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HIGH EFFICIENCY LASER-DIODE-PUMPED CAVITY-DUMPED YTTERBIUM-DOPED $Y_3Al_5O_{12}$ LASER

[1]H. Hitotsuya, [1]N. Shimojo, [1]S. Matsubara, [1]M. Inoue, [1-3]S. Kawato
[1]Graduate School of Engineering, University of Fukui, Fukui, Fukui 910-8507, Japan, E-mail: hiro0904@u-fukui.ac.jp
[2]Japan Synchrotron Radiation Research Institute (JASRI), Sayo, Hyogo 679-5148, Japan, E-mail: kawato@u-fukui.ac.jp
[3]Research and Education Program for Life Science, University of Fukui, Fukui, Fukui 910-8507, Japan

***Abstract*— We developed a laser-diode (LD)-pumped cavity-dumped ytterbium-doped yttrium aluminum garnet (Yb:YAG) laser. The slope efficiency and optical-to-optical conversion efficiency were 72% and 56%, respectively for an absorbed pump power of 780 mW at a pulse repetition rate of 100 kHz. The pulse width was 15 ns. To our knowledge, the efficiencies are the highest for LD-pumped short pulse lasers with pulse widths of hundred nanoseconds or less.**

Keywords— Yb:YAG, cavity-dumped, high-efficiency, diode-pumped, nanosecond pulsed

I. INTRODUCTION

Recently, ytterbium (Yb)-doped materials are believed to be the most promising materials because of its high quantum efficiency and wide gain spectrum. Yb-doped yttrium aluminum garnet (Yb:YAG) crystal, which is one of the Yb-doped materials, has a high quantum efficiency of 91%, a long fluorescence life time of around 0.9 ms. The YAG host material also has a high thermal conductivity of around 11 W/(m·K) and low thermal birefringence. Its absorption peak of around 940 nm and absorption band width of around 20 nm are suitable for laser diode (LD) pumping with commercially available indium gallium arsenide (InGaAs) LD with high power and high reliability. The Yb:YAG is also suitable for ultrashort pulse generation because of its wide gain bandwidth. These features are most appropriate for short pulse lasers, which pulse width is hundred nanoseconds or less, with excellent characteristics, i.e., high power, high efficiency, high pulse repetition rate, high stability, high reliability, compactness, and cost-effectiveness. These lasers have many applications in scientific, industrial, and bio-medical fields such as non-linear spectroscopy, material processing, and laser surgery.

Only one of the undesirable futures is a considerable loss induced by the quasi-four or quasi-three level nature of ytterbium-doped laser materials, i.e., the thermal population of the lower laser level. Although one of the techniques to overcome the loss is low-temperature cooling of the gain material below around 100 K [1], many of the excellent characteristics are lost because of large, complex, and non-affordable scheme of the low-temperature cooling technique. Another technique to overcome the loss without the low temperature cooling is increasing the gain of the laser medium, which was obtained by high pump intensity above 100 kW/cm^2, and precise compensation of the thermo-optic effects. The high-gain technique, which includes the gain increase and the precise compensation, is simple and affordable compared to the others, therefore it is appropriate to maintain the excellent characteristics. To our knowledge, the highest efficiencies for continuous wave (CW) lasers were obtained by microchip Yb:YAG lasers at a room temperature by our group [2], [3]. For example, at an oscillation wavelength of 1048 nm, which is close to the second gain peak of Yb:YAG, the optical-to-optical conversion efficiency was 85%. The efficiencies are close to the quantum limit of 91%.

Although the efficiencies of CW lasers were close to the quantum limit, those of the short pulse lasers are considerably lower than the limit. The basic methods for generating the short pulses are cavity dumping, Q-switching, and so on [4], [5]. The Q-switching technique is a commonly used method to generate high peak power nanosecond and sub-nanosecond pulses. However, the pulse width of the Q-switched lasers is longer than that of the cavity-dumped lasers under the same conditions of the cavity length, optical switching speed, gain of the laser medium, cavity loss, and so on. In contrast, cavity dumping can realize a constant short pulse width, which is determined by the cavity length and optical switching speed. High efficiency cavity-dumped pulse lasers with a high repetition rate have been reported [6]–[8]. For example, to our knowledge, the highest efficiencies for the short pulse lasers, also for the cavity-dumped lasers, were realized by a cavity dumped microchip Yb:YAG laser at room temperature in our previous research [9], [10]. The slope efficiency and optical-to-optical conversion efficiency for the absorbed pump power were 84% and 73%, respectively. The pulse width was 16 ns and the pulse repetition rate was 100 kHz. Although its pump source was Ti:sapphire laser, the results indicate a high capability of similar high-efficiency oscillation by LD pumping. For the LD-pumped short pulse Yb lasers with pulse widths of 10 ns or less, the highest slope efficiency of 46.9% and the highest optical-to-optical conversion efficiency of 37.9% were obtained by a microchip Yb:YAG laser [11], [12]. The pulse width was 10 ns and the

