Performance of a liquid-nitrogen-cooled CW Tm, Ho:YLF laser

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Received September 9, 2002

A liquid-nitrogen-cooled Tm, Ho:YLF laser is constructed with a 10-mm-long Tm(6%) and Ho(0.5%) co-doped yttrium lithium fluoride crystal pumped by a laser diode operating at 792 nm. The laser output power is improved by cooling the Tm, Ho:YLF crystal from 300 to 77 K. When the crystal is kept at 77 K, the laser threshold pump power is 230 mW, the slope efficiency is 27.4%, and the maximum optical-to-optical efficiency is 19.9%. At the same time, the relation between the input power and the output power at different temperatures is obtained.

OCIS codes: 140.3480, 140.3070, 140.0140, 140.3580.

Since Johnson *et al.* reported efficient CW operation in Er, Tm, Ho:YAG at 77 K in 1965[1], co-doped Tm, Ho laser has received a large amount of interest. These lasers seem to be the best candidates for a wide range of applications, including medicine[2] and eye-safe remote sensing systems[3−6] such as laser range, coherent Doppler lidar for wind sensing, wind-shear detection, differential absorption lidar (DIAL) water vapor profiling, etc. The Tm, Ho laser system exhibits many remarkable properties: two-for-one pumping of the Ho ions via cross relaxation, long fluorescence lifetime, moderate gain cross section, and energy storage capability. In addition, a YLF crystal as a host crystal has some excellent characteristics such as a low thermal lens effect because of negative dn/dt and inherent polarized oscillation because of its uniaxial structure. At elevated temperatures, however, the quasi-three level natures of the Ho laser transition results in the necessity of very highly excited state density to achieve useful gain. High-excited state density leads to "up-conversion" processes, which are manifested by a decrease of upper level lifetime and a nonlinear relationship between gain and pump energy. So, to achieve the highest gain, we have selected to operate at 77 K where the excited state density for fixed gain is minimized. In this paper, we investigated these performances of the liquid-nitrogen-cooled laser at different temperatures. The diode-pumped laser geometry is illustrated in Fig. 1. The Tm, Ho:YLF laser is pumped by a 3-W (S-79-3000-200-H/L) laser diode along the "c" axis of the laser crystal. Pump wavelength is temperature tuned to coincide with the 792 nm Tm absorption band.

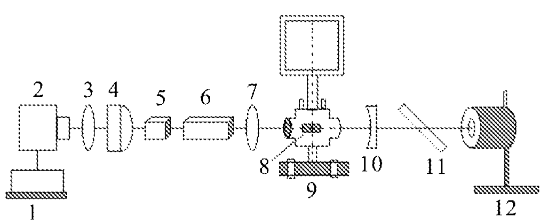

Fig. 1. Experimental setup used in LD end-pumped experiments. 1: diode drive source, 2: laser diode, 3 and 7: lens, 4: cylindrical lens, 5: Glan prism, 6: Faraday optical rotator, 8: crystal, 9: cooling container, 10: output coupler, 11: dichroic mirror, 12: power meter.

The laser diode output is collected by a spherical lens with focal length of 8 mm, followed by a cylindrical lens with focal length of 100 mm to reshape. The reshaped pump beam is input into a Glan prism and a Faraday optical rotator in order to avoid the unwanted feedback in the pump laser, then the pumping beam is incident onto a convergent lens with focal length of 100 mm. With this arrangement the pump beam can be focused to an elliptical spot of approximately 500×300 μm at the entrance face of the laser crystal. The total transmission efficiency of the beam-reshaping system is about 82% at 792 nm. The crystal from EKSMA corporation has dopant concentrations of 6% Tm, 0.5% Ho with dimension of $5 \times 5 \times 10$ mm^3. The polished faces are parallel. The output face of crystal is AR coated at 2 μm and the pump input face has highly transmissive coating at 792 nm and highly reflective coating at 2 μm. Cooling of the Tm, Ho:YLF crystal is accomplished by mounting it onto a cold finger and enclosing it in a housing with AR windows. The housing is then attached to a compact detector-type dewar used as the liquid nitrogen reservoir. The resonator is plano-concave. The pump input face of the Tm, Ho:YLF crystal is served as the plano high reflector. The radius of curvature of the output coupler is 30 cm. Laser output is achieved when the output coupler reflectivity is 70%. The temperature of the laser rod is increased from 77 to 240 K by cooling the laser rod with circulating liquid nitrogen vapor and then letting it warm slowly to room temperature. We placed the entire pumping cavity in a vacuum system to achieve thermal isolation. Good thermal isolation is necessary because the cooling capacity of the liquid nitrogen vapor is limited. Figure 2 shows the output power as a function of incident pump power at 77 K. The incident pump power threshold is 230 mW and a linear regression fit to the experimental data yields a slope efficiency of 27.4%. The laser wavelength is 2.065 μm measured with a monochromator. Figure 3 shows the optical-to-optical efficiency versus the incident pump power, we note that the maximum optical-to-optical efficiency is 19.9% at the incident power of about 1.4 W. The measured laser output powers as a function of operating temperature at various input powers with a 70% reflectivity mirror are shown in Fig. 4. The

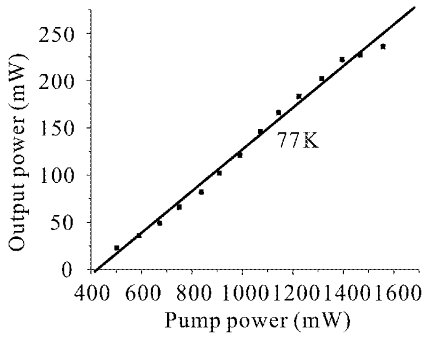

Fig. 2. The pump power versus output power.

