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CAVITY-DUMPED MODE-LOCKED YTTERBIUM-DOPED $Y_3Al_5O_{12}$ LASER

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***Abstract*— We have developed a cavity-dumped mode-locked ytterbium-doped yttrium aluminum garnet (Yb:YAG) laser. An optical-to-optical conversion efficiency of 34.8% was obtained with a pulse width of 15 ps at a repetition rate of 100 kHz. To our knowledge, this efficiency is the highest in cavity-dumped mode-locked lasers.**

***Keywords*—** solid-state lasers, ytterbium, cavity-dumped, mode-locked, high-efficiency

I. INTRODUCTION

In recent years, short pulse lasers are required to have favorable properties, namely, high efficiency, high pulse energy, and high repetition rate with high reliability, high stabilization, compactness, and cost-effectiveness. These lasers are useful for scientific, industrial, and bio-medical applications such as non-linear spectroscopy, material processing, and laser surgery. To achieve the favorable properties, it is important that the laser gain medium has high gain, long fluorescence lifetime, high quantum efficiency, broad gain spectrum, and a capability of laser diode pumping. Ytterbium (Yb)-doped media are believed as one of the most promising media to satisfy these needs.

In continuous wave (CW) oscillation of the Yb-doped materials, A. Giesen *et al.* demonstrated a Yb-doped yttrium aluminum garnet (Yb:YAG) laser and obtained a high optical-to-optical conversion efficiency of 82% for the absorbed pump power under direct pumping of the upper laser level to minimize heat generation [1]. The Yb:YAG crystal was cooled at 119 K to reduce the reabsorption loss caused by thermal population of the lower laser level. At room temperature, high-efficiency operation of the thin-disk Yb laser was realized by utilizing a complex pumping scheme with 16 to 32 absorption passes using a parabolic mirror and folding mirrors to reduce the reabsorption loss [2]–[5]. For example, R. Peters *et al.* obtained an optical-to-optical conversion efficiency of 72%. To our knowledge, the highest optical-to-optical conversion efficiency of 85% was obtained from a CW microchip Yb:YAG laser with a simple pumping scheme at room temperature [6], [7]. This efficiency is close to the quantum limit of 91% for Yb:YAG laser, and it is the highest for lasers. The architecture characteristics are followings; 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. The high gain overcomes the laser cavity loss such as the reabsorption loss of the Yb-doped materials.

As mentioned above, the efficiency of the CW laser was approaching to the quantum limit, however, the efficiency of short pulse lasers are lower than that of the CW lasers. The basic methods for generating high energy short pulses with high repetition rate are cavity-dumping and cavity-dumped mode-locking. Cavity dumped thin-disk lasers were realized in a long pulse region by utilizing the complex pumping scheme [5]. C. Stolzenburg *et al.* obtained a high optical-to-optical conversion efficiency of 45% with a pulse width of 350 ns at a repetition rate of 100 kHz. To our knowledge, the highest efficiency for the cavity-dumped lasers was realized by our group. The optical-to-optical conversion efficiency for the absorbed pump power was 73% with a pulse width of 16 ns at a repetition rate of 100 kHz [8], [9]. These results were 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.

For cavity-dumped mode-locked lasers, the efficiency is much decreased. A $Nd:YVO_4$ laser with two gain medium was demonstrated by U. Wegner *et al.* and the optical-to-optical conversion efficiency was 28.6% for the absorbed pump power [10]. The pulse energy was 10 μJ with a pulse width of 9 ps at a repetition rate of 1 MHz. G. Palmer *et. al.* realized a chirped pulse Yb:KYW laser with two gain medium [11]. The optical-to-optical conversion efficiency was 19.5% for the absorbed pump power with a pulse repetition rate of 1 MHz.

Here, we report a cavity-dumped mode-locked laser which gain medium was a microchip Yb:YAG crystal. The optical-to-optical conversion efficiency was 34.8% for the absorbed pump power. The pulse width was 15 ps at a pulse repetition

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rate of 100 kHz. The efficiency is highest for cavity-dumped mode-locked lasers, to our knowledge.