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pulse repetition rate was 50 kHz. Although for LD-pumped short pulse lasers with direct pumping, the highest optical-to-optical conversion efficiency of 44.9% was realized by a cavity-dumped Nd:GdVO$_4$ laser, in which the gain medium is not suitable for ultrashort pulse generation [13]. For the short pulse Yb lasers with a relatively long pulse width of hundred nanoseconds, the highest optical-to-optical conversion efficiency of 45% was realized by a cavity dumped thin-disk Yb:YAG laser with a complex, multi pass pumping and cooling scheme. The pulse width was 350 ns, and the pulse repetition rate was 100 kHz [6]

In this letter, we report on a LD-pumped cavity-dumped microchip Yb:YAG laser with the highest efficiencies for the LD-pumped short pulse lasers. The slope efficiency and optical-to-optical conversion efficiency are equivalent to those of the Ti:sapphire-laser-pumped cavity-dumped microchip Yb:YAG laser with the highest efficiencies for the short pulse lasers. The pulse width was 15 ns and the repetition rate was 100 kHz. These results are also realized by the high gain technique which is already described earlier for the high efficiency microchip CW lasers. The efficiencies of the cavity dumped lasers is also increased by the high gain technique to overcome the loss in the cavity. Furthermore, the stability of the cavity dumped lasers with high repetition rate is improved by decrease in the intra-cavity pulse buildup time, which means the time of pulse amplification in the laser cavity, due to the high gain technique.

II. LD-PUMPED CW Yb:YAG LASER

Schematic of the LD-pumped CW Yb:YAG laser is shown in Fig. 1. The Yb:YAG crystal (Scientific Material Corp.) had a thickness of 1 mm and an ion density of 20 at.%, and it was antireflection coated at around 940 nm on two surfaces and high-reflection coated at around 1030 nm on one surface. The crystal was attached to a 1-mm-thick sapphire plate for which both surfaces were antireflection coated at around 940 nm, and it was mounted on a copper holder at a room temperature of 23°C.

A low-brightness LD (Eagleyard Photonics GmbH.) with an emitter width of 60 μm and a wavelength of 934 nm was used as a pump source. Because the center wavelength of the LD was different from that of the absorption spectrum of the Yb:YAG, the pump absorption efficiency was a relatively low value of 52%. An aspherical lens with a focal length of 4.5 mm was used for collimating the LD beam. For the horizontal direction, corresponding to the slow axis of the LD beam, two cylindrical lenses with focal lengths of −6.6 mm and 80 mm, as shown in Fig. 1, were used to reduce the divergence angle and astigmatism. The beam was focused by an achromatic doublet lens with a focal length of 40 mm. The pump spot diameter for the vertical direction and horizontal direction were 20 μm and 40 μm, respectively. Figure 2 shows the output power of the LD-pumped CW laser and the Ti:sapphire-laser-pumped CW laser as a function of the absorbed pump power. The maximum pump intensity was 120 kW/cm^2 for the maximum absorbed pump power of 780 mW. The average output power was 450 mW for the maximum absorbed pump power. The slope efficiency and optical-to-optical conversion efficiency were 72% and 57%, respectively. The slope efficiency and optical-to-optical conversion efficiency are equivalent to those of the Ti:sapphire-laser-pumped laser. Especially for the absorbed pump power of below 600 mW, the efficiencies are approximately equal to those of the Ti:sapphire-laser-pumped laser. These high efficiencies are obtained by the high gain technique as mentioned before.

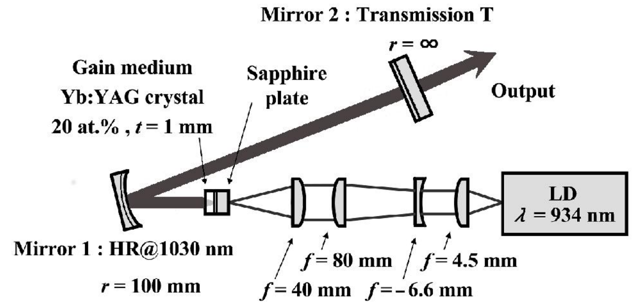

Fig. 1 Schematic of the LD-pumped CW Yb:YAG laser.

