Efficient nanosecond and sub-picosecond pulse lasers with high average power are needed for various applications such as micromachining, laser processing, and remote sensing. In comparison with the conventional neodymium-doped yttrium aluminum garnet (Nd:YAG) laser, the diode-pumped ytterbium-doped yttrium aluminum garnet (Yb:YAG) laser is particularly useful for high-power and ultrashort-pulse oscillation and amplification because of low heat generation with a quantum defect of 9% and a wide gain spectrum of 9.5 nm full width at half maximum (FWHM) with a long fluorescence lifetime of 0.95 ms. It also exhibits a simple two-level electronic structure without undesired loss processes such as excited-state absorption and concentration quenching. The broad absorption spectrum of 18 nm is useful for efficient and temperature stable pumping using high-power InGaAs laser diodes.

However, a high pumping intensity of more than 10 kW/cm² is required to reduce the reabsorption loss originating from the lower level population of the quasi-four-level system. An efficient cooling mechanism is required to prevent temperature increase in the laser crystal by high intensity pumping. Several types of Yb pumping architectures have been developed for high-power and efficient oscillation, including end-pumped thin disk, edge-pumped microchip or thin disk, end-pumped zigzag slab, edge-pumped zigzag slab, end-pumped circular rod, side-pumped circular rod, and fiber structures. Recently, a diode end-pumped thin-rod Yb:YAG scheme was proposed and analyzed in detail for high-average-power laser oscillation and amplification.

In this paper, CW oscillation characteristics of an end-pumped rectangular thin-rod Yb:YAG laser are presented. A schematic of the thin-rod Yb:YAG laser gain module is shown in Fig. 1. Two fiber-coupled laser diode diodes (JOLD-100-CAXF-15A, JENOPTIK, Laserdiode GmbH, Germany) were used for pumping. The laser diodes deliver CW 100 W output power through a fiber with a 0.6 mm core diameter with a numerical aperture of NA = 0.22. The center wavelengths at maximum output power of the two laser diodes are 935 and 939 nm. The pump beam of the laser diodes is focused on the end surface of the rod by 1 : 1 imaging optics using two planoconvex lenses with a focal length of 50 mm. The focus diameter of the beams is 0.85 mm. A low ytterbium concentration of 0.5 at. % is selected to reduce the temperature increase in the rod. The cross section of the rectangular rod is 1 × 1 mm². The pump beam axis is tilted by θp ~ 30° from the laser beam axis to separate the pump beam and the laser beam and to obtain a high pump absorption efficiency and a high pump intensity uniformity by multiple reflection along the rod axis. The optical transfer efficiency of the pump system was measured to be higher than 95%. The fluorescence distribution at the rod end is measured and is shown in Fig. 2. A uniform intensity distribution was observed.

It is shown in ref. 10 that the optical-to-optical conversion efficiency of the quasi-four-level systems is decreased when the total number of the ytterbium ions in the rod Nf is extremely large, thus, optimization of the pump absorption efficiency is required. When the spatial distribution of the fractional population is assumed to be uniform in the rod, the optimum pump absorption efficiency for maximum optical-to-optical conversion efficiency is obtained from

$$\eta_{opt} = 1 - \frac{f_0}{f_a + f_b} \frac{h \nu_L \Delta \cos \theta_p}{\eta_p P_p},$$

where f_a and f_b are the fractional populations of the lower and upper laser levels, respectively, f_0 is the initial value of the fractional population of the lower laser level, hν_L is the laser photon energy, τ_f is the fluorescence lifetime of the upper laser level, and S is the cross section of the thin-rod Yb:YAG crystal. Laser material parameters of the Yb:YAG are adopted from ref. 1 and used in the following estimation. The optimum pump absorption efficiency is estimated to be around 88 to 94% for the pump power range from 100 to 200 W and the optimum length of the thin-rod Yb:YAG to be 30 to 50 mm. The unsaturated pump absorption efficiencies of the two laser diodes are measured to be 78 and 83% for the 40-mm-long rod at a temperature of 10 °C. The measured values are slightly smaller than the designed values; this is mainly attributed to...
an error of the ytterbium ion concentration of the rod.

The cooling structure of the thin-rod is similar to the slab. Two parallel side surfaces are placed in contact with the copper heat sink cooled using water to remove the heat generated in the rod. The cooling-side surfaces are covered with a gold film for reflecting and confining the pump beams in the rod. An indium foil is inserted between the gold film and the heat sink to increase the contact area in order to decrease the thermal resistance between the rod and the heat sink. A simple temperature distribution is induced in the rod by one-dimensional heat flow, which results in a simple thermal-stress-induced birefringence and a laser-beam-focusing structure. The transmission loss caused by the thermal birefringence of the rod is reduced for the laser beam, that is linearly polarized in parallel or perpendicular to the cooling direction. The loss is measured to be less than an experimental error of about 3% at the maximum absorbed pump power of 166 W, that agrees well with the estimation for one-dimensional cooling of the rectangular rod. The measured loss is significantly smaller than the gain of the thin-rod Yb:YAG laser and hardly decreases the optical-to-optical conversion efficiency.