II. Experiments and Results

The experimental setup for the cavity-dumped mode-locked microchip 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 approximately 940 nm on two surfaces and high-reflection coated at approximately 1030 nm on one surface. The crystal was attached to a 1-mm-thick sapphire plate for which both surfaces were antireflection coated at approximately 940 nm, and it was mounted on a copper holder at a room temperature of 23°C. The pump source was a Ti:sapphire laser with a wavelength of 969 nm for the direct pumping. The pump absorption efficiency was 85.0%. The pump beam was focused using an achromatic doublet lens with a focal length of 40 mm. The pump spot diameters for the vertical and horizontal directions were 40 μm and 39 μm, respectively. The maximum pump intensity was approximately 100 kW/cm^2 for the absorbed pump power. 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 was 0.5%, which was much smaller than the p-wave transmission loss of approximately 10%. A semiconductor saturable absorber mirror (SESAM) was used for mode-locking. The radius of curvature of the mirror 1 and 3 were 100 mm and 200 mm, respectively. The cavity length was 2600 mm. To obtain high efficiency, it is necessary to achieve maximum energy storage in the Yb:YAG crystal [12]. 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 almost the same as the time for which the voltage is applied to the Pockels cell. The average output power was 500 mW with a repetition rate of 100 kHz at an absorbed pump power of 1.15 W when the gate time was 800 ns. However, the average output power was decreased immediately because of damage of the SESAM. When the gate time was 400 ns, no damage was observed on the SESAM's surface. Therefore, the gate time was set to 400 ns. The average output power was 400 mW with a repetition rate of 100 kHz at the absorbed pump power. The optical-to-optical conversion efficiency was 34.8% for the absorbed pump power and the central wavelength was 1031 nm. To our knowledge, the optical-to-optical conversion efficiency is the highest reported to date for cavity-dumped mode-locked lasers. The intra-cavity pulse buildup was measured with the output pulse, and these pulses are shown in Fig. 2. The output pulse shown in Fig. 2 was stretched due to the resolution of measuring instruments which consist of a PIN photodiode and digital oscilloscope. The actual output pulse width was measured to be 15 ps using an autocorrelator (APE Pulse Check). The Fourier transform limited pulse width of the output spectrum was 550 fs. The group delay dispersion was not compensated in this experiment; therefore, the output pulse width was much longer than the Fourier transform limited pulse width owing to a large positive dispersion of the RTP Pockels cell. An SF10 prism pair or chirped mirrors are not sufficient to compensate for the large positive dispersion, but it is certain to compensate by using a pair of diffraction gratings or Gires-Tournois Interferometer mirrors, and the pulse width will be shorter than 15 ps.

From Fig. 2, the pulse cycle in the intra-cavity pulse buildup corresponds to a round-trip time of 18 ns in the

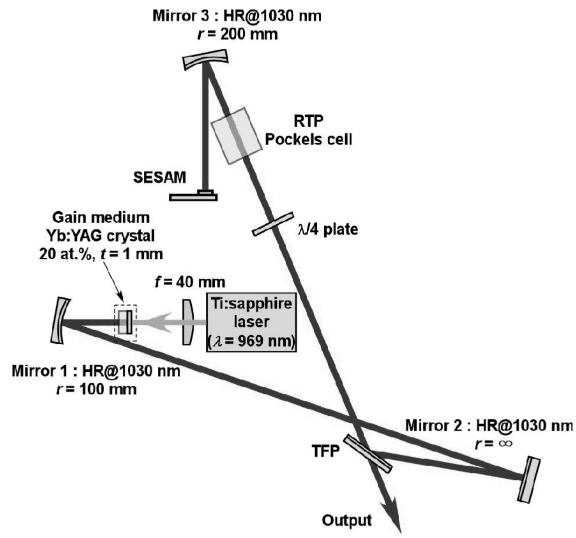

Fig. 1 Schematic of the cavity-dumped mode-locked Yb:YAG laser with SESAM. The pump source is the Ti:sapphire laser at 969 nm for the direct pumping. The TFP, RTP Pockels cell, and quarter-wave plate are inserted.

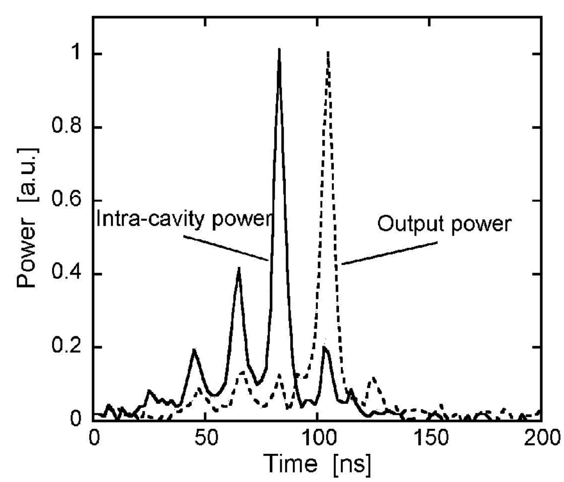

Fig. 2 Output pulse shape of the cavity-dumped mode-locked Yb:YAG laser pumped by the Ti:sapphire laser and the intra-cavity pulse buildup (intra-cavity power). The solid and dashed lines indicate the intra-cavity pulse buildup and the output pulse shape, respectively.