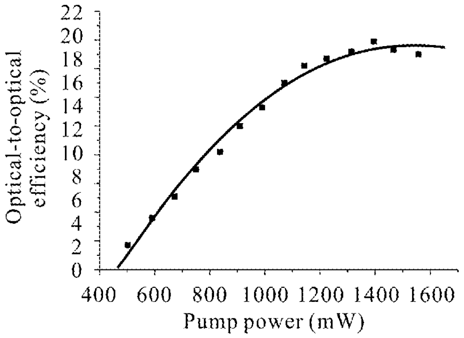

Fig. 3. The pump power versus optical-to-optical efficiency.

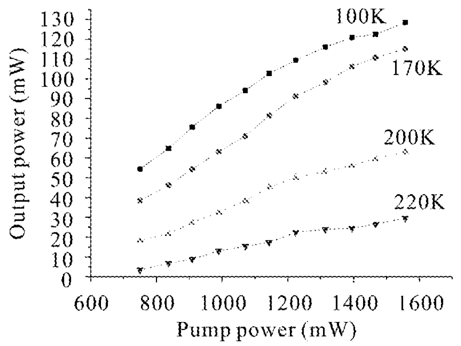

Fig. 4. The output power as the function of pump power at different temperatures.

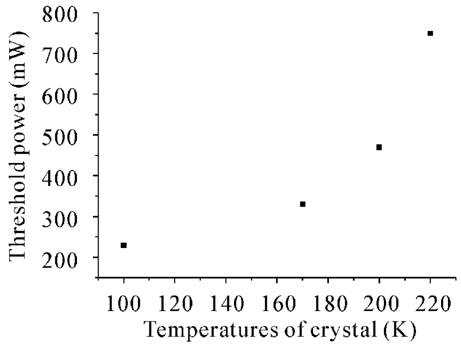

Fig. 5. The threshold power as the function of temperature.

threshold is the incident pump power that the laser begins to oscillate. Figure 5 shows the thresholds at four different temperatures. We note that under the same pump power, when the crystal temperature decreases, the output power increases and the threshold pump power decreases. The decrease of the laser output power with

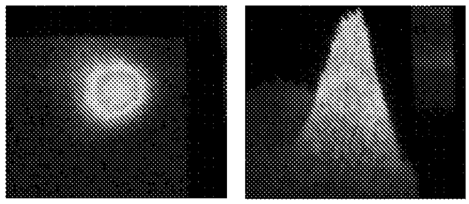

Fig. 6. Far-field profile of Tm, Ho:YLF laser (The left is plane image and the right is three-dimensional image).

the increasing temperature is mainly due to the decrease of thermal population in the upper laser level, the increase of that in the lower laser level, and the increase of the up-conversion possibility with the increasing temperature. These up-conversion processes take place between $Tm^{3+}(^3F_4$ to $^3H_6)$ and $Tm^{3+}(^3F_4$ to $^3H_4)$, and between $Tm^{3+}(^3F_4$ to $^3H_6)$ and $Ho^{3+}(^5I_7$ to $^5I_5)$, increase with the increasing temperature and cause lowering of the laser output power by increasing the upper state population loss. The decrease of the slope efficiency with the increase of the crystal temperature can be explained mainly with the decrease of the transfer efficiency of the Tm^{3+} $^3F_3$ levels to Ho^{3+} $^5I_7$ levels, and the rate of the cross-relaxation process between Tm^{3+} $^3H_4$ and Tm^{3+} $^3H_6$ manifolds. Figure 6 shows a typical far-field beam profile of Tm, Ho:YLF laser measured with a pyroelectric vidicon camera. Only single transverse-mode oscillation was observed; higher-order transverse mode oscillation was not observed during the experiments.

In conclusion, a liquid-nitrogen-cooled Tm, Ho:YLF has been demonstrated. When the crystal temperature is at 77 K, the laser threshold pump power is 230 mW, the slope efficiency is 27.4%, and the maximum optical-to-optical efficiency is 19.9%. When the crystal temperature increases, the threshold power increases and the slope efficiency decreases. So decreasing crystal temperature can improve the output characteristics of crystal. At the same time, we only observed the single transverse-mode during the experiments.

The project (HIT.2002.14) is supported by the Scientific Research Foundation of Harbin Institute of Technology. X. Zhang is the author to whom the correspondence should be addressed, his e-mail address is zhangxinlu1@sohu.com.

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