To obtain the thin-rod lasing characteristics, a simple linear laser cavity with two flat mirrors is used for the experiment. The cavity lengths of lasers (a) and the laser (b) are 90 and 280 mm, respectively. The length of 280 mm was chosen for generating a TEM\(_{00}\) beam. The output power of the thin-rod Yb:YAG laser was measured as a function of pump power and the results are shown in Fig. 3. Maximum output power was measured to be 55 W from laser (a) and 25 W from laser (b) at the maximum absorbed pump power of 166 W. The optical-to-optical conversion efficiency and the slope efficiency were 32 and 45%, respectively, for laser (a) at a cooling water temperature of 10 °C. For laser (b), the optical-to-optical conversion efficiency and the slope efficiency were 15 and 25%, respectively. The optical-to-optical conversion efficiency does not change appreciably with the cooling water temperature as shown in Fig. 3. The beam quality factor \(M^2\) values of laser (a) were 5.5 for the direction transverse to the cooling axis and 6.0 for the direction longitudinal to the cooling axis at full pump power. The \(M^2\) value of laser (b) for both transverse and longitudinal directions is 1.3 at full pump power.

The threshold power in the experiment agrees well with the theory,\(^{(10)}\) but the slope efficiency decreased significantly from theory. The reason for the discrepancy mainly consists of the decrease in the mode matching efficiency caused by the strong thermal focusing, the increase in the quasi-four-level laser loss caused by a temperature rise, and the existence of the parasitic oscillation in the rod.\(^{(11,12)}\) For multi-mode beam oscillation, the laser beam is extended to the rod cross section. Therefore, the decrease in the mode matching efficiency is estimated to be small. The temperature increase of the rod was measured. The optical-path-length change transverse to the rod axis caused by a temperature increase was measured using a Mach–Zehnder interferometer and was used to obtain the temperature increase of the rod. The average temperature increase of the rod is measured to be around 20 °C at full pump power. Most of the temperature increase is caused by the thermal resistance between the rod and the heat sink. The loss of the optical-to-optical conversion efficiency caused by the temperature increase is estimated to be smaller than only 10%. Consequently, the main reason is the parasitic oscillation in the thin-rod.

The interference pattern, measured using the Mach–Zehnder interferometer, was used to obtain the distribution of the optical path length transverse to the rod axis. The thermal focal length longitudinal to the cooling axis was estimated to be about 100 mm at full pump power. The experimental thermal focal length also agrees well with theory. The experimental thermal focal length perpendicular to the cooling axis was about 10 times larger than the longitudinal value. The pump intensity distribution transverse to the rod is almost uniform as shown in Fig. 2. Thermal flow perpendicular to the cooling axis is estimated to be significantly small and the temperature distribution...
along this direction is estimated to be almost uniform. Therefore, the beam focusing perpendicular to the cooling axis is caused by the thermal stress-induced birefringence in the rectangular rod. The value of the experimental focal length is almost the same as the value estimated by the birefringence theory. Figure 4 shows the result of the calculated beam radius at the center of the rod as a function of the pump power in the directions parallel and transverse to the cooling axis, assuming uniform pumping intensity in the rod. The thermal focal length of the thin-rod was experimentally confirmed. At the full pump power of 166 W, the TEM$_{00}$ beam diameter parallel to the cooling axis is almost equal to that transverse to the cooling axis for a cavity length. This means the beam quality factor parallel to the cooling axis is almost equal to that transverse to the cooling axis.

In conclusion, a diode end-pumped rectangular thin-rod Yb:YAG laser has been developed for CW oscillation at room temperature. A CW output power of 55 W with 45% slope efficiency and 34% optical-to-optical conversion efficiency in absorbed pump power is demonstrated from a 1 mm$^2$ cross-sectional rectangular rod with 0.5 at.% Yb ion concentration. The beam quality of the thin-rod laser has been discussed.

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Fig. 4. Beam diameter calculations longitudinal and transverse to cooling axis. The beam spot size for Gaussian beams at the end surface of the thin-rod is calculated as a function of the pump power. (a) Beam diameter parallel to cooling axis. (b) Beam diameter transverse to cooling axis.

heat conduction theory. To explain the reason why the beam qualities of the thin-rod laser for both transverse and longitudinal directions to the cooling axis are the same, the single mode beam diameter is calculated by the ABCD matrix method for the laser cavity with flat-flat mirrors.