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POWER LASER BEAMING AND APPLICATIONS IN SPACE

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Abstract - A brief overview of the concept of power laser beaming in space and its applications are presented. A direct solar-pumped iodine laser with the iodide $t\text{-C}_4\text{F}_9\text{I}$ lasant is described as an example of the power laser system.

1. Introduction

In space, sunlight is one of the few natural resources. However, the technology for conversion of sunlight to electrical power and the mass required to accomplish that conversion are primary constraints which shape space missions. The emerging concept of laser-power beaming, which may provide more power, increased flexibility, and improved economics to missions, offers the potential for an important evolution in space power. When high-power ($> 1 \text{ kW}$) levels are required, a solar-pumped laser operating as the central power transmitter could become valuable /1/.

The first solar-pumped laser was successfully demonstrated in 1963 after the invention of the laser itself. However, until recently, solar-pumped lasers have attracted little attention. Since 1980, NASA has been pursuing high-power solar lasers as part of a space power-beaming research program /2/. The power-beaming system consists of a laser transmitter, beam-directing optics, a laser receiver, and a laser-to-electric power converter. Two basic characteristics of solar insolation, namely low intensity (0.1 W/cm^2) and 5800-K blackbody-like spectrum, impose rather stringent requirements for laser excitation. The low maximum solar concentration achievable and limited utilization of the solar spectrum by the laser medium, which result in a poor system efficiency, are disadvantages in comparison with sources tailored to pump lasers, such as flashlamps, arc lamps, and lasers for pumping.

The advantages of solar lasers are that the solar energy is free, non-local, pollution free, and abundant. Indeed, direct solar-pumped lasers using existing solar furnaces have been reported from Japan (H. Arasi, 18-W, Nd:YAG, 1984 /3/) and Israel (M. Weksler et al., 100 W, Nd:Cr:GSGG, 1987 /4/); (R. M. M. Benmair et al., 12 W, Er:Tm:Ho:YAG, 1989 /5/). A recent high-power accomplishment in the United States is the excitation of a 30-W CW iodine photodissociation laser using an argon-arc solar simulator at NASA Langley Research Center. The NASA program has evaluated theoretically and experimentally IBr, alkyl iodides, such as $\text{C}_2\text{F}_5\text{I}$, $\text{C}_3\text{F}_7\text{I}$, $\text{C}_4\text{F}_9\text{I}$ in various forms in vapor phase; organic dyes and Nd in the liquid phase; Nd in various solid hosts, such as YAG, YLF, GSGG, and alexandrite. In addition, the technology for an electrically powered, large-scale, laser diode amplifier array is being developed /6/. These power-beaming technologies offer the potential for providing the required electricity to advanced space stations, lunar and Mars bases, manned long-range rovers, and

planetary-mission spacecraft /7/. A brief overview of such applications in space and the development of solar-pumped iodine laser systems as the space beam power transmitters will be presented.

2 Laser Power Beaming in Space

Power beaming to spacecrafts can be made with microwave or laser beams from a central beam-power station in orbit, on Earth, or on the lunar surface. The similarities and complementarities of these two bands of electromagnetic waves for future space missions have been discussed elsewhere /7/. While microwave beaming over relatively short distances (< 500 km) can be efficient, only laser beaming is practical for large distances (> 500 km), as shown in figure 1. Because of the wavelength difference, the product of transmitter and receiver diameters for laser-beam systems is approximately 10^4 times that of microwave systems. With mirror diameters of a few tens of meters, laser beaming can cover a range of 10^6 km, encompassing the Moon from the Earth. One study /6/ shows that diffraction-limited laser beams can be transmitted through space at a high efficiency (~ 80 percent) to a receiver of several meters in diameter at 10,000-km ranges.

