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FINAL REPORT

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INSTITUTION:	Department of Physics Hampton University Hampton, Virginia 23668
TITLE OF RESEARCH:	Direct Solar-Pumped Iodine Laser Amplifier
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PRINCIPAL INVESTIGATOR:	Kwang S. Han
CO-PRINCIPAL INVESTIGATOR:	In Heon Hwang
RESEARCH ASSOCIATE:	Larry V. Stock

Abstract

This report gives the final summary of the research work performed under the NASA grant NAG1-441 entitled "Direct Solar-Pumped Iodine-Laser Amplifier" which has been performed from March 1, 1984 to February 28,1990. The optimum conditions of a solar pumped iodine laser are found in this research for the case of a continuous wave operation and a pulsed operation. The optimum product of the pressure(p) inside the laser tube and the tube diameter(d) was pd=40~50 torr-cm on the contrary to the case of a high intensity flashlamp pumped iodine laser where the optimum value of the product is known to be pd=150 torr-cm. The pressure-diameter product is less than 1/3 of that of the high power iodine laser.

During the research period, various laser materials were also studied for solar pumping. Among the laser materials, Nd:YAG is found to have the lowest laser threshold pumping intensity of about 200 solar constant. The Rhodamine 6G was also tested as the solar pumped laser material. The threshold pumping power was measured to be about 20,000 solar constant.

The amplification experiment for a continuously pumped iodine laser amplifier was performed using Vortek solar simulator and the amplification factors were measured for single pass amplification and triple pass amplification of the 15 cm long amplifier tube. The amplification of 5 was obtained for the triple pass amplification.

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I. Introduction

A solar pumped laser may serve as a prime power source for the future space investigation. Although there could be various alternatives for power generation in space, the lasers can easily be employed in the power distribution to various distant space systems such as the orbital transfer vehicles, lunar transfer vehicles and various satellites, due to the highly directional characteristics of the beam. The laser beam can be concentrated in a small area with high power density due to its shorter wavelength compared with that of the micro-wave and its low divergence angle from generation, which is very advantageous property for certain application such as the laser propulsion of space vehicles.

The research on the development of "Direct Solar Pumped Iodine Laser Amplifier" was initiated from March 1, 1984, and continued for 6 years at NASA Langley Research Center. During the research period, most of our efforts were concentrated on the development of the basic concept of the Solar Pumped Iodine Laser MOPA (master-oscillator power-amplifier). On the other hand, various laser materials were also tested its possibility as the solar pumped laser candidate.

The MOPA concept is employed in the high power fusion laser development using energy storable laser medium such as Nd^{+3}:YAG(or Glass), CO_2 and atomic iodine that have long excited level lifetime. The iodine laser MOPA system is considered as a fusion driver and is extensively studied in Max Planck Institute at Garching, West Germany[1]. However, the solar pumped iodine laser should somewhat be different in

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operational conditions from the short pulse flashlamp pumped high power laser used in laser fusion research.

The MOPA system is very advantageous to obtain high peak power in space, however, the material should have sufficient long upper state lifetime to store high energy from the weak solar pumping. Among the various laser materials, the atomic iodine has long upper state lifetime of 130 msec. The population inversion in the iodine laser is mostly obtained by photodissociation with UV radiation of the perfluoro-alkyliodide such as i-C_3F_7I or n-C_3F_7I which absorbs radiation in the range from 230 nm to 320 nm. When the iodides are dissociated with UV radiation, it produces almost 100% of the excited atomic iodine. Subsequently, the excited atomic iodine transits to the ground state and generates the laser radiation at the wavelength 1.315 μm.

In this research, we could identify the solar pumped iodine laser amplifier characteristics under the solar simulating radiation pumping. We found that the operational condition of the solar pumped iodine laser is quite different from that of the high power flashlamp pumped short pulse iodine laser.

In addition to the experimental works, the theoretical modeling of the iodine laser was performed to understand the physics involved in the laser performance and to provide the optimum experimental conditions. However, due to the many unknown physical and chemical processes in the iodine laser action, the theoretical calculation does agree with the experimental results in a very limited experimental situation.

II. Iodine Laser Amplifier Experiment

As a first step of the experiment, we constructed a long flashlamp pumped iodine laser amplifier. To simulate the solar radiation in space, a parabolic cylindrical reflector was employed to make the light from the flashlamp parallel. Another same parabolic cylindrical collector was used for the collection of the light into the laser amplifier tube. The flashlamp was 115 cm long and the inner diameter was 5 mm. The flashlamp was driven with a 12.5 μF capacitor at various charging voltage and the pulse width was about 100 μsec at 30% of the peak.

The amplifier tube was made of a UV transmission tailored quartz tube (Germisil) of length 117 cm. The inner diameter of the amplifier tube was 11.5 mm. To compare the pumping intensity by the flashlamp with the AMO (air mass zero) solar radiation, the spectral irradiance was measured from inside of the tube. The radiation energy in the absorption band of i-C_3F_7I concentrated into the amplifier was measured to be 0.09% of the electrical energy applied to the flashlamp. From this measurements, the pumping intensity was estimated to be equivalent to 3.0×10^4 solar constants and 2.4×10^4 solar constants when the flashlamp was driven with electrical energy 1.41 kJ and 0.97 kJ respectively.

