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Efficient laser oscillation of Yb:$Y_3Al_5O_{12}$ single crystal grown by temperature gradient technique

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Low-threshold and highly efficient continuous-wave laser performance of Yb:$Y_3Al_5O_{12}$ (Yb:YAG) single crystal grown by a temperature gradient technique (TGT) was achieved at room temperature. The laser can be operated at 1030 and 1049 nm by varying the transmission of the output coupler. Slope efficiencies of 57% and 68% at 1049 and 1030 nm, respectively, were achieved for 10 at. % Yb:YAG sample in continuous-wave laser-diode pumping. The effect of pump power on the laser emission spectrum of both wavelengths is addressed. The near-diffraction-limited beam quality for different laser cavities was achieved. The excellent laser performance indicates that TGT-grown Yb:YAG crystals have very good optical quality and can be potentially used in high-power solid-state lasers. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2197933]

Laser-diode-pumped solid-state lasers have attracted a great attention for applications in military, machining, surgery, and so on. The investigation of Yb^{3+} doped materials has gained a lot of attention because Yb^{3+} lasers have several advantages over Nd^{3+} doped materials, such as the absence of the cross relaxation, upconversion and excited-state absorption, and easy growth of high concentration crystals.[1] Yttrium aluminum garnet ($Y_3Al_5O_{12}$ or YAG) is an attractive laser host material because of its excellent thermal, chemical, and mechanical properties. Yb:YAG crystal has been a promising candidate for high-power laser-diode-pumped solid-state lasers.[2–4] Owing to the congruent melting properties, commercially available Yb:YAG single crystals are usually grown by Czochralski (Cz) method in inert (N_2) or oxidizing atmosphere (N_2+2 vol % O_2). However, there are some shortcomings to grow Yb:YAG crystal by using Cz method. There are defects such as cores and light-scattering particles in Yb:YAG crystals grown by Cz method.[5] Although the cores can be reduced by annealing after growth, the cores cannot be eliminated, the available area of Yb:YAG crystal will be limited by the core. The weight loss of the iridium crucible cannot be avoided during Cz growing process, especially in oxidizing atmosphere. These factors limit the growth of large-size, high-quality Yb:YAG crystals. High-optical-quality, large-size Yb:YAG crystals are needed for high-power solid-state lasers, therefore, growth of high-quality, large-size Yb:YAG crystals is a very important factor to realize high-power lasers. We have successfully grown high-optical-quality, large-size sapphire crystal,[6] Nd^{3+}:YAG crystal,[7] and Ti:sapphire crystal[8] by using temperature gradient technique (TGT). Because flat or slightly convex solid-liquid interface can be easily maintained in the suitable and stable temperature field by temperature gradient technique, large-size, high-optical-quality Yb:YAG crystals without cores and scattering particles can be easily obtained by using molybdenum crucible. A 3 in. in diameter Yb:YAG crystal doped with 5 at. % Yb was successfully grown by TGT.[9] Although a concentration gradient along the growth axis exists, which is larger than those grown by Cz method, the cores and secondary particles are eliminated. Moreover, the distribution along the radius of the crystal boule is nearly unity. To improve the crystal quality and the laser performance, 3 in. diameter Yb:YAG crystal doped with 10 at. % Yb has been successfully grown using TGT. In this letter, we report highly efficient laser performance of laser-diode-pumped TGT-grown Yb:YAG lasers at 1030 and 1049 nm. The slope efficiency is as high as 68% and the optical-to-optical efficiency is over 51%, even when the laser is working at room temperature without water-cooling system, just using the conduction cooling through the copper sample holder. The results show that the TGT-grown Yb:YAG crystals have excellent optical quality, the loss of the crystals is very small. Large-size, high-quality Yb:YAG crystals grown by TGT will be potential laser materials for high-power solid-state lasers. The laser characteristics (output power and laser spectrum) under different output couplings are investigated as a function of the pump power.

