Diode-pumped efficient continuous-wave $Yb{:}Y_3Ga_5O_{12}$ laser at 1035 nm

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An efficient diode-pumped $Yb{:}Y_3Ga_5O_{12}$ (Yb:YGG) laser was demonstrated by using a high-quality Yb:YGG crystal grown by the optical floating zone method. Continuous-wave laser power up to 2.65 W had been obtained under an incident pump power of 6.71 W at 970 nm, corresponding to an optical-to-optical efficiency of 39.5% and maximum slope efficiency of 84.5%. A modeling calculation of the Yb:YGG laser was also performed, and the theoretical results were consistent with the experimental results.

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As a candidate of high-power and ultrafast laser medium, the trivalent ytterbium ion (Yb^{3+}) doped materials have many outstanding properties, such as simple energy-level structure, long energy storage lifetime, and broad absorption and emission bandwidth. A variety of hosts have been studied, and crystals belonging to the family of garnets (like Yb:YAG) proved to be promising for high-power applications, mainly because they have good spectroscopic parameters and exhibit high thermal conductivity [1–3]. With gallium replacing aluminum in the YAG crystal, another garnet material—yttrium gallium garnet (YGG)—has been generated. Like other garnets, YGG crystal also has good thermal conductivity ($9\,Wm^{-1}K^{-1}$) and is acceptable substitutionally for trivalent ions of both rare-earth and transition metal ions [4,5].

Yb^{3+} doped yttrium gallium garnet (Yb:YGG) was first reported as a scintillator. The most interesting property is that the bandwidth of its emission spectrum is nearly four times broader than Yb:YAG's [6]. The high-quality Yb:YGG crystal suitable for laser operation had been grown through the optical floating zone method by H. Yu *et al.* for the first time [7], and the special thermal properties, including the specific heat, thermal expansion coefficient, thermal diffusion coefficient, and thermal conductivity had been investigated. Femtosecond operation was first demonstrated in 2009 [8]. All the results showed that Yb:YGG should be an excellent laser medium applied in high-power and ultrafast pulsed lasers. In this Letter, we report a highly efficient diode-pumped continuous-wave (CW) Yb:YGG laser. Under the full incident pump power of 6.71 W, output power up to 2.65 W has been gained, corresponding to an optical-to-optical efficiency of 39.5% and maximum slope efficiency of 84.5%. Although recently a slope efficiency of 91.9% for the absorbed pump power was demonstrated in a heat-fraction-limited CW Yb:YAG [9], which operated at 77 K and was pumped by a solid-state laser, our result could be comparable to this record slope efficiency. Under diode pumping and normal cooling conditions, the highest reported slope efficiency of garnets was about 70% for the incident pump power [1,10]. By modeling a longitudinally pumped quasi-three-level system, we also calculated the slope efficiency of a Yb:YGG laser, and the results are consistent with the experimental results.

The Yb:YGG single crystal grown by the optical floating zone method [7] was finely polished and antireflection-coated at a broad spectrum range around 1 μm with a cross section of $3\,mm \times 3\,mm$ and a length of 3.2 mm. For efficient heat dissipation, the crystal was mounted tightly in a water-cooled copper heat sink, and the water temperature was maintained at 7 °C during the experiment. A high-brightness fiber-coupled diode laser emitting at 970 nm (Jenoptik, JOLD-7.5-BAFC-105) was used to end-pump the crystal. The pump laser output from the fiber (with 50 μm core diameter and 0.22 numerical aperture) was coupled into the laser medium through a coupling system with a magnification of 0.8, in which the laser spot radius was about 20 μm. A Z-fold cavity was designed for the CW experiment. Figure 1 shows a schematic of the pump geometry and laser cavity. M1 is a plane dichroic mirror with high transmission at 970 nm ($R < 5\%$) and high reflection at 1020–1100 nm ($R > 99\%$); M2 and M3 are concave mirrors, with radii of curvature of 300 and 200 mm, respectively. M4 is an end mirror with high reflection at 1000–1100 nm ($R > 99\%$). Two plane mirrors with different transmissions (6% and 8%) in the range of 1020–1080 nm were used as output couplers (OCs). The total length of the cavity was about 1.2 m.

