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Experimental Study of Solar Pumped Laser for Magnesium-Hydrogen Energy Cycle

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Abstract. 24.4 W of laser output has been obtained by sun-pumped, Cr-codoped Nd:yttrium aluminum garnet ceramic. The water-cooled laser rod was pumped with a Fresnel lens focusing the natural sunlight. By using the advantages of the Fresnel lenses, the maximum output for unit area of sunlight was 18.7 W/m^2. Direct concentrated solar illumination was used to pump a 9mm-diameter, 100mm length rod of Cr:Nd:YAG, which was obtained 9%–14% slope efficiency for the laser output. We have analyzed the Cr:YAG laser medium and found it to be an excellent high-power laser candidate for direct solar-pumping schemes which enhances the laser output about 1.8 times more than Nd:YAG.

1. Introduction

Solar radiation as a renewable energy source can be converted directly or indirectly into other forms of energy, such as heat and electricity. The major drawbacks or issues to overcome of utilization of solar energy are: (1) the intermittent and variable manner in which it arrives at the earth's surface and, (2) the large area required collecting it at a useful rate. Although solar power has many downfalls, its future remains bright as we develop more efficient solutions, and find better ways to use it.

Due to these mentioned barrier in utilizing solar energy, and the huge resource of magnesium, 1.8×10^{15} tons in ocean, we proposed a renewable energy cycle which uses solar laser and magnesium as solar energy reservoir. [1] In this cycle, magnesium reacts with water and produces hydrogen, magnesium oxide, and releases an immense amount of energy which can be used in any engine such as automotive engines. We need to recycle the reaction product, MgO, to obtain magnesium again to close the cycle in terms of material resource. High-power laser irradiation will be necessary for such deoxidization. Solar pumped laser can be an appropriate candidate for converting sunlight to high quality radiation, which is needed in new proposed Magnesium-Hydrogen Energy Cycle. In such a process, solar energy is stored in the magnesium as a potential energy, thus can be used in cloudy days. [2]As shown in the previous paper, 1kW laser is sufficient for magnesium refinement with a 1-mm laser spot. A 300-laser beam (0.5–1 kW each)array scans over MgO surface would produce a hundred kg of magnesium a day. Therefore, the key issue is to build the 0.5–1 kW laser in a way it can be used as one component of arrayed lasers. [1] In order to introduce this cycle as a candidate of renewable energy cycle, development of a high-efficiency solar pumped laser became a vital task.

Shortly after the invention of the laser, scientists began study on directly converting incoherent broadband sunlight into coherent monochromatic laser radiation. Several researchers have investigated lasers powered directly from solar energy; but the efficiencies of the sun-pumped lasers have been too low. The maximum reported slope efficiency for Nd:YAG, 7.1% slope efficiency has been observed.[3] For iodine lasers, solar to laser power efficiency of about 0.5% is expected [4].

In this paper, an economical and high efficiency laser system will be discussed. The proposed solar pumped laser system uses the Fresnel lens of 1.3 m^2 surface area as a sunlight collector which pumped to the Cr-codoped Nd:YAG ceramic medium. The concept of using Fresnel lens as sunlight concentrator improved the maximum output for unit area of sunlight significantly, in comparison with parabolic mirrors or heliostat collector systems.

The maximum output of emitted laser was 24.4 W with a slope efficiency of 12.5±1.5%. The results constitute a record maximum output for unit area of sunlight of 18.7[W/m^2] which is much larger than previous results.

The second approach is Cr-co-doping to Nd:YAG, which will increase the possibility of efficient absorption and optical pumping rate to Nd ion in the solar spectrum. We will discuss the result of enriching Cr to Nd:YAG ceramic which is capable of increasing the fluorescence yield at 1064 nm for various pumping wavelengths by 1.8 times.

2. An effective concentrating device

A solar-pumped laser requires a concentrating device that tracks the sun. The laser cavity and its associated optics are then placed near or at the focal point of the collector. The collector is an optical device used to increase the amount of solar radiation intensity, i.e., the result is a beam of concentrated solar radiation which can reach high levels of optical and thermal insolation.