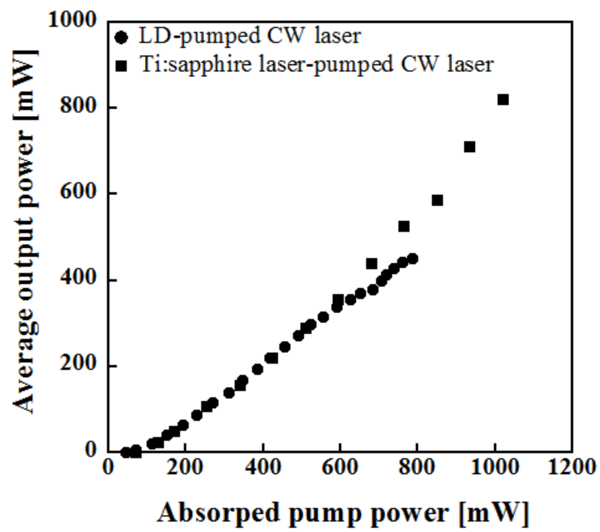

Fig. 2 Average output power of the LD-pumped CW laser and the Ti:sapphire-laser-pumped CW laser as a function of the absorbed pump power. The filled circle and square represent the output power of the LD-pumped CW laser and the Ti:sapphire-laser-pumped CW laser, respectively.

III. LD-PUMPED CAVITY-DUMPED Yb:YAG LASER

Schematic of the LD-pumped cavity-dumped Yb:YAG laser is shown in Fig. 3. A thin-film polarizer (TFP), a quarter-wave plate, and a rubidium titanyl phosphate (RTP) Pockels cell were inserted for cavity dumping. The Pockels cell was constructed of two RTP crystals to compensate for thermal birefringence. The crystals had a cross section of 4 mm × 4 mm and a length of 20 mm. To minimize the cavity loss, the polarizer for the s-wave reflection was inserted because the s-wave reflection loss of the polarizer is 0.5%, which is much smaller than the p-wave transmission loss of around 10%. The cavity length was 2020 mm. To obtain high efficiency, it is necessary to confine the spontaneous emission in the cavity until the gain balances with the loss [14]. Therefore, we optimized the gate time which is defined as the resonating time in the high-reflection cavity. The gate time is similar to the time for which a voltage is applied to the Pockels cell. Figure 4 shows the average output power as a function of the gate time at a pulse repetition rate of 100 kHz for the maximum absorbed pump power. The maximum average output power was obtained at a gate time of 800 ns. This result means that the gain balanced with the losses when the gate time is 800 ns. When the gate time excessively increases, typical cavity-dumped lasers with high repetition rate indicate an instability in the output pulse energy [6], [15], [16]. However, the output pulse energy was stable at the gate time of 800 ns. Therefore, in this experiment, the gate time was optimized to be 800 ns.

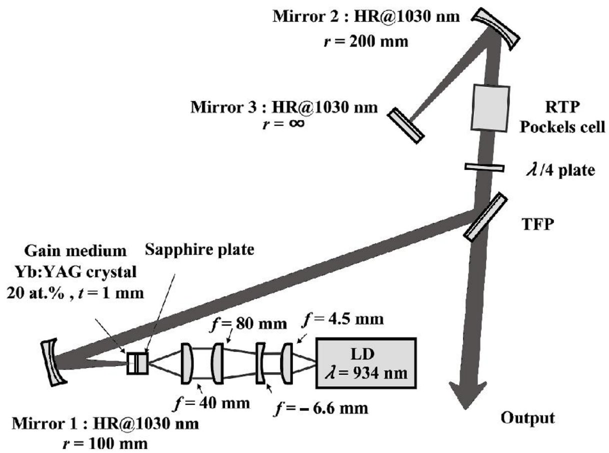

Fig. 3 Schematic of the LD-pumped cavity-dumped Yb:YAG laser.

