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A new concept of solar energy harvesting using solar-pumped lasers coupled with monochromatic photovoltaics

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Abstract

We have proposed a new concept of highly efficient energy conversion from sunlight to electricity: a combination of a solar pumped laser (SPL) using a Nd, Cr-codoped $Y_3Al_5O_{12}$ (YAG) transparent ceramics rod oscillating at 1064 nm and a specially designed silicon photovoltaic (PV) cell. Energy transfer efficiency from Cr^{3+} to Nd^{3+} ions in the Nd,Cr:YAG rod was evaluated to be as high as around 70% under the laser oscillation conditions, which was comparable to that under spontaneous emission. Stable laser oscillation under natural sunlight was achieved for over ten minutes with no active cooling systems.

1. Introduction

A solar pumped laser (SPL) converts sunlight to monochromatic and coherent light, which realizes high energy density and highly efficient long-distance energy transport. One of the promising applications for the SPL is highly efficient photovoltaics [1]. Generally, photovoltaic (PV) cell performance is lowered due to the temperature rise. A combination of an SPL and a PV cell suppresses heat generation due to thermalization of high-energy carriers by matching the absorption edge of the PV cell material and the lasing wavelength. Further, the PV cell can be installed indoors, which allows us to use a PV cell that would not be highly durable.

2. Material choice of the SPL and PV cell

Overall energy conversion efficiency of the SPL-PV cell combination is expressed by the following equation,

$$\eta = \eta_{SPL} \cdot \eta_{PV} \qquad (1)$$

where η_{SPL} is the energy conversion efficiency of the SPL from sunlight to laser, η_{PV} is the efficiency of the PV cell from the laser to electricity. η_{SPL} is represented from the laser wavelength λ_l and solar spectrum I_s (λ_i) ranging from λ_s to λ_e, assuming the ideal condition with no energy dissipation,

$$\eta_{SPL} = 1 - \frac{\int_{\lambda_s}^{\lambda_l} I_s(\lambda_i)\cdot\left(1-\frac{\lambda_i}{\lambda_l}\right)d\lambda_i}{\int_{\lambda_s}^{\lambda_e} I_s(\lambda_i)d\lambda_i} - \frac{\int_{\lambda_l}^{\lambda_e} I_s(\lambda_i)d\lambda_i}{\int_{\lambda_s}^{\lambda_e} I_s(\lambda_i)d\lambda_i} \qquad (2)$$

The second term of right side indicates the energy loss due to quantum defects determined from the ratio of the laser photon energy to the absorbed photon energy, whereas the third term originates from the fact that the photons which wavelengths are longer than λ_l do not contribute to the laser oscillation. Figure 1 shows the relationship of λ_l and η_{SPL}. The direct sunlight spectrum AM1.5D is also shown for comparison.

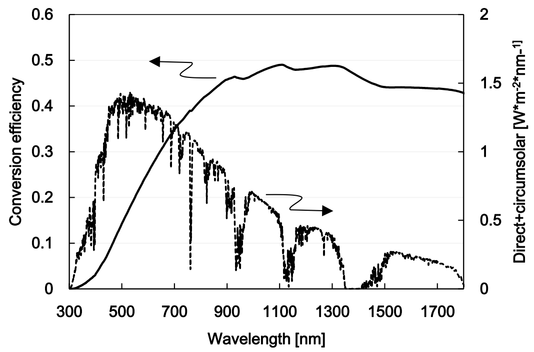

Fig. 1. Energy conversion efficiency η_{SPL} from sunlight to laser light.

η_{SPL} is higher than 45% in the wavelength range from 880 nm to 1450 nm, and is the maximal 49% at 1100 nm. Nd^{3+} ions have been widely used as laser active ions, with a laser wavelength of around 1060 nm. The laser oscillation mechanism involves a four-level system, in which the energy difference between the ground state and the initial state of the laser oscillation corresponds to around 900 nm. Even considering the slight loss originating from the difference between 900 nm and 1060 nm, Nd^{3+} ions have a potential to achieve a conversion efficiency over 45%.

A silicon (Si) PV cell seems suitable to be coupled with the SPL using Nd^{3+}, because the absorption edge is slightly longer than λ_l. However, a conventional Si cell does not perform well under SPL illumination extremely more intense than sunlight. We have specially designed a Si cell with a new light-trapping mechanism, which realizes superior performance coupled with an SPL [2].

3. Evaluation of energy transfer efficiency from Cr^{3+} to Nd^{3+} ions under laser oscillation conditions

One of the drawbacks of Nd^{3+} is the discrete and narrow-band absorption spectrum, resulting in insufficient absorption of sunlight. Cr^{3+} ions which exhibit broad absorption bands in the visible range have attracted attention as sensitizers, as shown in Fig. 2. Although energy transfer efficiency from Cr^{3+} to Nd^{3+} under spontaneous emission of Nd^{3+} has been reported [3], no report is available under the oscillation conditions. We evaluated the efficiency in a Nd,Cr:YAG ceramics rod by using two pump sources of 561 nm and 808 nm, which excite the Cr^{3+} and Nd^{3+}, respectively [4].

