\) 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 (Lee, 1984). The experimental setup consists of a solar simulator (40-kW 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 output 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 factor correction \((\eta_f = 0.8488)\) because of the frustum-like formation 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 (thermal, mass, optical power) can be relaxed and the overall weight estimated in this design study can be drastically reduced. Even though the theoretical modeling significantly understimates the laser output power, the difference does not indicate a problem with the theoretical model. This difference may also be attributed to the difference in configurations 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...
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 weight. 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 communication (from laboratory notes).

The 50-kW DSPIL system is $10,725 \text{ kg}$ and the specific power is $4.7 \text{ W/kg}$.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|}
\hline
Year & Iodide & V (cm) & S (sec) & P (Watt) & Ref. \\
\hline
1981 & t-C₄F₁₁ & 16 & ~10,000 & 4 & Lee and Weaver (1981) \\
1982 & t-C₄F₁₁ & 30 & ~1,300 & 10 & Lee, Lee, and Weaver (1986) \\
1989 & t-C₄F₁₁ & 47 & ~1,000 & 14 & Lee et al. (1989) \\
1990 & t-C₄F₁₁ & 153 & ~1,000 & 20 & From laboratory notes (1990) \\
1992 & t-C₄F₁₁ & 203 & ~1,300 & 30 & Tabibi et al. (1992) \\
1993 & t-C₄F₁₁ & 203 & ~1,000 & 46 & Tabibi et al. (1993) \\
\hline
\end{tabular}
\caption{Performances of laboratory-scale DSPIL}
\end{table}

The aperture area, $A_{\text{c}}$, of a concentrator is determined by the requirement of a solar concentration rate (1180 AM0) into a laser cavity to generate a 50-kW net laser beam power. The aperture diameter is

$$D_e = \frac{4}{\pi} A_{\text{c}} + D_i^2$$

where $D_e$ 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

$$\rho'_{\text{max}} = \frac{D_e}{2 \sin \theta_{\text{max}}}$$

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

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

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 formula

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

The pseudo-parabolic reflector concept for a formation of frustum-like focal volume is shown in Fig. 6.
Fig. 7 A geometry for determining a geometric factor that compensates the geometrical deviation of laser cavity from the frustum-like focal volume.

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

\[ dS = \alpha S_f \sin \theta \frac{d\theta}{A_q} \]

where

\[ A_q = \pi (r_q + r'_q) L \]

and

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

and

\[ r'_q = \frac{\rho \alpha}{2} \left[ 1 - \frac{\alpha}{2} \cot \theta \right] \cos \theta' \]

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

\[ A_w = 2\pi \int_{\theta}^{\theta_{max}} \rho'^2 d\theta \]

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

\[ A_q = \frac{\pi a L}{2} \{ \rho \cos \theta + \rho \cos (\theta - \beta) + L \cos (\theta - \beta)^2 \} \]

in which \( dS_{ref} = 2\pi\eta_s S_f d\theta \). Eventually,

\[ dS_4 = \frac{8\alpha \eta_4 \eta_3 \eta_v S_f}{aL} \int_{\theta}^{\theta_{max}} \frac{\sin \theta d\theta}{(1 + \cos \theta) \left[ \cos \theta + \cos (\theta - \beta) + \frac{L}{2f} (1 + \cos \theta) \cos (\theta - \beta)^2 \right]} \]