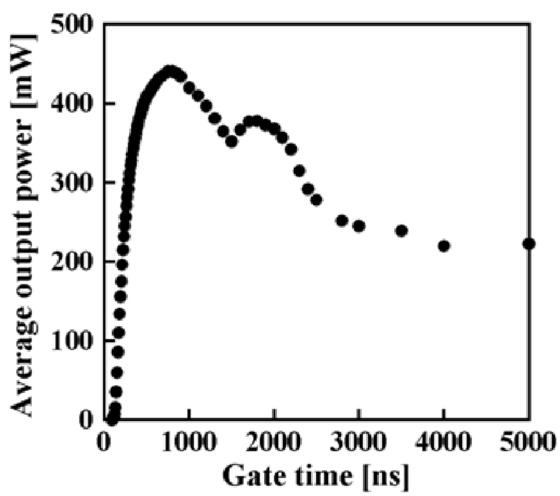

Fig. 4 Average output power of the LD-pumped cavity-dumped Yb:YAG laser as a function of the gate time.

Figure 5 shows the output power of the LD-pumped and the Ti:sapphire-laser-pumped cavity-dumped lasers as a function of the absorbed pump power. The maximum average output power was 440 mW for the LD-pumped laser at a pulse repetition rate of 100 kHz. The pulse energy was 4.4 μJ and the pulse width was 15 ns. The slope efficiency and optical-to-optical conversion efficiency were 72% and 56%, respectively for the absorbed pump power. These results are equivalent to those of the Ti:sapphire-laser-pumped cavity-dumped laser for the maximum absorbed pump power or less. The slope efficiency and optical-to-optical conversion efficiency are the highest reported to date for the LD-pumped short pulse lasers. The high gain technique is also advantageous for the short pulse lasers with the favourable properties as mentioned in section I. For example, as shown in the experiment, the high gain technique led the short pulse lasers with high repetition rate to be stable. Furthermore, the efficiencies of the short pulse lasers were increased. Generally, it is difficult to increase the coupling efficiency of short pulse lasers owing to the insertion loss of optical switch which consists of the TFP, Pockels cell, and quarter-wave plate. However, the coupling efficiency was increased by the high gain. By the way, these efficiencies are higher than our previous results by almost the same high-gain technique [11], [12]. It is considered that the differences in the efficiencies are caused by a difference of the mode-matching efficiency between the laser beam and the pump beam, i.e., the mode-matching efficiency in the previous research was lower than that in this research. In addition, it is certain to obtain stable shorter pulses with higher repetition rate by using a shorter cavity and monitoring the intra-cavity radiation to control the gate time [6].

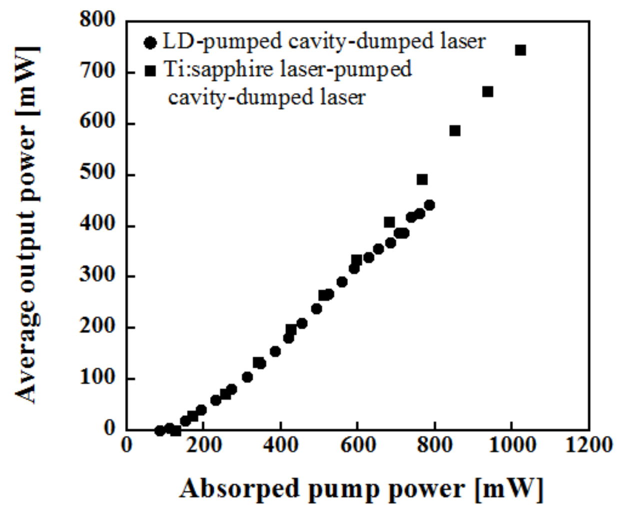

Fig. 5 Average output power of the LD-pumped cavity-dumped laser and the Ti:sapphire-laser-pumped cavity-dumped laser as a function of the absorbed pump power. The filled circle and square represent the output power of the LD-pumped laser and the Ti:sapphire-laser-pumped laser, respectively.

IV. Conclusions

We demonstrated high-efficiency LD-pumped CW laser and cavity-dumped laser using a microchip Yb:YAG crystal as a gain medium by the high-gain technique. For the CW laser, the slope efficiency and optical-to-optical conversion efficiency were 72% and 57%, respectively at the maximum pump power. For the cavity-dumped laser, the slope efficiency and optical-to-optical conversion efficiency were 72% and 56%, respectively at the maximum absorbed pump power. The pulse width was 15 ns, and the pulse repetition rate was 100 kHz. The slope efficiency and the optical-to-optical conversion efficiency are the highest reported to date for the LD-pumped short pulse lasers. These results indicate a sufficient possibility of realizing higher efficiency CW lasers and short pulse and high-pulse repetition rate lasers with the excellent characteristics.

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