To investigate the amplification characteristics of the amplifier, we set up a small iodine laser oscillator. The oscillator was pumped with a 10 cm long flashlamp and was enforced to lase in TEM_{00} mode by inserting 2 mm diameter aperture in the laser cavity. The laser output from the oscillator was about 6 mJ with pulse duration of 4 μsec. The amplification was measured at different injection times of the laser

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pulse from the oscillator to the amplifier. The highest amplification by this experimental arrangement was about 3.2 (output laser energy/input laser energy) at the injection time of about 100 μsec from the beginning of the amplifier pumping. This results shows that the energy storage of the amplifier is the highest at the end of the amplifier pumping and proves the long excited state lifetime.

We also studied the temperature effect of the laser gas on the amplification by varying the temperature of the amplifier tube. Keeping the iodide molecule density the same in the amplifier tube at each temperature, the amplification was measured at different injection time of the oscillator output into the amplifier. The experimental results shows that the amplification reaches its maximum at the injection time of around 100 μsec for the temperature range from room temperature (23 oC) to 141 oC. However. the amplification after 100 μsec reduces drastically for hotter gas. This indicates that the higher the temperature of the gas, the shorter the energy storage time in the amplifier tube after pumping. The detail of the experimental set up and results are described in Appendices 1 and 2.

We also tested other perfluoro-alkyliodides as the amplifying medium of the solar pumped iodine laser amplifier such as $t-C_4F_9I$ and $n-C_4F_9I$ with the same experimental set up. The $n-C_4F_9I$ has very similar UV absorption characteristics with the $n-C_3F_7I$ due to the similar chemical structure. However, the $t-C_4F_9I$ has the widest absorption band in the UV range of spectrum among other iodine laser materials and also the absorption peak is at 290 nm which is much longer wavelength compared with the absorption peak wavelength of other iodides[2]. The fact that the

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$t-C_4F_9I$ has the absorption peak at the longer wavelength indicates the high rate of the solar spectrum utilization in the pumping and high efficiency of the laser performance due to the low spectral irradiance in the solar spectrum below 250 nm. The amplification factor obtained with the $t-C_4F_9I$ is about twice of that obtained with $i-C_3F_7I$. Moreover, the energy storage capability after the amplifier pumping is superior than other iodides (see Appendix 3). This measurement is quite contradictory with the high measured value of the quenching rate of the excited state atomic iodine by the parent molecule[3]. This requires more careful and precise measurement of the quenching rate of the excited iodine by the parent molecule.

III. Continuous Wave Iodine Laser

The best material for the solar radiation pumped laser is the one which can be pumped continuously and can produce CW laser radiation. A couple of research group did experiment on the CW solar pumped laser using some solid state laser materials such as Nd+:YAG[4],[5]. However, the solid state laser has definitely some drawbacks for the development of scaled-up solar pumped laser system. The most serious one is the heat management produced in the course of pumping. The produced heat is very difficult to remove due to the very low heat conductivity of the solid material. Moreover, the heat removal from the laser material should rely on the radiation when the laser is operated in space, which requires unacceptably large radiator.

Another difficulty of the solid state laser material is the available

size. Due to the limited durable power density of the solid material, a large size of laser material is necessary to obtain high power laser output. Not only the weight of the laser material is a disadvantage but also the crystal growing is another problem.

In contrast to the solid laser material, the heat management in gas or liquid laser material is comparatively easy. The heat produced in the laser could be removed by circulating the medium. Moreover, the refractive index change in gas is usually negligibly small compared with the solid material, which causes the thermal lensing in solid laser material.

In this research period, we tested the CW laser possibility of the perfluoro-alkyl iodide by pumping with a solar simulator. The solar simulator used in this research was an argon arc lamp which could generate optical output upto 45 kW. As a first attempt we installed a 12 mm I.D. laser tube in an elliptic cylindrical pumping cavity with the solar simulator. The iodide used was n-C_3F_7I in this experiment and the iodide gas was flowed through the laser tube with a evaporator-condenser unit. With this system, we could obtained 2 W CW laser output for over 2 hours (see Appendix 4). This experimental result is the first CW solar simulator pumped iodine laser.

In the subsequent experiment, we used a 16 mm I.D. laser tube and obtained 10 W CW laser output with pumping power of about 1300 solar constant in the absorption band of the n-C_3F_7I. This output power is the highest ever obtained in the solar pumped gas laser experiment. The detailed experimental configurations and conditions are described in Appendix 5.