Most of the previous studies employed the parabolic mirror or heliostat for collecting the sunlight, since the mirror has been believed to collect all range of wavelengths to a small spot without dispersion. Furthermore, the preceding works aimed at larger laser output with larger collector [5, 6, 7]. In this case, Fresnel lens collector is an ideal selection as a main collector for a compact solar pumped laser system which is shown in Fig.1.

Figure1- Test system for laser from natural sunlight. Two pieces of Fresnel lens are used.

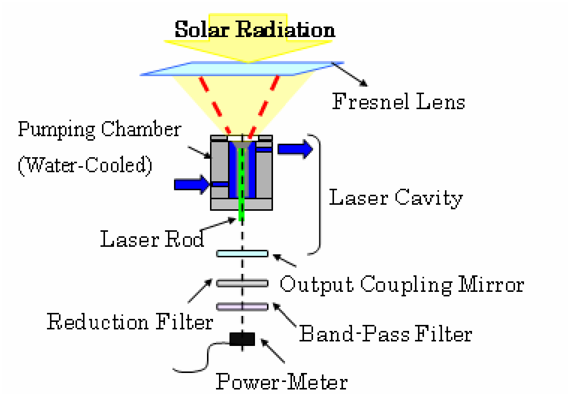

Figure 2. The schematic view of experimental setup. All the system is in one unit and moves together.

As shown in Fig.1, two Fresnel lenses (1400 × 1050mm, f=1200mm) is mounted on a two-axis sun tracker platform and focuses the solar radiation towards laser cavities, Since the focusing of Fresnel lens is limited to a size of 11 mm, we used a cylindrical cavity to enhance the solar power with laser media. The cavity holds the laser rods of 3–9 mm in diameter and 100 mm in length along the central axis. The focused sunlight is incident into the edge of the cavity along the direction of cylinder axis. One end of the laser rod has high- reflection at laser wavelength coating while the other end has antireflection coating. As shown in figure 2, a 1064-nm band-pass filter with a 10-nm bandwidth was used to measure laser output power. Two pieces of Fresnel lens were used in order to test simultaneously two cases of laser cavity, as oscillator and amplifier.

The absolute value of the focused power was measured by the power meter placed at the focal point. The power at the focal point averaged over 2 min was 674 W for source sunlight of 779 W/m^2. Therefore, the sunlight of 1016 W is incident on the Fresnel lens and the 66.4% is focused at the focal point. The effect of concentrating device on overall solar pumped laser system performance can be evaluated by a parameter defined as laser output power in unit of concentrating area. The authors achieved 24.4 watts over 1.33×0.98 m^2 area of Fresnel lens, which is calculated to a record total area performance of 18.7 W/m^2. Among the previous works, the largest total area performance was 6.7 W/m^2 from collecting segmented mirrors. Indeed, Fresnel lens can be effective in compact solar lasers.

3. The effects of Co-doping Cr to Nd:YAG crystal

Among optically pumped lasers, the solid-state lasers are the most attractive for solar pumping because of their compactness, reliability and efficiency as well as long and good experiences in many applications [8].There have been several publications on solar pumped solid-state lasers operating at room temperature. Up to now, most of works on solar laser use the Nd:YAG laser, which has high heat resistance and its' lasing wavelength is close to visible spectra [5, 6, and 7].

According to Saiki et al. results, Cr-codoped Nd:YAG can enhance absorption in the wavelength range near 400–500nm and 600–700 nm which is inside the solar spectrum [9]. The fluorescence yield was measured at 1064 nm from Cr-codoped and nondoped Nd:YAG laser media pumped by various wavelengths. The mass fractions of Nd and Cr are 1 and 0.1 % respectively. Figure 2 shows a relative fluorescence yield that includes the solar spectrum. When integrated through the spectrum, the Cr-co-doped medium yields 1.8 times higher fluorescence than Nd:YAG.

