A SOLAR-PUMPED LASER FOR SPACE USE

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Abstract

A solar-pumped laser for space use is reviewed in relation to the laser medium employed. The characteristics of a solar-pumped solid-state, gas and liquid laser are discussed respectively. Our experimental results on the solar-pumped Nd:YAG laser using a large solar concentrator are reported also.

1. Introduction

Coherent laser light is important in space for optical communication, laser propulsion, energy conversion and materials processing. Concentrated solar radiation can be used there to excite a laser medium optically. Although it is possible to operate a laser using the electric power generated by solar cells or other solar-electric conversion devices, a direct conversion of concentrated solar radiation to coherent laser output is more attractive because of high conversion efficiency and design simplicity. A high conversion efficiency in a direct solar pumped laser system is arising from the direct photon-to-photon conversion. In addition, an energy source naturally available in space is limited to the solar radiation. Therefore, a direct conversion of solar radiation into coherent laser light is an important space technology to be developed.

The application of solar-pumped laser to a solar power satellite (SPS) is discussed by R. Taussig et al. (Ref. 1) and C. N. Bain (Ref. 2). The solar-pumped laser appears to be the best candidate for SPS project from the viewpoint of weight and efficiency. The principal advantage of laser power transmission resides in its capacity to be tightly collimated, hence, requires a relatively small receiving antenna or collector on the earth, compared to microwave beaming.

A solar-pumped laser can be classified into three types according to the laser media utilized. In the following, solid-state, gas, and liquid laser are reviewed successively. In the last section, our experimental results on a solar-pumped Nd:YAG laser using a large solar concentrator will be presented.

2. Solar-pumped solid-state laser

A solid-state solar-pumped laser system utilizes a crystal or glass as a laser medium. The attainable maximum cw output of this laser is limited to several hundred watts due to small crystal size and low thermal conductivity of crystal and glass. Therefore, this system is adequate for the use of optical communication and laser micro processing of materials in space.

The first attempt of a solar-pumped solid-state laser was reported by C. G. Young(Ref. 3), who excited Nd:YAG crystal using a paraboloidal concentrator 61 cm in diameter and obtained a laser output of 1 W.
Nd$^{3+}$ ions in YAG (Yttrium Aluminium Garnet: $Y_3Al_5O_{12}$) crystal absorb some part of solar radiation to realize the inverted population condition which is necessary for laser oscillation. The Nd$^{3+}$YAG laser is a four-level system as represented by a simplified energy level diagram in Fig. 1. The laser transition, giving wavelength of 1.06 $\mu$m, originates from the $^4F_{3/2}$ state and terminates at $^4I_{11/2}$ state. The ground state of Nd$^{3+}$ is the $^4I_{15/2}$ state. Nd$^{3+}$ ions sited on the ground state absorb pumping light (solar radiation in the case of solar-pumped laser) and make a transition to the $^4F_{3/2}$ state or a number of relatively broad excited states. Nd$^{3+}$ ions pumped to the excited states make a non-radiative transition to the $^4F_{3/2}$ state. As a result of these transitions, Nd$^{3+}$ ions are accumulated to the $^4F_{3/2}$ state and an inverted population condition between the $^4F_{3/2}$ state and the $^4I_{11/2}$ state is achieved.

Excitation spectrum of $^4F_{3/2} \rightarrow ^4I_{11/2}$ fluorescence is shown in Fig. 2 (Ref. 4). Due to the narrowness of excitation bands, only a small part of solar radiation is absorbed by Nd$^{3+}$ ions. In order to increase a conversion efficiency of solar radiation to coherent laser light, the doped ions in crystal must have wide absorption bands in the spectral range of solar radiation. The Cr$^{3+}$ ions doped in crystal generally show strong and wide absorption bands in visible region. From this fact, J. Falk et al. (Ref. 5) examined solar-pumped Nd:Cr$^{3+}$YAG laser by using the optics similar scale to that of Young, and achieved 5.6 W laser ouput in multi-mode. Doping with 0.1 $\%$ Cr$^{3+}$ ions in addition to 1$\%$ Nd$^{3+}$ ions increases the effective pumping of Nd$^{3+}$ ions to the upper laser level by energy transfer from the Cr$^{3+}$ ions, which have initially absorbed the solar radiation with high efficiency.