Figure 3 compares the laser oscillation characteristics at 1064 nm with and without the 561 nm pump. The energy transfer efficiencies, $\eta_{\mathrm{Cr,Nd}}$ determined from the increase by the additional 561 nm pump was around 70% when the 808 nm pumping power is sufficiently higher than the threshold P_{th}. These values are comparable to that for spontaneous emission. This suggests no bottleneck phenomena in the laser oscillation process including the energy transfer from Cr^{3+} and Nd^{3+}.

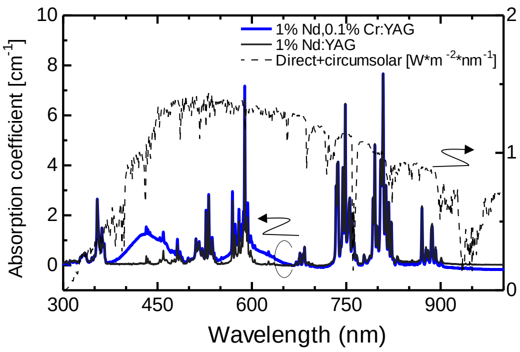

Fig. 2. Absorption spectra of the Nd^{3+} singly doped and Nd^{3+}, Cr^{3+} codoped YAG transparent ceramics rods.

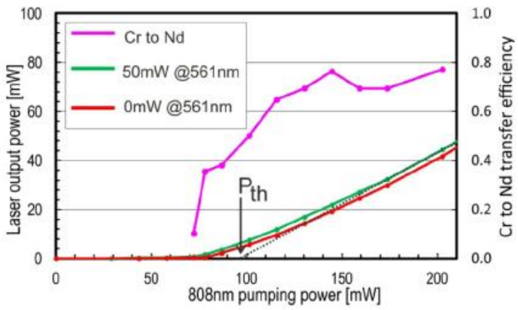

Fig. 3. Output power of the 1064 nm laser excited by the 808 nm pump source under on/off switching of the 561 nm pump source at 50 mW (left axis), and the energy transfer efficiencies $\eta_{\mathrm{Cr,Nd}}$ from Cr^{3+} to Nd^{3+} (right axis).

4. Nd^{3+}, Cr^{3+}: YAG micro rod solar pumped laser under air cooling condition

Previously reported SPL systems need water cooling systems that lead to large size, high cost and additional energy consumption. Our concept to realize stable SPL operation with no active cooling is the use of a small-sized rod; a concrete implementation is illustrated in Fig. 4(a). In the emission spectrum of the SPL under natural sunlight excitation shown in Fig. 4(b), a laser line is observed at 1064 nm. The inset of Fig. 4(b) depicts a time evolution of the laser output power (red line) and direct solar power density (blue line) simultaneously detected. The laser output was continuously detected for over ten minutes. However, the power more fluctuated than the solar power, suggesting the effects of temperature rise, vibration of the optics, etc.

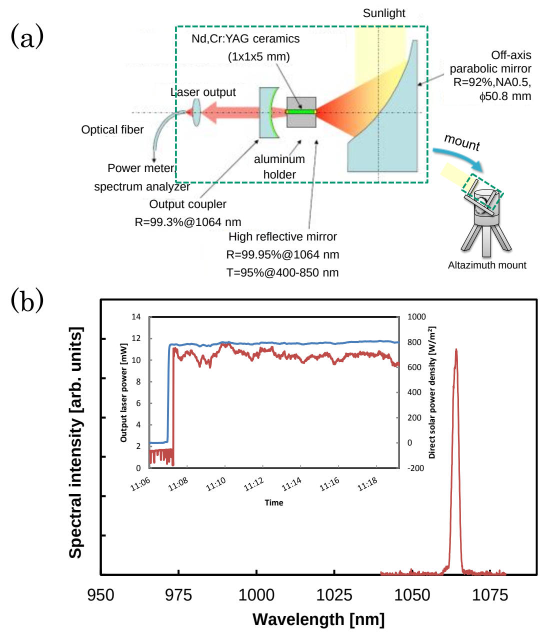

Fig. 4. (a) Schematic diagram of the air cooling SPL system and (b) laser line spectrum and time evolution of the laser output power (inset, red line) and the direct solar power density (inset, blue line).

5. Conclusions

With the aim of highly efficient energy conversion from sunlight to electricity, we have analyzed the characteristics of an SPL in detail. We have found that Nd,Cr:YAG laser oscillating at 1.06 μm is suitable to achieve high conversion efficiency from sunlight to laser, and to be coupled with a specially designed Si PV cell. The energy transfer efficiency from Cr^{3+} used as sensitizer to Nd^{3+} ions in the YAG was evaluated to be as high as around 70%. Using the Nd,Cr:YAG transparent ceramics rod, we have realized stable laser oscillation under natural sunlight for over ten minutes with no active cooling systems.

Acknowledgements

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