cavity. The single-pass gain of the Yb:YAG crystal is estimated to be 1.5 times. The population inversion was not depleted owing to the non-optimal gate time of 400 ns. These results indicate that higher-efficiency operation is certainly realized by optimizing the gate time. On the other hand, as shown in Fig. 2, some pre-pulses might appear because the leakage of the optical switch, which consists of the TFP, Pockels cell, and quarter-wave plate, existed during the intra-cavity pulse buildup. The leakage also causes cavity losses in the buildup. Furthermore, there might be a post-pulse, due to the oscillation outside the gate time, caused by the non-ideal optical switch. Even if the non-ideality of the optical switch existed, the pulse energy of the main pulse is estimated to be more than 2.5 μJ.

III. CONCLUSIONS

In conclusion, we demonstrated a cavity-dumped mode-locked Yb:YAG laser, for which the optical-to-optical conversion efficiency was 34.8% and the average output power was 400 mW. The pulse width was 15 ps at a repetition rate of 100 kHz. To our knowledge, the optical-to-optical conversion efficiency is the highest reported to date for cavity-dumped mode-locked lasers. These results indicate a sufficient possibility of realizing high energy short pulse lasers with high efficiency, high repetition rate, high reliability, compactness, and cost-effectiveness.

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REFERENCES

[1] A. Giesen, H. Hügel, A. Voss, K. Wittig, U. Brauch, and H. Opower, “Scalable concept for diode-pumped high-power solid-state lasers,” *Appl. Phys. B*, vol. 58, pp. 365–372, May 1994.

[2] R. Peters, C. Kränkel, K. Petermann, and G. Huber, “Broadly tunable high-power Yb:Lu_2O_3 thin disk laser with 80% slope efficiency,” *Opt. Express*, vol. 15, pp. 7075–7082, May 2007.

[3] C. Stewen, K. Contag, M. Larionov, A. Giesen, and H. Hugel, “A 1-kW CW thin disc laser,” *IEEE J. Sel. Top. Quantum Electron.*, vol. 6, pp. 650–657, Jul.-Aug. 2000.

[4] K. Petermann, D. Fagundes-Peters, J. Johannsen, M. Mond, V. Peters, J. J. Romero, S. Kutovoi, J. Speiser, and A. Giesen, “Highly Yb-doped oxides for thin-disc lasers,” *J. Cryst. Growth*, vol. 275, pp. 135–140, Feb. 2005.

[5] C. Stolzenburg, A. Voss, T. Graf, M. Larionov, and A. Giesen, “Advanced pulsed thin disk laser sources,” in *Proc. SPIE*, 2008, vol. 6871, 68710H, pp.1-14.

[6] S. Matsubara, T. Ueda, S. Kawato, and T. Kobayashi, “Nearly quantum-efficiency limited oscillation of Yb:YAG laser at room temperature,” in *Advanced Solid-State Photonics*, 2005, Technical Digest (Optical Society of America), paper TuB38.

[7] S. Matsubara, T. Ueda, S. Kawato, and T. Kobayashi, “Highly Efficient Continuous-Wave Laser Oscillation in Microchip Yb:YAG Laser at Room Temperature,” *Jpn. J. Appl. Phys.*, vol. 46, pp. L132–L134, Feb. 2007.

[8] S. Matsubara, T. Ueda, M. Inoue, M. Tanaka, K. Otani, S. Kawato, and T. Kobayashi, “High Efficiency Cavity Dumped Operation of Yb:YAG Laser at Room Temperature”, in *Advanced Solid-State Photonics*, 2006, Technical Digest (Optical Society of America), paper MB13.

[9] M. Takama, S. Matsubara, T. Ueda, M. Inoue, M. Tanaka, K. Otani, S. Kawato, and T. Kobayashi, “Highly efficient nanosecond-pulse Yb:YAG laser,” *Smart Processing Technology 07*, vol. 2, pp. 281–283, Mar. 2008.

[10] U. Wegner, J. Meier, and M. J. Lederer, “Compact picosecond mode-locked and cavity-dumped Nd:YVO_4 laser,” *Opt. Express*, vol. 17, pp. 23098–23103, Dec. 2009.

[11] G. Palmer, M. Emons, M. Schultze, and U. Morgner, “High peak power from a mode-locked two-crystal Yb:KYW oscillator with cavity-dumping,” in *Advanced Solid-State Photonics*, 2011, Technical Digest (Optical Society of America), paper AWB3.

[12] W. Koechner, *Solid-State Laser Engineering*, 6th ed., New York, USA: Springer, 2006.