However, the doping of Cr$^{3+}$ ions in Nd$^{3+}$YAG crystal degrades the optical quality of crystal due to the difference of ionic radius between doped ions and constituent ions in host crystal. Recently, Nd$^{3+}$ and Cr$^{3+}$ doped GSGG (Gadolinium Scandium Gallium Garnet) crystals have been grown successfully. Since there is no problem about miss matching of ionic radius in this crystal, we can obtain a large laser crystal with high optical quality. In this crystal, the Cr$^{3+}$ ions which have initially absorbed the pumping light, transfer their energy to Nd$^{3+}$ ions to realize the inverted population condition. The addition of Sc$^{3+}$ ions promotes the transfer rate of energy from Cr$^{3+}$ to Nd$^{3+}$ ions. It has been reported that by using Xe or Kr lamp as
a pumping light source, the conversion efficiency from electric power to laser output in this crystal is 3-4 times higher than that of Nd:YAG crystal. In the case of a solar-pumped Nd:Cr:GSGG, this value of conversion efficiency can be expected also. Therefore, Nd:Cr:GSGG crystal is considered to be one of the candidates for obtaining a high power laser pumped by solar radiation.

Other interesting laser crystal containing Cr$^{3+}$ ions is Alexandrite Cr:BeAl$_2$O$_4$ (Ref. 6). The energy level diagram of Cr$^{3+}$ ion in BeAl$_2$O$_4$ crystal is shown in Fig. 3 considering a four-level laser system. Absorbing visible light, Cr$^{3+}$ ions are optically pumped from $^4$A$_2$ ground state to $^4$T$_1$ or $^4$T$_2$ excited state. As these exited Cr$^{3+}$ ions make a non-radiative transition to $^4$T$_2$ or $^2$E state, an inverted population arises between $^4$T$_2$ state and vibronic states. The laser transition is initiated from $^4$T$_2$ electronic state and terminates at vibronic states. As the vibronic states spread over the width of 2000 cm$^{-1}$, we can make tuning of laser frequency by means of a wavelength selector. Alexandrite is the solid-state lasant in which the oscillation wavelength can be changed. Since the Cr$^{3+}$ ions sited in $^2$E state can be thermally excited to $^4$T$_2$ state, the efficiency of laser oscillation becomes higher with increasing temperature up to 300 °C. These characteristics may be maintained in the case of solar pumping.

The feasibility model of solar-pumped Nd:YAG laser communication system in space has been discussed by J. Falk et al. (Ref. 4) and M. Ross et al. (Ref. 7). To support a 1000 Mbit/s data transfer capability, Nd:YAG laser must be mode-locked. Additionally, it is preferable to use a frequency-doubled Nd:YAG laser, because the much shorter frequency-doubled wavelength at 532 nm enables much narrower beamwidths for the optics of same size. From these considerations, solar-pumped Nd:YAG laser was acoustooptically mode-locked and frequency-doubled simultaneously using a Ba$_2$NaNb$_5$O$_{15}$ single crystal.

The highest output so far reported in solar-pumped solid-state laser is 40 W in multi-mode which has been obtained in our solar-pumped Nd:YAG laser experiments using a large solar concentrator. Our experimental results will be described later.

3. Solar-pumped gas laser

A lasant in gaseous state is capable of obtaining a high power solar-pumped laser due to a large excitation volume. A theoretical investigations on solar-pumped gas lasers have recently been reported by J. W. Wilson (Ref. 8). He had an interest to find out the gases to be utilized as a lasant in a solar-pumped gas laser which makes a better match to the solar spectrum and have high quantum efficiency. He has investigated the basic kinetic processes and the range of rate constants for energy for various gases and gas combinations. On the basis of these considerations, he has given the critical gas properties to guide the choice of candidate gases for testing as a solar-pumped gas laser in space.