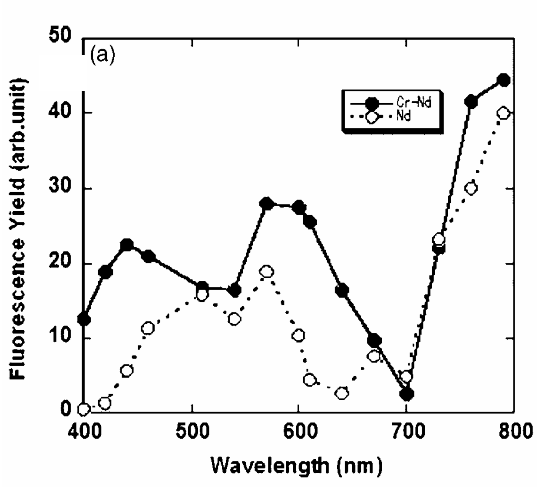

Figure3- Measured fluorescence yield at 1064 nm various pumping wavelengths for Cr-codoped and nondoped laser media.

4. High slope efficiency solar laser

An important property of an optically pumped laser is its slope efficiency (*or* differential efficiency), defined as the slope of the curve obtained by plotting the laser output versus the pump power. Usually, this curve is close to linear, so that the specification of the slope efficiency as a single number makes sense. For comparisons of power efficiency, it is usually fair to compare slope efficiencies with respect to incident powers since the efficiency of a real system with full power pumping reaches it asymptotically. Figure 4 shows the results on the output laser power for various incident sunlight powers. Incident sunlight was measured simultaneously during the experiment. Since the sunlight is not variable, the incident power was changed by covering the Fresnel lens surface proportionally by well-set masks. 1000W solar power is needed to reach the threshold limit to stimulate the laser medium. The slope efficiency from sunlight to laser was 9%, for 700-800 solar power and nonlinearly increased up to 14% as shown in Figure4. It is expected it will increase more than 14% by improvements of Fresnel lens quality, and higher incident solar power which is much larger than the threshold of lasing process.

Figure 5 depicts the spectrum of the output radiation which apparently coincides with oscillation band width of Cr:Nd:YAG.

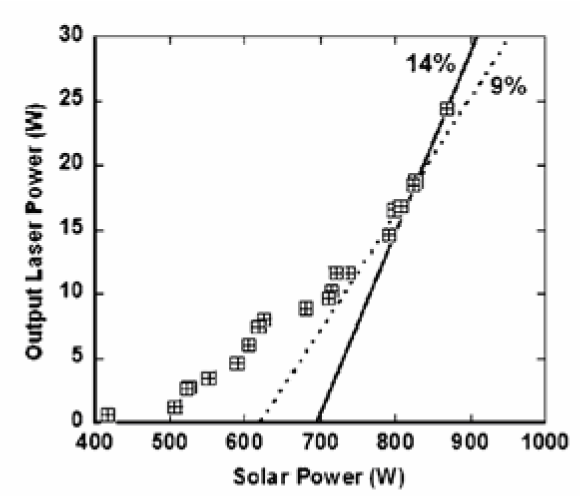

Figure 4. Laser output for various powers of incident sunlight graph, which estimates the slope efficiency of lasing process.

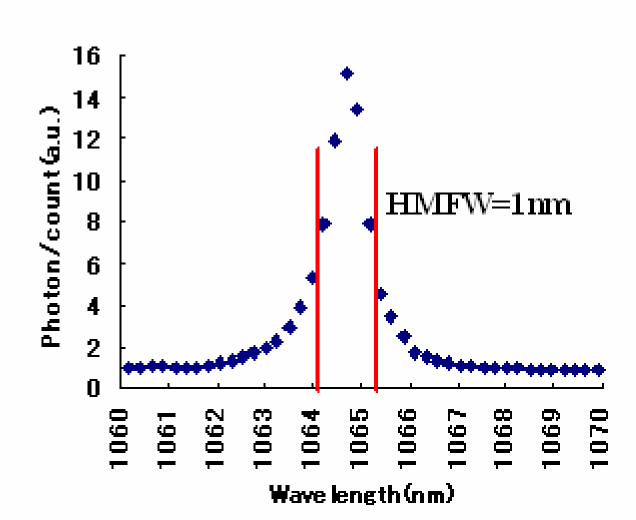

Figure 5. Spectrum of the measured output laser

5. Conclusion

A direct solar laser system has been developed in which Cr:Nd:YAG crystal is directly pumped by concentrated sunlight. A high efficiency laser output power was observed. The slope efficiency in the system was estimated to be 9%-14%, and we expect 14% conversion efficiency with 3-4 kW solar power obtained by 4 m^2Fresnel lens which is in operation in Chitose, Hokkaido.

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