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SINGLE-EMITTER LASER-DIODE-PUMPED CAVITY-DUMPED YTTERBIUM-DOPED $Y_3Al_5O_{12}$ LASER

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Abstract— **We have developed a single-emitter laser-diode (LD)-pumped cavity-dumped ytterbium-doped yttrium aluminum garnet (Yb:YAG) laser. For an absorbed pump power of 1.98 W, the slope efficiency and the optical-to-optical conversion efficiency were 46.9% and 37.9%, respectively. The absorption efficiency was 82.0%. An average output power of 748 mW and a pulse energy of 15μJ were obtained with a pulse repetition rate of 50 kHz. The pulse width was 10 ns. To our knowledge, these efficiencies are the highest values for single-emitter LD-pumped nanosecond pulse lasers as well as for LD-pumped cavity-dumped lasers without direct pumping with a pulse width of less than or equal to 10 ns.**

Keywords— solid-state lasers, diode-pumped, ytterbium, cavity-dumped, high-efficiency

I. INTRODUCTION

In recent years, nanosecond pulsed lasers are required to have favorable properties, namely, high efficiency, high reliability, high stabilization, compactness, high repetition rate, 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. To achieve high efficiency for short pulse lasers with a high repetition rate, it is important for the laser gain materials to have high gain, favorable thermal properties, high quantum efficiency, and capability of laser-diode (LD) pumping. Ytterbium (Yb)-doped materials are believed to be the most promising materials to satisfy these needs.

In CW oscillations of Yb-doped materials, T. Y. Fan *et al.* obtained a high optical-to-optical conversion efficiency of 76% for the absorbed pump power at a temperature of 100 K [1]. A. Giesen *et al.* demonstrated a Yb-doped yttrium aluminum garnet (Yb:YAG) laser at a crystal temperature ranging from 100 K to 340 K, and obtained a high optical-to-optical conversion efficiency of 82% for the absorbed pump power at a temperature of 119 K under direct pumping with a wavelength of 969 nm [2]. Furthermore, also at room temperature, a high-efficiency operation of the thin-disk laser was realized by utilizing a complex pumping scheme with 16–32 absorption passes using a parabolic mirror and folding mirrors [3]–[6]. For example, R. Peters *et al.* obtained a slope efficiency of 80% and an optical-to-optical conversion efficiency of 72%.

To our knowledge, the highest optical-to-optical conversion efficiency of 85% was obtained for CW lasers with Yb-doped material as the gain medium at room temperature by our group [7], [8]. This efficiency is higher than the maximum optical-to-optical conversion efficiency of 79% previously demonstrated by a Nd laser with direct pumping at 880 nm [9]. The Yb laser utilizes a microchip Yb:YAG crystal as a gain medium with a simple pumping scheme. At an oscillation wavelength of 1030 nm, which is close to the first gain peak of Yb:YAG, the optical-to-optical conversion efficiency was measured to be 84% for the absorbed pump power and 78% for the incident pump power. 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% for the absorbed pump power and 81% for the incident pump power. The highest optical-to-optical conversion efficiency was achieved by architecture of [8], [9]. Characteristics of the architecture are high gain of the laser medium, which was obtained by high pump intensity above 100 kW/cm^2, and precise compensation of the thermo-optic distortion by the high-intensity pumping.

As mentioned above, the CW Yb laser realized high-efficiency operation close to the quantum limit, however, all of the short pulse lasers are inefficient when compared to CW lasers. The basic methods for generating nanosecond pulse are cavity dumping [10], [11], Q-switching, and so on. The Q-switching technique is a commonly used method to generate nanosecond and sub-nanosecond pulses. Although a large variety of Q-switching methods have been invented [6], [12]–[20], the active Q-switching and cavity dumping are appropriate for the stabilization, which is useful for the applications. 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 [21]–[23]. Cavity dumping can also realize a constant short pulse width, which is determined by the cavity length and optical switching speed. Several types of highly efficient nanosecond pulse lasers have been reported [6], [24]–[30]. For example, to our knowledge, the highest efficiency cavity-dumped laser oscillation was realized at room temperature by our group. The optical-to-optical conversion efficiencies for the absorbed pump power and the incident pump power at 1031

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nm were 73% and 62%, respectively [31], [32]. Although the pump sources used were Ti:sapphire laser, the results indicate a high capability of similar high-efficiency oscillation by LD pumping. A LD-pumped high-efficiency cavity-dumped thin-disk laser was realized by utilizing the complex pumping scheme as mentioned above [6]. For example, in a long pulse width region, C. Stolzenburg *et al.* obtained an optical-to-optical conversion efficiency of 45% with a pulse width of 350 ns.