The experiment was carried out with a plane-parallel, 1-mm-thick Yb:YAG crystal doped with 10 at. % Yb as a gain medium. The experimental setup is shown in Fig. 1. One surface of the Yb:YAG crystal is anti-reflection-coated at 940 nm and highly reflecting at 1030 nm to act as a cavity mirror of the laser. The other surface of the Yb:YAG is anti-reflection-coated at 1030 nm to reduce the cavity loss and

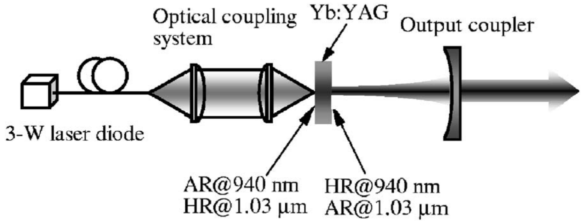

FIG. 1. Schematic diagram of laser-diode-pumped Yb:YAG laser.

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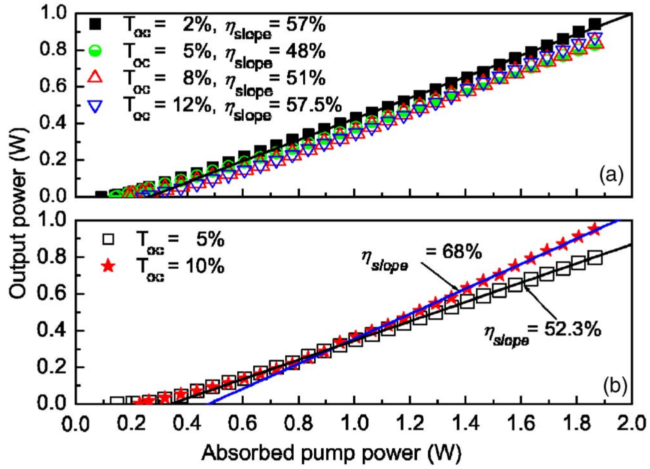

FIG. 2. (Color online) Output power as a function of the absorbed pump power for different transmissions of the output coupler. (a) Plano-concave cavity, the solid line is the linear fitting for $T_{oc}=2\%$; (b) monolithic microchip Yb:YAG laser for $T_{oc}=5\%$ and 10%, respectively.

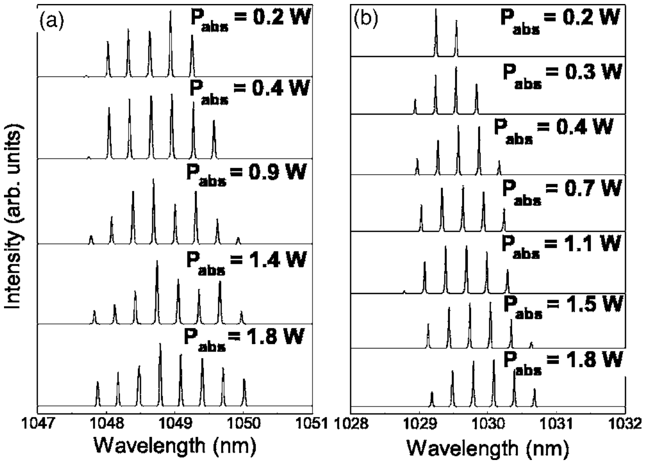

FIG. 3. Laser spectra of Yb:YAG laser under different pump power levels for (a) $T_{oc}=2\%$ and (b) $T_{oc}=8\%$.

total reflection at 940 nm to increase the absorbed pump power. Four concave mirrors were used as output couplers. All concave mirrors had the same radius of curvature of 70 mm but different transmissions of 2%, 5%, 8%, and 12% at 1.03 μm. The overall cavity length was about 35 mm. A 3 W fiber-coupled 940 nm laser diode with a core diameter of 100 μm and numerical aperture of 0.15 was used as the pump source. Two lenses of 8 mm focal length were used to focus the pump beam on the crystal rear surface and to produce a pump light footprint in the crystal of about 100 μm in diameter. About 92% of the total pumping power is incident on the Yb:YAG crystal after the coupling optics. The Yb:YAG laser was operated at room temperature without active cooling of the active element.