3. Power Laser-Beaming Applications

Laser beaming can be used as the prime power source, replacing the onboard power source or boosting the built-in power levels of the spacecraft, surface bases, and rovers. For example, surface power sources contemplated for the Moon and Mars could be supplemented by beamed laser power from an orbiting laser power station. The following applications are considered especially important and will be feasible with laser powers of the order of 100 kW. (a) Extending a lunar rover's excursion range by laser beaming. With a 100-kW level laser power station in a lunar orbit the range of the lunar rover could be extended indefinitely (see figure 2). A fuel-cell-powered rover has a range of 50 km because of the mass of the fuel to be carried. However, to provide significant information on lunar geology requires a range of over 3000 km /8/. (b) Boosting onboard power levels of Space Station Freedom (SSF). Figure 3 depicts the concept of power beaming from a solar-pumped iodine laser power station to a photovoltaic receiver on the SSF. The laser station is placed in a high Earth orbit and co-orbiting with the SSF below in a low-Earth orbit (LEO). By receiving power from the laser, SSF frontal area can be reduced by removing the solar panels. This area reduction results in a reduction of the drag and the mass of the SSF, thus minimizing orbit reboost fuel necessary to keep the SSF in the correct orbit. (c) Laser propulsion. This concept has received considerable attention in the past, but its practicality became clear as the laser-power levels increased dramatically in recent years. Even cargo launching to LEO from Earth by laser propulsion is now contemplated /9/. Orbit transfer vehicles to be used for LEO to GEO transfers by laser propulsion may be feasible in the near term and have been studied extensively. However, this topic will not be elaborated here. (d) Probing planetary soil. Using a high-power laser to probe and assay planetary soil has also been proposed. Although a spacecraft failure thwarted the experiment, the LIMA-D project led by USSR was the first such attempt in space. The probing method was based on mass spectroscopy of the ions produced in the plasma formed by the focused beam of a Nd:YAG laser (0.5 J/pulse) close to the surface of the Martian satellite Phobos. Ion time-of-flight was to be recorded with the corresponding range to the surface. A recent concept which uses a solar-pumped iodine laser (2 J/pulse) for a similar mass analysis of the composition of soils on Ceres, an asteroid which a spacecraft may pass at an altitude of 10 km. During one cycle of measurements, approximately 10^4 ions (sufficient for the signal-to-noise considerations), could be counted at this altitude. (e) Many other applications for industrial processes in space are conceivable, and the extension of development efforts on terrestrial laser system to processes for space are expected. One interesting application proposed by a LANL team is to use the laser beam (10 kJ/pulse) as a space "broom" for cleaning up the debris which is ever accumulating in near-Earth orbits /10/.

4 Solar-Pumped Iodine Photodissociation Lasers

Direct solar-pumped laser systems to be operated in space place special requirements on system components. The most important of these are (1) the laser medium should be in a gas or liquid phase to provide continuous cooling and recharging in the laser cavity for high-power (megawatt level) output and continuous operation; (2) high temperature operation should be possible at high laser efficiency to reduce radiator size; (3) chemical reversibility for lasant renewal in space must be possible to alleviate frequent refueling; and (4) efficient use must be made of the solar spectrum to reach laser threshold excitation power below the solar concentration limit.

Among various lasants evaluated, the iodine photodissociation laser was found to be the best qualified and could be scaled up to a lightweight, spaceborne system. Since 1980, NASA Langley Research Center has pursued experimental and theoretical studies to establish a technical base for scaling of laser-power systems. Currently, a 30-W (1.3 μm) CW laser, to our knowledge the world's highest CW power, is operating with a 40-kW solar-simulating arc lamp. Figure 4 shows the absorption curves of various alkyl iodides used for the experiment. Also shown is the air-mass-zero (AMO) solar irradiance spectrum. From the overlapped portion of the absorption curve, the pump power P_a available to the iodide can be estimated

$$P_a = \int_0^{\infty} \Phi(\lambda) (1 - e^{-n\sigma(\lambda)D}) d\lambda \quad (1)$$