To apply LD-pumped cavity-dumped lasers in various fields, it is important to develop compact and simple lasers with a short pulse width and a high repetition rate. Therefore, we present a single-emitter LD-pumped high-efficiency cavity-dumped Yb:YAG laser with a short pulse width, high repetition rate, and simple pumping scheme. This result was realized by high gain of the laser medium owing to the high-intensity pumping. The efficiency and the stability of the cavity dumped lasers with high repetition rate can be improved by the decrease in the intra-cavity pulse buildup time due to high gain of the laser medium. However, a thermo-optic distortion is caused by the high-intensity pumping, and this increases the loss in the gain medium. We solved this problem by the precise compensation for the distortion that succeeded in the CW laser. Furthermore, it is easy to miniaturize and simplify the laser using a single-emitter LD with a simple pumping scheme. As a result, in spite of long cavity length, we realized a short pulse cavity-dumped laser with high repetition rate. Therefore, by shortening the cavity length, we can realize shorter pulsed lasers with higher repetition rate.

This paper is organized as follows. In section II, the properties of a LD-pumped CW laser is described. In section III, we discuss experimental results for a LD-pumped cavity-dumped Yb:YAG laser. The cavity-dumped Yb:YAG laser was fabricated based on the CW laser described in section II. Finally, conclusions are given in section IV.

II. LD-PUMPED CW LASER OSCILLATION

The experimental setup for the LD-pumped CW laser is shown in Fig. 1. The Yb:YAG crystal (Scientific Material Corp.) has a thickness of 1 mm and an ion density of 20 at.%, and it is antireflection coated at approximately 940 nm on two surfaces and high-reflection coated at approximately 1030 nm on one surface. The crystal is attached to a 1-mm-thick sapphire plate for which both surfaces are antireflection coated at approximately 940 nm, and it is mounted on a copper holder at a room temperature of 23°C. A low-brightness LD with 100-µm-broad area at a wavelength of 941 nm was used as a pump source. To collimate the pump beam, an aspherical lens with a focal length of 2.5 mm was positioned near the output facet of the LD. Cylindrical lenses at the tangential plane with focal lengths of −7.7 mm and 100 mm were used to reduce the divergence angle of LD and the astigmatism caused by the difference in the LD far-field emission angles in the sagittal and tangential planes. The pump beam was focused by an achromatic doublet lens with a focal length of 40 mm. The pump spot diameters for the vertical and horizontal directions were 25 µm and 75 µm, respectively. The beam quality factor M^2 was measured to be 1.2 for the sagittal plane and 23 for the tangential plane. The maximum pump intensity was calculated to be approximately 150 kW/cm^2 for an absorbed pump power of 2.09 W. The absorption efficiency of the Yb:YAG crystal was 82.0%.

Figure 2 shows the CW output power of the Yb:YAG laser as a function of the absorbed pump power. With an output coupler of the transmission T = 20%, the threshold of the laser oscillation was nearly 200 mW and the maximum laser output power was 1.45 W for a 2.09 W absorbed pump power at a wavelength of 1030 nm. The optical-to-optical conversion efficiencies for the absorbed pump power and the incident pump power were calculated to be 69.4% and 56.9%, respectively. With a T = 5% output coupler, the maximum laser output power was 1.40 W at an oscillation wavelength of 1048 nm. The optical-to-optical conversion efficiencies for the absorbed pump power and the incident pump power were calculated to be 67.0% and 54.9%, respectively. The oscillation wavelength depends on the total cavity losses, and hence it changes by the transmission of the output coupler. Therefore, the laser oscillation was observed at 1030 nm, which is near the first gain peak of Yb:YAG, when T = 20% and at 1048 nm, which is near the second gain peak of Yb:YAG, when T = 5%.