Taking into account the loss caused by the coupling system and M1, 6.71 W incident pump power was available. However, it is an unavoidable problem for the diode

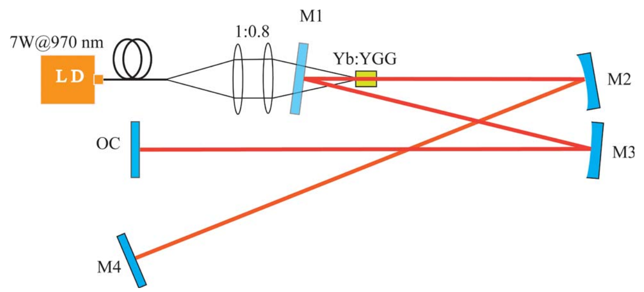

Fig. 1. (Color online) Experimental setup of the Yb:YGG laser.

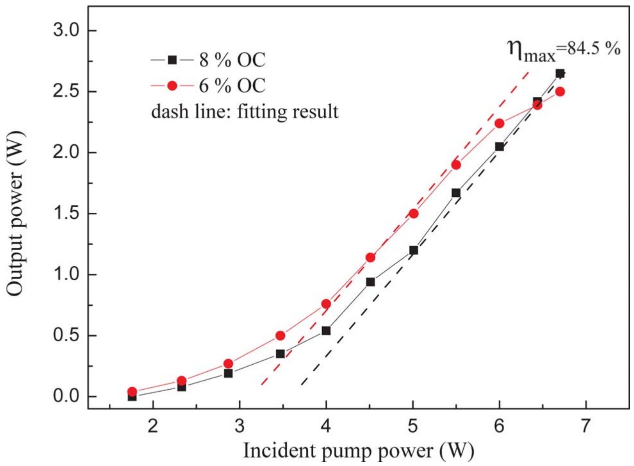

Fig. 2. (Color online) Relationship between output power and incident pump power.

laser that the laser spectrum gets broader and the central wavelength shifts to the longer range when the pump power gets higher. When the temperature of the laser diode (LD) was set to 19 °C, the central wavelength of the LD was 971 nm at maximum output power and 964 nm near the threshold. Figure 2 shows the measured CW output power of the Yb:YGG laser as a function of the incident pump power for two different OCs. Limited by the available pump power, the maximum output power was obtained with an 8% transmission OC, leading to a power of 2.65 W (PM30V1, Coherent Inc.) at 1035 nm under an incident pump power of 6.71 W. The slope efficiency reached the maximum when the pump power was in the range of 5–6.7 W, for which the emission spectrum of the LD and the absorption spectrum of Yb:YGG were matching well and about 70% of the pump power was absorbed. At the maximum output power, the pattern was a perfect TEM_{00} transverse mode. The beam quality was measured by a laser beam propagation analyzer (M2-200s-FW, Ophir-Spiricon Inc.). Figure 3 shows the

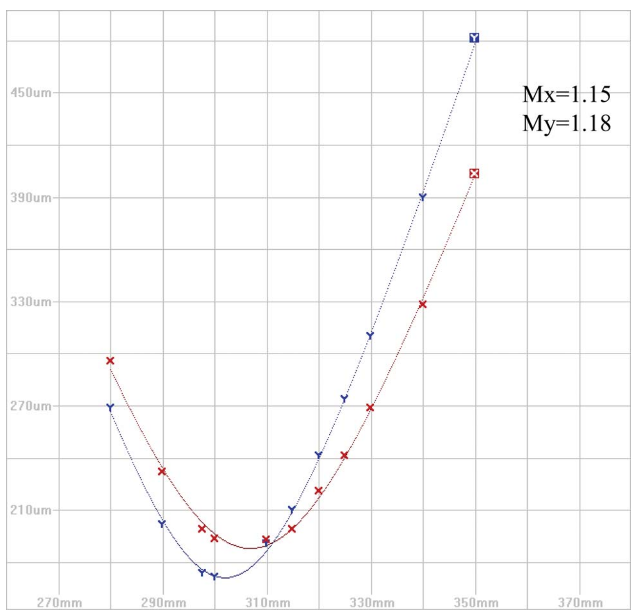

Fig. 3. (Color online) Measurements of beam width versus position for a given run.