The laser output power of plano-concave cavity as a function of the absorbed pump power for different output couplers is shown in Fig. 2(a). The absorbed pump power threshold increases from 90 to 240 mW when increasing the transmission of the output coupler (T_{oc}) from 2% to 12%. The maximum output power was achieved with $T_{oc}=2\%$. Output power of 940 mW was achieved when the absorbed pump power was 1865 mW, and the slope efficiency was about 57%. The measured slope efficiencies are 48%, 51%, and 57.5% for $T_{oc}=5\%$, 8%, and 12%, respectively. For $T_{oc}=2\%$, the laser automatically oscillates at 1049 nm because of the lower reabsorption loss around the weak emission peak of 1049 nm for Yb:YAG crystal. The lasers oscillate at 1030 nm when the transmission of the output coupler is 5% or higher. The round-trip cavity loss L was estimated to be less than 5% from the measured values of the pump power threshold for different transmission of the output couplers according to the formula,[10] $-\ln R=2KP_{th}-L$, where R is the reflectivity of the output coupler, P_{th} is the pump power threshold, and K is the pumping coefficient defined as the product of all the coefficients that lead to the population of the upper laser state.

We also tested the laser performance of the microchip Yb:YAG crystal grown by TGT by applying the direct coating on both sides of the crystal. A 1-mm-thick Yb:YAG crystal was polished to a plane-parallel geometry as a laser resonator. The planar rear surface is coated for high transmission at 940 nm and total reflection at 1030 nm. The planar front surface serving as output coupler is coated for 5% and 10% transmissions at 1030 nm and total reflection at 940 nm. The absorbed pump power thresholds are 150 and 230 mW for $T_{oc}=5\%$ and 10%, respectively. The lasers oscillate at 1030 nm, the output power as a function of the absorbed pump power for microchip laser is shown in Fig. 2(b). The output power increases linearly with the absorbed pump power when the pump power is well above the pump power threshold, which is the nature of quasi-three-level system, the high efficiency can be achieved by using high pump power intensity. The maximum pump power intensity is estimated to be 25.5 kW/cm^2 by using the pump beam diameter of 100 μm. Under this high pump power intensity, the optical-to-optical efficiency is as high as 51% for $T_{oc}=10\%$. The slope efficiencies of the two microchip lasers are 52.3% and 68% for $T_{oc}=5\%$ and 10%. The slope efficiency of 68% of laser-diode-pumped Yb:YAG laser is the highest efficiency achieved even at room temperature just cooling the Yb:YAG sample by air. The increase of the efficiency of microchip laser comparing to the plano-concave laser configurations is attributed to the decrease of the intracavity loss by direct coating on the both sides of the crystal.

The laser output beam profile was monitored using a charge coupled device camera both in the near field and the far field of the output coupler. The output laser transverse intensity profile was close to fundamental transverse electromagnetic mode in all the pump power range. The near-diffraction-limited beam quality M^2 of less than 1.1 for microchip laser and less than 1.5 for plano-concave cavity was achieved.

The Yb:YAG laser spectrum was analyzed by using an ANDO AQ6317 optical spectrum analyzer. The laser spectrum of these lasers indicates that several longitudinal modes oscillate simultaneously (around 1049 nm when T_{oc} is 2% and around 1030 nm when T_{oc} is 5%, 8%, and 12%, respectively). For $T_{oc}=2\%$, six longitudinal modes oscillate when the pump power is just above threshold, while seven or eight longitudinal modes oscillate with further increase of the pump power, as shown in Fig. 3(a). For $T_{oc}=8\%$, the number of oscillating longitudinal modes was found to increase from two, just above threshold, to six at higher pump power, as shown in Fig. 3(b). The separation of each longitudinal mode under different pump power was about 0.29 nm. The separation of the longitudinal modes in a laser cavity was given by[10] $\Delta\lambda=\lambda^2/2L_c$, where L_c is the optical length of the resonator. Mode selection in this plano-concave cavity multimode laser is mainly determined by the gain medium used in the experiment. For 1-mm-thick Yb:YAG planar-parallel gain medium studied here, $\Delta\lambda$ was calculated to be 0.2915 nm with the laser wavelength of 1030 nm, which was in good agreement with the experimental data. The linewidth at each mode was measured to be less than 0.02 nm, i.e., the resolution limit of the instrument. The central wavelength (1049 nm) of the output power does not change with the absorbed pump power for $T_{oc}=2\%$, however, the laser emission wavelength (around 1030 nm) shifts to the longer wavelength with the absorbed pump power when T_{oc} is 5% or higher. The redshift of the laser wavelength around 1030 nm is caused by the emission spectrum of Yb:YAG shifts to longer wavelength with the increase of the temperature[11] due to more heat generated inside the gain medium with the pump power. Therefore, 1030 nm Yb:YAG laser oscillates at longer wavelength because the maximum gain shifts to the longer wavelength with the increase of the temperature inside the gain medium. For 1049 nm oscillation, although the emission wavelength of Yb:YAG crystal at 1049 nm shifts to longer wavelength with temperature, the emission spectrum around 1049 nm is flatter than that around 1030 nm. The effect of the temperature on the gain at 1049 nm is smaller than that at 1030 nm, therefore, the laser spectrum at 1049 nm is nearly independent on the pump power. The more longitudinal-mode oscillation at 1049 nm comparing to those at 1030 nm at the same pump power level also demonstrates that the broader and flatter emission spectrum centered at 1049 nm is more suitable for multi-longitudinal-mode oscillation compared to that at 1030 nm due to the spatial hole burning effect.