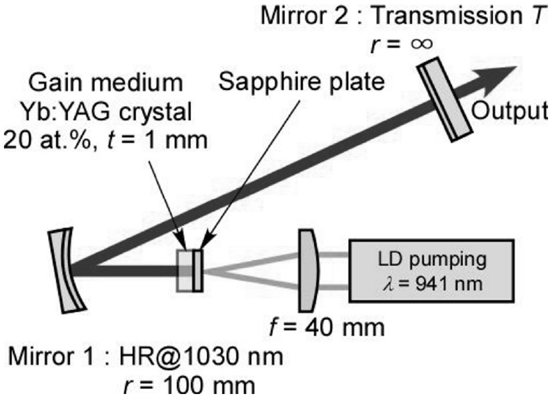

Fig. 1 Schematic of the LD-pumped CW laser with the microchip Yb:YAG crystal. The crystal is 1 mm thick with the ion density of 20 at.%. The curvature radius of the mirror 1 is 100 mm.

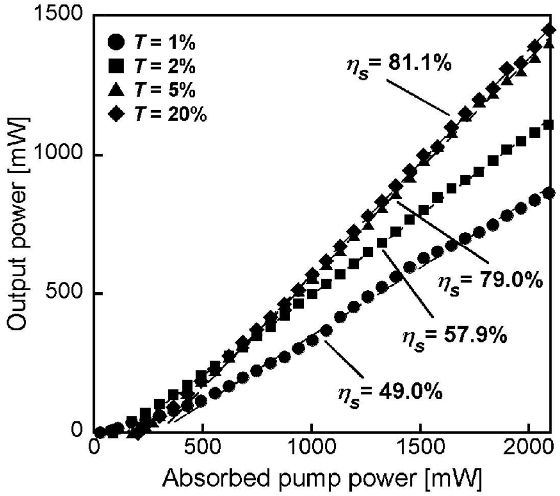

Fig. 2 Average output power of the LD-pumped CW Yb:YAG laser as a function of the absorbed pump power. The filled circle, square, triangle, and diamond represent the output power when the transmission of output coupler are 1%, 2%, 5%, and 20%, respectively. The solid and dashed lines are linear fit lines. η_s is the slope efficiency.

III. LD-PUMPED Yb:YAG LASER WITH CAVITY DUMPING

The experimental setup for a single-emitter LD-pumped cavity-dumped laser is shown in Fig. 3. A thin-film polarizer (TFP), a quarter-wave plate, and a rubidium titanyl phosphate (RTP) Pockels cell are inserted into the cavity for cavity dumping. The Pockels cell is constructed of two RTP crystals to compensate for thermal birefringence. The crystals have 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 approximately 10%. The cavity length was 1660 mm.

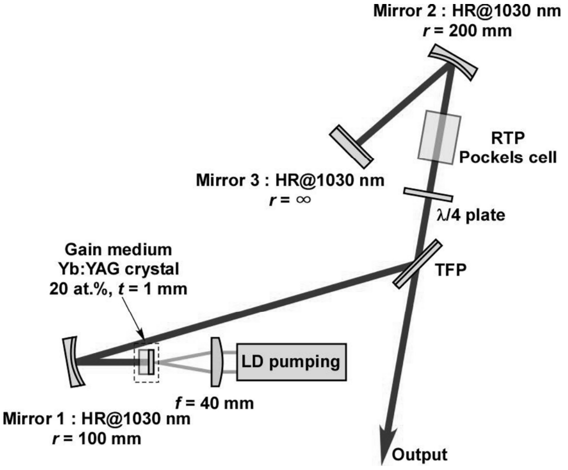

Fig. 3 Schematic of the LD-pumped cavity-dumped Yb:YAG laser. The RTP Pockels cell is used as the Q-switch and its rise time is 8 ns. The TFP and the quarter-wave plate are inserted, and the cavity length is 1660 mm.

To obtain high efficiency, it is necessary to achieve maximum energy storage in the Yb:YAG crystal [21]. This is achieved by confining the spontaneous emission in the cavity until the gain balances with the loss. In particular, 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 the 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 50 kHz. The absorbed pump power was 1.98 W and the absorption efficiency was 82.0%. The maximum average output power was obtained at a gate time of 1100 ns when the Pockels cell had an applied voltage of 468 V. This result suggests that the gain balanced with the losses when the gate time is 1100 ns, and the average output power was reduced for over 1100 ns because the gain was depleted. From this result, we estimated the optimal gate time to be 1100 ns. However, the multipass amplification indicates an instability in the output pulse energy owing to the seed pulse energy, repetition rate, gate time, and cavity length [6], [33], [34]. In the case of cavity dumping, the seed pulse corresponds to an amplified spontaneous emission, and its energy is very low. In addition, the output pulse becomes unstable if the gate time excessively increases. Therefore, in this experiment, the gate time was optimized to be 800 ns and the voltage applied to the Pockels cell was a quarter-wave voltage of 442 V. The output power has the sufficient potential to be higher than the current result by increasing the gate time.