The first experimental study of solar-pumped gas laser to obtain
higher powers has been done by W. R. Weaver and J. H. Lee (Ref. 9) using perfluoropolyiodide \((C_3F_7I)\) as lasant. They have examined the requirement on the choice of lasant for a solar-pumped gas laser in space. Important characteristics are: (1) a gas-phase lasant to effect continuous cooling and recharging for high-power operation; (2) high temperature operation to minimize cooling requirement; (3) chemical reversibility to renew the lasant in space; and (4) broadband pumping to use the solar spectrum efficiently. They selected perfluoropolyiodide \((C_3F_7I)\) as a preferable lasant for initial laboratory tests due to low threshold, high gain, high temperature operation, and suitable lasing wavelength. The upper level \(I(5^2P_{1/2})\) of the iodine laser transition is produced by photoysis: \(C_3F_7I+I(5^2P_{1/2}) \rightarrow C_3F_7 + I(5^2P_{3/2})\) and the lower level is the ground state of the iodine atom \(I(5^2P_{3/2})\). The lasing wavelength is 1.315 \(\mu\)m and the effective pumping band is between 250 and 290 nm, corresponding to the utilization of only 1% of the total solar spectrum. The solar radiation on the earth is lacking in intensity below 300 nm due to the atmospheric scattering and absorption. Therefore, \(C_3F_7I\) is optically pumped with the radiation from a xenon arc solar simulator with a 4 kW beam power and a spectral distribution of air mass zero solar spectrum with an average spectral deviation of 20%. Continuous lasing for over 10 ms and output exceeding 4 W were obtained for a single static. The laser was also operated with quasi-steady flow for up to 200 ms at a 30 Hz pulse rate.

B. M. Elson (Ref. 10) has also reported a solar-pumped \(C_3F_7I\) laser experiment. To increase a laser gain, he has investigated long path \(C_3F_7I\) laser pumped by two 5 kW solar simulators. He has obtained 14 W of cw laser output in simulated solar pumping experiments.

Recently, W. H. Christiansen (Ref. 11) have been demonstrated a laser oscillation in other type of solar-pumped gas laser. The infrared radiation from an intermediate blackbody cavity which is heated by focused solar radiation is used to optically pump a laser medium. They employed the mixtures of \(CO_2\), He, and Ar as a lasant. These mixed gas are contained within a laser tube which is surrounded by a heated blackbody cavity and transparent to visible and infrared radiation. A laser oscillation occurs from a transition between vibrational levels of \(CO_2\) molecules. Its laser wavelength is 10.6 \(\mu\)m. A main excitation band of \(CO_2\) lies in the wavelength region around 4.3 \(\mu\)m. Radiation emitted by the wall of a blackbody impingres on a transparent laser tube containing the laser gas. The \(CO_2\) absorbs a radiation near 4.3 \(\mu\)m. The residual radiation is reabsorbed and thermalized by the wall of blackbody. Then, the radiation having the original spectral distribution is re-emitted from the wall of blackbody and the process is repeated. In this way, the pumping radiation of this type of laser is continuously replenished and all of the energy source is utilized. From this fact, it is expected to obtain efficiency greater than that obtained when solar radiation is used directly with media having narrow-band absorption.

R. J. Insik and W. H. Christiansen (Ref. 12) have reported the experimental results on a blackbody-radiation-pumped \(CO_2\) laser. An electrically heated oven is used to simulate the solar heated blackbody cavity. They have obtained for the first time, a continuous lasing of a blackbody-radiation-pumped laser with mixtures of \(CO_2\), He and Ar. A maximum laser output of 6.1 mW occurred for a mixture containing 20 percent \(CO_2\), 15 percent He and 65 percent Ar at the pressure of about 8 torr.

4. Solar-pumped liquid laser

A suitable dye-solvent can be employed as a lasant of a solar-pumped liquid laser system. The energy level diagram of a typical
organic dyestuff molecule is shown in Fig. 4. \( S_0, S_1, S_2 \) etc. designate the ground singlet, first excited singlet, and higher excited singlet electronic states, respectively, and \( T_1, T_2 \) etc. designate the consecutive triplet electronic states. The horizontal lines represent vibrational sublevels of the electronic states. Dye molecules sited on the ground vibrational level \( G \) within the ground electronic state \( S_0 \) absorb concentrated solar radiation and make a transition to the excited vibrational level \( e \) of the first excited singlet \( S_1 \). Dye molecules excited to \( e \) state are deactivated to the ground vibrational level \( E \) of the \( S_1 \) state by non-radiative transition and also make a transition to the first triplet state \( T_1 \) via intersystem crossing. Laser operation occurs between \( E \) and the excited vibrational level \( g \) of the \( S_1 \) state. Depending on the dye molecule selected, the optimum laser frequency varies within the near infrared and visible region.