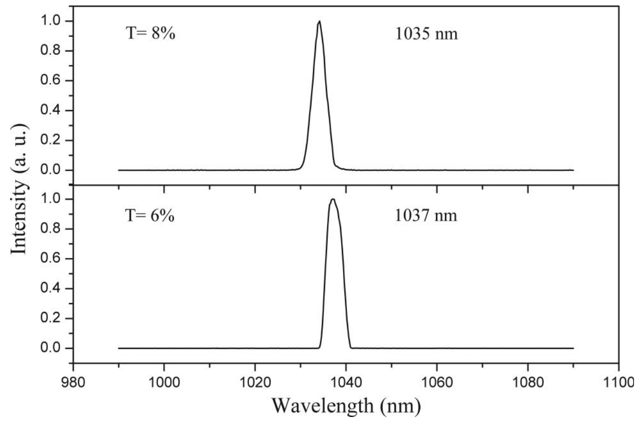

Fig. 4. Emission spectra of the Yb:YGG laser for different couplers under 6.71 W pumping.

measurements of beam width versus position for a given run, which correspond to the beam quality factors (M2, given automatically by the analyzer) of 1.15 and 1.18 for tangential direction and sagittal direction, respectively. The fluctuation of the output power was less than 2% during two hours. Like other isotropic crystals (such as Yb:YAG), the output laser was not polarized without polarization-selective elements in the resonator. The laser emission wavelength, which was associated with the gain cross section as shown in [7], varied with both the transmission of the output coupler and the pumping intensity [11]. Figure 4 shows the laser emission spectra recorded for different OCs at the same incident power of 6.71 W. The emission wavelength and the bandwidth of the output laser decreased with increasing output coupling.

The energy level diagram of Yb:YGG is shown in Fig. 5, which is classified as a quasi-three-level system. For theoretical computation, the modeling of longitudinally pumped solid-state lasers exhibiting reabsorption losses was applied to the Yb:YGG laser. The output power as a function of incident pump power can be obtained by solving the following equation [12]:

$$F = \frac{1 + \frac{B}{fS}\ln(1 + fS)}{f \int_0^\infty \frac{\exp[-(a^2+1)x]}{[1+fS\exp(-a^2x)]} dx}, \qquad (1)$$

where $f = f_1 + f_2$, f_1 and f_2 denote the fractions of the $^2F_{7/2}$ and $^2F_{5/2}$ population density residing in the lower and upper crystal-field component, a is the ratio of pump

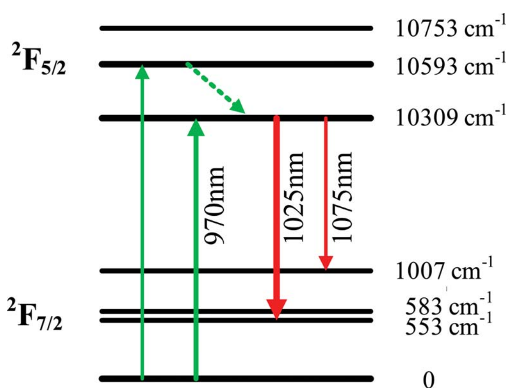

Fig. 5. (Color online) Relevant energy levels of Yb^{3+} ion in Yb:YGG crystal.

Table 1. Pertinent Parameters for Yb:YGG Crystal

Radiative lifetime at room temperature	1.1 ms	[13]
Peak emission cross section (at 1025 nm)	2.6×10^{-21} cm^2	[8]
Peak absorption cross section (at 970 nm)	2.7×10^{-21} cm^2	[8]
Refraction ratio	1.89	
Doping density (10 at.%)	4.1×10^{19} cm^3	

beam and laser beam waists, B is the ratio of the reabsorption loss to fixed cavity loss, F is a normalized variable proportional to pump power, and S is a normalized variable proportional to internal laser power. Assuming the temperature of the active area of the crystal was 300 K, the computed Boltzmann factors were $f_1 = 0.054$ and $f_2 = 0.727$. According to the ABCD matrix, $\omega_L = 34\,\mu$m, so therefore $a = \omega_p/\omega_L \approx 0.6$. Other Yb:YGG laser parameters were listed in Table 1 [8,13]. The calculated results of the output power versus the launched pump power are shown by dash lines in Fig. 2. For the 6% OC, there is a power rollover near the maximum pump power, which is caused by thermal effects such as thermally enhanced reabsorption losses resulting from the high intracavity intensity [14]. At a lower pump power, the laser operated at a shorter wavelength, which caused the actual threshold to be smaller than the theoretical results, and the mismatch between the pump wavelength and the peak absorption led to the smaller slope efficiency.

In conclusion, we have demonstrated a high-efficiency CW Yb:YGG laser by using two different OCs. The maximum output power of 2.65 W was achieved by using the 8% OC with a central wavelength at 1035 nm. The maximum slope efficiency as high as 84.5% achieved in these lasers is quite noticeable. Excellent laser performance suggested that the Yb:YGG crystal should be an excellent laser medium applied in high-power and ultrafast pulsed lasers.

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