IV. Other Laser Materials

In this period of research, Nd:YAG, Cr:Nd:GSGG and Nd:YLF were tested as the solar pumped solid laser materials by using the Tamarack solar-simulator. Among the three laser materials, Nd:YLF shows the lowest laser threshold pump power of about 210 solar constants with a 1/8" diameter by 3" long laser rod[6]. Nd:YAG shows slightly higher laser threshold pump intensity of 236 solar constants. Cr:Nd:GSGG shows the highest laser threshold pump power of 1,500 solar constants and even the solar utilization efficiency is the highest among the three laser materials. Moreover, it has been shown that Cr:Nd:YAG crystal cannot be pumped with higher than 2,000 solar constants due to the serious thermal lens effect. This crystal shows also very weak resistance to the thermal shock. This crystal was very hard to pump with higher than 2,000 solar constant due to the crystal breakage originated from the thermal stress.

The heat conductivity of Nd:YAG is the highest among the three crystals and thus the thermal lens effect is the lowest, which indicates the possibility of high solar constant pumping. However, this crystal has the lowest solar utilization efficiency among the three crystals due to the narrow absorption band and the spectral mismatch between the absorption band and the solar irradiance. The three solid laser materials shows the possibility of solar pumped laser. However, due to the high thresold pump intensity, heat removal from the laser rod looks like the major issue when they are pumped with highly concentrated solar radiation.

Another laser material tested in this period of research was rhodamine 6G solution in methanol. The absorption band of this solution matches very well with the peak of solar irradiance so that the solar

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utilization efficiency reaches to 15%. However, the lifetime of excited state is so short that the laser threshold pump power exceeds 20,000 solar constant, which is obtainable with a very elaborate solar collector. the experimental details and results are shown in Appendices 6 and 7.

V. Solar-Simulator Pumped MOPA

Although many space applications are best served by CW lasers, a continuosly pulsed laser also has good applicability in space, especially for laser propulsion. Among various schemes of continuously pulsed laser, a solar-pumped MOPA(master-oscillator power-amplifier) is a suitable system for generation of high peak power. However, due to weak solar irradiance on earth, a laser material with very long excited state lifetime is necessary to store large amount of energy in amplifier. The excited state lifetime of the atomic iodine is known to be the longest among various laser materials($\sim$130 msec).

In this research period, we attempted to test the solar-simulator pumped laser as a continuously pumped amplifier. To perform this experiment, we had to develop an iodine laser oscillator which could generate highly repetitive pulses. Most of flashlamp pumped iodine laser oscillators are operated below 5 Hz. To increase the repetition rate, a XeCl laser pumped iodine laser was developed in this research period. The laser material used in the oscillator was t-C_4F_9I. As mentioned in the previous section, this laser material is much superior in XeCl laser pumping than n-C_3F_7I or i-C_3F_7I because this chemical has very high photochemical stability. This chemical allowed us to operate the

oscillator almost sealed-off manner. This oscillator could be operated upto 5 Hz which is limited by the power supply for the XeCl laser. Moreover, this chemical showed much higher laser efficiency than n-C_3F_7I or i-C_3F_7I. The detailed experimental set up and results are shown in Appendices 8 and 9.

With this oscillator, we performed an amplification measurement with the continuously solar-simulator pumped amplifier for the first time. The measured small signal amplification was 1.5 with 15 cm long continuously pumped amplifier. When we fold the oscillator beam path twice such that the oscillator beam could pass the amplifier three times, the measured small signal amplification was 5 for both 2 Hz operation and 5 Hz operation. This fact indicates that we could increase the repetition rate much higher. A brief report of the experimental results are shown in Appendix 10.

VI. Theoretical Modeling

In parallel with the experimental works, a theoretical modeling of the iodine laser was conducted. The modeling efforts for the iodine laser were concentrated on the pulsed iodine laser by other research groups aiming on the development of high power fusion driver. In our case, the modeling effort should be concentrated on a CW laser or a long pulse pumped laser.

In the modeling of a CW iodine laser, due to the molecular iodine accumulation, the inclusion of gas flow is very important. To reduce the molecular iodine the iodide gas should be circulated and reprocessed for

long term operation. However in this research period, a kinetic model for a static fill iodine laser was developed and compared to the experiments. A complete kinetic model of the flowing gas iodine laser is under development. The previous modeling results are shown in Appendices 11

VII. Conclusions

The purpose of this research was to realize a solar-pumped iodine laser and to establish a scaling law for the future development of a large scale solar-pumped laser system in space. We tested the iodine laser as a future solar-pumped laser and tested various aspects of the laser system using a solar-simulator which simulates the AMO solar radiation. In the course of this research, we obtained a 10 W laser output power for the first time. Also we have first run a continuously pumped iodine laser amplifier and measured the small signal amplification. Among the various findings of our experiment, the following features are very important for the future research.

1. The operational conditions of the solar-pumped iodine laser are quite different from that of the high intensity flashlamp pumped iodine laser. Therefore, the characteristics of the solar-pumped iodine laser should be more clearly manifested.

2. The new iodine laser material t-C_4F_9I, which was found in the Langley Research Center, needs more precise study to measure the kinetic coefficients and requires concentrated experimental efforts to compare with other iodine laser chemicals such as i-C_3F_7I or n-C_3F_7I that are commonly used in iodine laser experiment.

3. The modeling effort should be more stressed to establish a realistic model for a real solar-pumped iodine laser system and to establish a scaling law for the development of a high power space-based solar-pumped iodine laser.

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