For obtaining the efficient dye-laser system, it is important to investigate the quencher which depopulates the \( T_1 \) state, because the long life time of \( T_1 \) state degrades the dye molecules and decreases laser efficiency. H. C. Volkin (Ref. 13) has been analysed the rate equation for solar pumped dye laser system. From known transition-rate characteristics in relation to electronic state properties and energy level spacings, he obtained criteria for the molecular energy level structure by which to select candidate dye-molecules for planned synthesis. He proposed some specific dye-molecules that satisfy the predicted criteria.

5. Experimental studies on solar-pumped Nd:YAG laser using a large solar concentrator

We started the research on solar-pumped laser by using a large solar concentrator installed in the Solar Energy Laboratory of our Institute and made the first step in operating a cw 18 W Nd:YAG laser successfully (Ref. 14). This solar concentrator was designed and constructed as a solar furnace to obtain high temperatures up to 4000 K for the crystal growth of materials with high melting points, and also for high-temperature physics (Ref. 15). The solar concentrator consists of a heliostat and a paraboloidal mirror. The heliostat can follow the sun and always reflects the solar radiation parallel to the optical axis of the fixed paraboloidal mirror. The paraboloidal mirror, 10 m in aperture and 3.2 m in focal length, is a mosaic composed of 181 mirror segments. As each mirror segment is polished accurately into portion of a paraboloid, an accurate sun image is formed at the focal point and its image size is the same as that of theoretically given. On clear days, this mirror concentrates 55 kW of solar power within the circular area about 40 mm in diameter. The concentration ratio of solar radiation by a paraboloidal mirror has been calculated by O. Kamada (Ref. 16) for a flat and cylindrical target as a function of aperture ratio. The calculated results are shown in Fig. 5. Since the apperture ratio of our solar concentrator is 3.2, the concentration ratio of solar radiation is about 5.2 X 10^4.
for a flat target. This value of concentration is quite sufficient for the optical excitation of laser medium.

We have chosen Nd:YAG crystal as a laser material, because Nd:YAG has the advantages of high efficiency, the ability to perform the cw operation, and good beam quality among the laser materials available at present. Furthermore, solid-state laser materials are preferable as compared with gaseous or liquid laser materials for the use in space, because the problem of recharging or recycling does not occur.

In the initial stage of experiment, a Nd:YAG laser rod was irradiated laterally by concentrated solar radiation. The Nd:YAG rod was supported in the center of a pyrex glass tube 50 mm in diameter and was cooled directly by running water at a flow rate of 2.4 l/min. The YAG rod is 4 mm in diameter and 75 mm in length and was grown by Union Carbide Co., Ltd., with 0.9 atomic percent Nd³⁺ ions. The end surfaces perpendicular to the rod's axis are anti-reflection coated. The laser cavity consists of two dielectric mirrors; one is a totally-reflecting concave mirror 2.5 m in focal length and the other, a plane output mirror 7% in transmission. The cavity length is 60 cm.

The laser assembly was mounted at the focal point of the paraboloidal mirror as shown in Fig. 6. Since a considerable amount of the solar radiation concentrated at the focal point is not absorbed by the Nd:YAG rod, owing to the difference in cross-section between the sun's image and the rod, and to the relatively small absorption coefficient of the lasant, a water-cooled cylindrical mirror was placed just behind the pyrex glass tube to reflect the transmitted solar radiation back to the rod. The laser output was monitored with a Scientech model 38-0101 disc calorimeter and the beam profile was examined, at a distance of 2 m from the output mirror, using a fluorescence plate in which rare-earth ions convert the infrared laser light to visible light by stepwise processes.