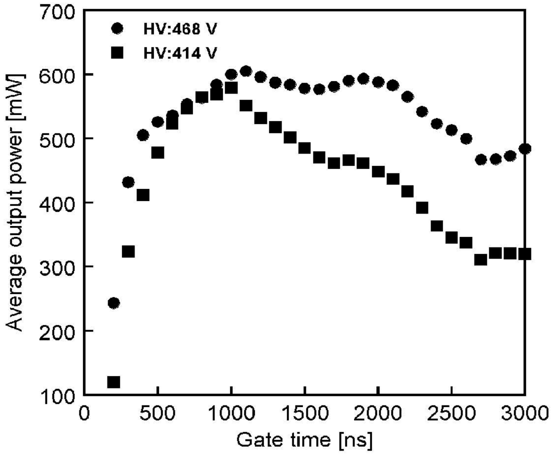

Fig. 4 Average output power of the LD-pumped cavity-dumped Yb:YAG laser as a function of the gate time. The filled circle and square represent the output power when the Pockels cell has an applied voltage of 468 V and 414 V, respectively.

Figure 5 shows the output power of the cavity-dumped laser with LD pumping and Ti:sapphire laser pumping [31], [32], CW laser without the Pockels cell, and CW laser with the Pockels cell as a function of the absorbed pump power. For CW oscillation, the rotatable quarter-wave plate acts as a variable output coupler in combination with the TFP. The plate angle was optimized to maximize the coupling efficiency. We obtained a CW output power of 955 mW without the Pockels cell with an optical-to-optical conversion efficiency of 48.2% at an absorbed pump power of 1.98 W, and a CW output power of 860 mW with the Pockels cell with an optical-to-optical conversion efficiency of 43.4% at the absorbed pump power. The 4.8% decrease in the efficiency at the absorbed pump power was mainly attributed to thermal birefringence of RTP crystals. It is certain to obtain the higher-efficiency operation by using β-barium borate (BBO) crystals because these crystals exhibit much lower thermal birefringence loss than RTP crystals.

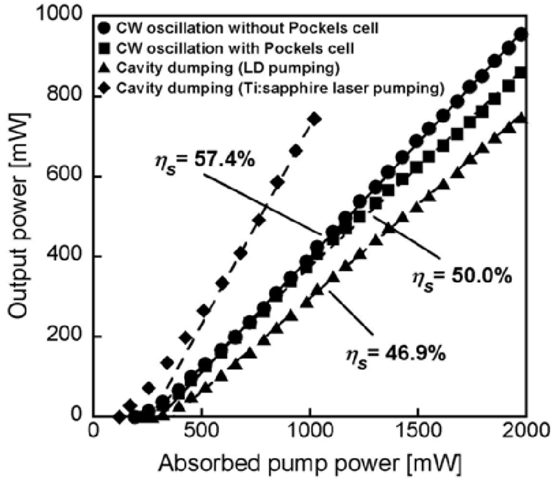

Fig. 5 The dependence of the output power on the absorbed pump power. The filled circle, square, triangle, and diamond represent the output power of the LD-pumped CW laser without the Pockels cell, the CW laser with the Pockels cell, the cavity-dumped laser, and the Ti:sapphire laser-pumped cavity-dumped laser, respectively. The solid and dashed lines are linear fit lines. η_s is the slope efficiency.

By adjusting the plate angle, the laser has been operated as a cavity-dumped laser. An average output power of 748 mW and a pulse energy of 15 μJ were obtained with a repetition rate of 50 kHz at an absorbed pump power of 1.98 W. For the absorbed pump power, the slope efficiency and the optical-to-optical conversion efficiency were 46.9% and 37.9%, respectively.