Based on the estimated cavity loss and the threshold formula including the reabsorption loss at laser wavelength for quasi-three-level system,[12,13] the absorbed pump power threshold at both laser wavelengths (1030 and 1049 nm) as a function of the transmission of the output couplers is shown in Fig. 4. The pump power threshold for both laser wavelengths increases with the transmission of the output coupler, however, the pump power threshold for 1049 nm increases faster than that for 1030 nm owing to the emission cross section at 1049 nm of Yb:YAG is only one-sixth of that at 1030 nm. When the transmission of the output coupler is smaller than 4.2%, the threshold at 1049 nm is lower than that at 1030 nm because of the thermal distribution factor at 785 cm^{-1} is less than half of that at 612 cm^{-1} for Yb:YAG crystal. Therefore, under the same laser cavity configuration, when the transmission of the output coupler is smaller than 4.2%, Yb:YAG laser oscillates at 1049 nm preferentially instead of 1030 nm. These calculations are in good agreement with the Yb:YAG laser experimental results for different transmissions of the output couplers.

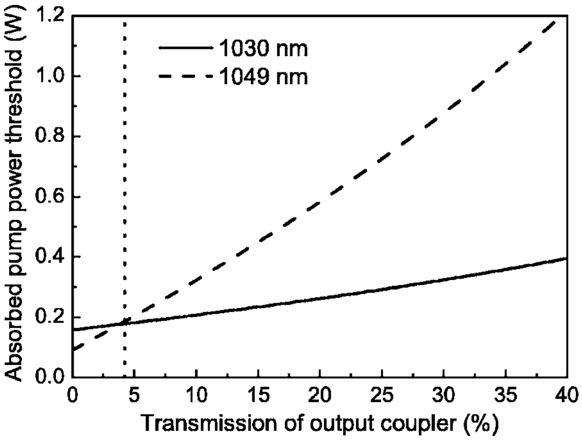

FIG. 4. Absorbed pump power threshold of Yb:YAG laser as a function of the transmission of the output coupler for two-wavelength oscillation.

In conclusion, efficient laser operation of laser-diode end-pumped Yb:YAG crystals grown by TGT was demonstrated both at 1030 and 1049 nm. The laser was operated at room temperature just cooling by the air. The slope efficiency of as high as 68% and optical-to-optical efficiency of over 51% was achieved for both wavelength operations. The beam quality factor (M^2) at full pump power range was measured to be less than 1.1. The laser oscillation wavelength can be changed by varying the transmission of the output coupler. A 1049 nm laser operation was automatically obtained by using 2% transmission output coupler. The laser wavelength around 1030 nm shifts to red with the increase of the absorbed pump power, while the laser wavelength around 1049 nm does not change with the pump power. The laser experiments show that Yb:YAG crystals grown by TGT have very good optical quality and can be a very good material for high-power laser performance at both 1030 and 1049 nm.

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