A typical example of the temporal variation of the laser output is shown in Fig. 7. The variation of laser output, with the period of 1-3 min, is caused by the tracking error of the sun. The higher-frequency component of the output variation is considered to be caused by the transverse-mode
fluctuations because the far-field pattern as observed on the fluorescence plate changes with a similar period. The maximum output of the laser exceeded 18 W in multi-mode.

To meet various applications of solar-pumped solid-state laser in space, a laser of higher output will be required. In order to increase the output power, it is necessary to use a large laser crystal and a highly concentrated solar radiation. When a laser rod is excited by intense radiation, it behaves like a convex lens with the focal length which depends on the intensity of excitation light. This phenomenon is called as the thermal lens effect, and is an important parameter to estimate a stability of a laser cavity.

In the next stage of experiment, a large laser crystal has been used to increase the output and to estimate the thermal lens effect. The employed crystal was grown by Tsuchi Metal Industries Co., Ltd. in Japan. The dimension of the laser crystal is 10 mm in diameter and 100 mm in length. The experimental setup is shown in Fig. 8. The laser rod is cooled by running water in similar way as in the previous experiment and irradiated longitudinally by the cone of concentrated solar radiation. The thermal lens effect was estimated by measuring a focal point of He-Ne laser beam which was transmitted through the laser rod. The He-Ne laser beam was expanded by lens system to have the same diameter as that of the laser rod. The measured focal length of laser rod under irradiation depends on the concentration ratio of the solar radiation as shown in Fig. 9. The focal length decreases as the intensity of excitation light increases.

![Fig. 8 Experimental setup of a solar-pumped Nd:YAG laser. Nd:YAG rod is irradiated longitudinally by the concentrated solar radiation.](image)

![Fig. 9 Focal length of laser rod vs. concentration ratio of solar radiation.](image)

In this experiment, the same laser cavity system as in the previous experiment is used. W. Koechner (Ref. 17) estimated a stability of laser resonator taking into account the thermal lens effect. According to his results, the measured focal length of irradiated laser rod is in the stable resonator region for the optical parameters of our laser cavity. The obtained laser output is shown in Fig. 10 as a function of the concentration of solar radiation. The maximum output exceeded 40 W in multi-mode, which is the highest value so far reported for solar-pumped laser (Ref. 18).

Some applications of solar-pumped laser might require high peak power obtained by Q-switching techniques and shorter wavelength light obtained by second harmonic generation from the fundamental laser light. Some of these experiments are now in progress.

The optimization of a laser pumping optics must be examined to increase a conversion efficiency of solar energy. The direct type solar concentrator is profitable for the laser pumping from the view point of effective utilization of solar energy, because a reflection loss of heliostat can be eliminated. If a laser rod is mounted at focal point of the concentrator of this type, however, the laser beam
changes its direction with the orientation of concentrator to follow the sun. This difficulty can be eliminated by transmitting the concentrated solar radiation to the laser pumping optics by using a flexible optical fiber as shown in Fig. 11. By this system, the laser can be fixed independently to the orientation of solar concentrator; thus, we can use coherent laser light at any desired place. The preliminary study on this system is now in progress also.

6. Conclusion

The characteristics of a solar-pumped solid-state, gas and liquid laser are discussed. These arguments have made clear that the direct solar-pumped laser described here offers the possibility of greatly enlarging the range of laser application in space. Therefore, a direct conversion of solar radiation to coherent laser light is an important space technology to be developed.

A solar-pumped solid-state laser is profitable for optical communication in space from the viewpoint of its simplified structure and moderate output power. We have obtained a stable laser output of 40 W in our solar-pumped Nd:YAG laser experiments using a large solar concentrator. This laser output is the highest power so far reported in solar-pumped laser. A solar-pumped gas laser is considered as a candidate to obtain high power solar-pumped laser. In both cases of solar-pumped solid-state and gas laser, it is necessary to survey new laser crystals or new gas mixtures applicable to a laser with high power and high efficiency.

7. Acknowledgements

The author would like to thank Emeritus Prof. Dr. T. Sakurai for his continued encouragement and critical reading the manuscript. He also expresses his thanks to A. Kaimai for technical assistance in solar-pumped Nd:YAG experiments and is also grateful to Dr. K. Shiroki of Tohoku Metal Industries Co., Ltd. for providing the Nd:YAG laser crystal.
References