In addition, the center wavelength was 1030 nm. The output pulse shape is shown in Fig. 6 with the intra-cavity pulse buildup. The pulse width was measured with an instrumental response time of 2 ns, and the instruments consist of a PIN photodiode and digital oscilloscope. Consequently, the actual pulse width was estimated to be 10 ns. The minimum pulse width of the output pulses depends on the cavity length and the optical switching time of the Pockels cell. Therefore, it is certain to obtain shorter pulses by shortening the cavity length or the switching time. To our knowledge, the slope efficiency and the optical-to-optical conversion efficiency are the highest reported efficiencies to date for several types of LD-pumped nanosecond pulse lasers. For example, these efficiencies are the highest for single-emitter LD-pumped nanosecond pulse lasers as well as for LD-pumped cavity-dumped lasers without direct pumping with a pulse width of less than or equal to 10 ns. As mentioned in section I, the architecture is advantageous for short pulse lasers with high repetition rate, because of the high gain obtained by the high-intensity pumping. For example, we compared these results with those of the cavity-dumped thin-disk laser [6]. The buildup of the intra-cavity pulse of the thin-disk laser was completed in the gate time of 800 ns under the following conditions: a cavity round-trip time of 4.5 ns, repetition rate of 1 MHz, and pump intensity of 5 kW/cm^2. In this case, the intra-cavity pulse made 178 round trips in the cavity within the gate time. On the other hand, in our experimental conditions, the buildup of the intra-cavity pulse was completed when it made 73 round trips in the cavity with a repetition rate of 50 kHz. Furthermore, considering a repetition rate of one-twentieth, the buildup of the intra-cavity pulse can be completed by making approximately one-fortieth round trips. Therefore, the high-intensity pumping is advantageous for high repetition rate stable operation.

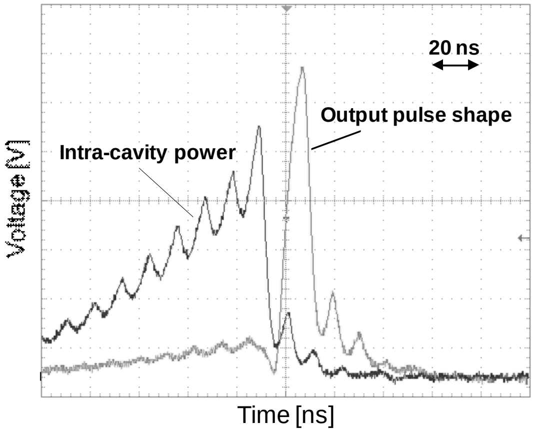

Fig. 6 Output pulse shape of the LD-pumped cavity-dumped Yb:YAG laser and the intra-cavity pulse buildup (intra-cavity power). The first line to rise indicates the intra-cavity pulse buildup, and the other line indicates the output pulse shape.

In addition, we can obtain stable shorter pulses, pulse energy, and higher repetition rate operation by monitoring the buildup of the intra-cavity pulse to control the gate time [6]. Besides, we can increase the optical-to-optical conversion efficiency and slope efficiency by obtaining better mode matching between pump and laser mode in the gain medium, theoretically.

IV. CONCLUSIONS

In conclusion, we demonstrated a high-efficiency LD-pumped CW laser and a cavity-dumped laser. First, a high-efficiency CW laser pumped by a single-emitter LD was realized using a microchip Yb:YAG crystal. With an output coupler having transmission *T* = 20% and *T* = 5%, the maximum laser output power was 1.45 W at 1030 nm and 1.40 W at 1048 nm. The slope efficiency was 81.1% for *T* = 20% and 79.0% for *T* = 5%. The optical-to-optical conversion efficiency was 69.4% for *T* = 20% and 67.0% for *T* = 5%. Next, a highly efficient, cavity-dumped Yb:YAG laser was constructed on the basis of the above-described CW laser. The slope efficiency and the optical-to-optical conversion efficiency were 46.9% and 37.9%, respectively. An average output power of 748 mW at 1030 nm and a pulse energy of 15 μJ were obtained with a repetition rate of 50 kHz. The pulse width was 10 ns. To our knowledge, these efficiencies of the cavity-dumped Yb:YAG laser are the highest reported to date for several types of nanosecond pulse lasers. These results indicate a sufficient possibility of realizing short pulse lasers with high efficiency, high reliability, compactness, high repetition rate, and cost-effectiveness by LD pumping.

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