where $\Phi(\lambda)$ is incident solar irradiance and n the number density of the iodide, $\sigma(\lambda)$ the absorption cross section, and D the absorbing thickness. Since $\Phi(\lambda)$ has its peak at $\lambda = 488 \text{ nm}$, it is desirable to have the absorption peak at or near this wavelength to have a large value of P_a . The pump or photodissociation rate W_p is proportional to P_a in the iodine laser kinetics. Table 1 lists some important values of laser parameters to compare the iodides. The W_p for $t\text{-C}_4\text{F}_9\text{I}$ is approximately two times that of $\text{C}_3\text{F}_7\text{I}$ because it has peak absorption at $\lambda = 290 \text{ nm}$ and has a slightly wider absorption band in comparison with $\text{C}_3\text{F}_7\text{I}$, which has the peak at $\lambda = 271 \text{ nm}$. Since the iodine laser kinetics are rather well known, no description will be made here. Figure 5 is the experimental setup used for pumping an iodine laser with a solar-simulating, argon-arc lamp. Up to 20 cm of pumping length and a pumping power equivalent to 3000 solar constants are available in the system. With this arrangement, the CW laser-power outputs of two iodides, $t\text{-C}_4\text{F}_9\text{I}$ and $n\text{-C}_3\text{F}_7\text{I}$, were compared under the identical operational conditions, and the output of $t\text{-C}_4\text{F}_9\text{I}$ was found to be approximately twice of that of $n\text{-C}_3\text{F}_7\text{I}$. However, calibrated irradiance measurements showed that the arc-lamp spectrum did not closely simulate the AMO solar spectrum, and the absorbed pumping power measured in solar constants (S. C.) were different for the two iodides. For $t\text{-C}_4\text{F}_9\text{I}$, it was 700 S. C., while for $n\text{-C}_3\text{F}_7\text{I}$, it was 1300 S. C. Therefore, the expected output from $t\text{-C}_4\text{F}_9\text{I}$ would be even higher under equivalent conditions. To verify this estimate, a separate experiment with a flashlamp was performed. The flashlamp light was modified to provide a closely simulated AMO spectrum to the laser medium by placing a filtering jacket to surround the laser tube. The jacket was filled with a mixture of acetone and water that significantly modifies the uv band.

Figure 6 shows the laser output energies obtained from $t\text{-C}_4\text{F}_9\text{I}$ and $n\text{-C}_3\text{F}_7\text{I}$ under identical operational conditions. At its optimum fill pressure for $t\text{-C}_4\text{F}_9\text{I}$ of 30 torr, the output energy is three times that of $n\text{-C}_3\text{F}_7\text{I}$. However, for equal pressures below 10 torr, the efficiency ratio is increased to approximately five, indicating that a high-power, space laser system will be significantly used. In addition to the high efficiency, the $t\text{-C}_4\text{F}_9\text{I}$ offers better chemical recovery, which saves reprocessing and refueling. Theoretical modeling to be used for scaling-up the laser system and synthetic system studies for space deployment have been made /11/.

These studies have shown that there are no technical hurdles for scaling-up the iodine laser system to high power and that this solar-pumped iodine space system will have the lowest specific weight for the laser output power among the many high-power laser systems considered. One possible exception is the laser diode array, which is yet to be developed.

5. Summary

The concept of laser-power beaming, which may have many applications in the space program, has been briefly reviewed. Progress on the direct solar-pumped iodine laser with a $t\text{-C}_4\text{F}_9\text{I}$ lasant is shown to be one of the few suitable laser power transmitters for space.

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TABLE 1. PHOTODISSOCIATION PARAMETERS OF IODIDES

Iodide	$i\text{-C}_3\text{F}_7\text{I}$	$n\text{-C}_3\text{F}_7\text{I}$	$t\text{-C}_4\text{F}_9\text{I}$
Absorption Peak λ_{max} , nm	273	271	288
Absorption Bandwidth $\Delta\lambda$, nm	42	42	50
Absorption Cross Section σ_{max} , 10^{-19} cm ²	6.0	7.8	6.0
<Quantum Yield>	0.91	0.98	0.88
Photodissociation Rate/s.c. 10^{15} s ⁻¹	1.4	1.22	2.6
Vapor Pressure at Room Temp., Torr	422	351	76
Dimer Formation, k_3 , 10^{-12}	0.65	3.0	≈ 0

Fig. 1. Transmitter and receiver dimensions required for microwave and laser systems.

Fig. 2. A lunar rover powered by an orbiting laser. The laser power of 10-100 kW will support the rover for excursion in unlimited ranges.

Fig. 3. Concept of power beaming from a solar-pumped laser station to the Space Station Freedom (SSF) for boosting the built-in power level.

Fig. 4. Absorption curves of iodides and solar irradiance spectrum in near uv band.

Fig. 5. Experimental setup for iodine laser pumping. The arc lamp is used to provide solar-simulated irradiance. The iodide vapor flow in the laser tube is due to thermal gradient between the evaporator and the condenser.

Fig. 6. Laser outputs from $t\text{-C}_4\text{F}_9\text{I}$ and $n\text{-C}_3\text{F}_7\text{I}$ under identical pumping conditions.