3.6-W cryogenic Tm,Ho:YLF laser pumped by fiber-coupled diodes module

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In this paper, we report a high power cryogenic cooling Tm(6 at.-%),Ho(0.5 at.-%):YLF laser end-pumped by a 19-fiber-coupled-diodes module with the central wavelength of 792 nm at 20 °. The highest continuous-wave power of 3.6 W at 2.051 μm is attained under pumping power of 13.6 W, corresponding to optical-optical conversion efficiency of 26%, and the slope efficiency is larger than 30%. The threshold power is only about 0.16 W because of the long lifetime, large effective emission cross section, and low re-absorption in Tm,Ho:YLF crystal.

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Co-doped Tm,Ho lasers seem to be the best candidates for a wide range of applications including medicine and eye-safe remote sensing systems: laser ranging, coherent Doppler lidar for wind sensing, wind-shear detection, differential absorption lidar (DIAL) water vapour profiling, etc.. Thereby, they received a large attention from the space and aviation agencies for both continuous-wave (CW) master oscillator or powerful transmitters[1]. We have studied microchip Tm(6 at.-%),Ho(0.4 at.-%):YLF laser longitudinally pumped by 2.7-W laser diode (LD) with output power of 0.3 W at 2.06 μm[2]. Because of quasi-three-level properties of Tm,Ho laser system, serious thermal effects and upconversion depletion occur, it is difficult to operate it with higher efficiency. Lotem *et al.* have studied the CW cryogenic Er,Tm,Ho:YLF laser pumped by lamp with 60-W power and 4.75% conversion efficiency[3]. The diodes-pumped Tm,Ho:YLF laser of Sanders in USA operating at 77 K attained optical-optical efficiency of 45.6%[4]. The design has been applied into eye-safe imaging lidar system by Kei *et al.*[5]. Wang *et al.* have studied cryogenic Tm,Ho:YLF laser pumped by a 2.7-W diode, and attained 20% optical conversion efficiency[6]. In this paper we focus on cryogenic Tm,Ho:YLF laser pumped by fiber-coupled LDs for higher power output.

The experimental setup is shown in Fig. 1. In the experiment, the gain medium is an *a*-cut Tm(6 at.-%),Ho(0.5 at.-%):YLF crystal with size of 10 mm in length and 5×5 mm^2 in cross section. Both faces of the crystal are polished plane and parallel, and the pump end is coated with reflectivity of about 99.5% at 2050 nm, and transmissivity of greater than 85% at 792 nm, and the output end is anti-reflection (AR) coated at 2050 nm with reflectivity $R < 0.2\%$. This crystal is wrapped by foil and held in a copper heat-sink connected with a small dewar filled with 450-ml liquid nitrogen. The windows of dewar are CaF_2 with 5-mm thickness and 25-mm diameter, and AR-coated with transmissivity of about 99.4% at 2050 nm and > 99% at 792 nm. The configuration of dewar is designed for experimental convenience, so that the crystal can be adjusted for optimal pumping and laser operation. The temperature of heat-sink could be measured by nickel-chromium versus nickel-aluminium thermocouple (OMEGA Corporation).

The pumping module is composed of 19 diodes arranged onto copper heat-sink with area of 20×8 cm^2. The temperature of diodes can be controlled by thermal-electronic device (TEC) with accuracy of 0.1°. The driver offers the driving capacity of compliance voltage of 38 V and the maximum current of up to 2.0 A. The threshold current of the module is 0.21 A, and the maximum operating current of that is 1.2 A. Each diode is coupled out by an optical fiber with efficiency of 75%, and then the fibers are bundled together, forming a diameter of 0.7 mm and numerical aperture of 0.22 at the face. The fiber-coupled diodes can deliver power of 15.1 W at 1.2 A with slope efficiency of 15.5 W/A. The central wavelength is 793.4 nm at 24 °C with linewidth of 2.5 nm (full-width at half-maximum, FWHM). It is tuned to Tm^{3+} absorption peak of 792 nm by changing temperature of LDs.

The collimating and focusing lens are a pair of AR-coated achromatic ones with focus length of 65 mm, which make the ratio of image to object 1 : 1. The total optical transferring efficiency is greater than 85%, and power into Tm,Ho:YLF crystal is about 72%.

For optimizing laser parameters, three different plano-concave mirrors with curve radius of 100, 200, 300 mm

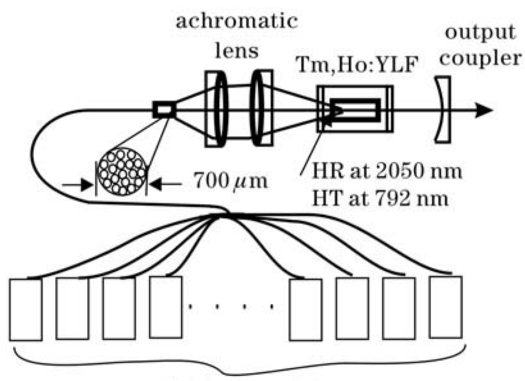

Fig. 1. The schematic of experimental setup of diode-pumped cryogenic Tm,Ho:YLF laser.

were employed as output coupler in the experiment. Different transmissivity output coupler of 5%, 10%, 23%, 30%, and 40% were tested for high output power and efficiency. The best one was the 40% output-coupling with curve radius of 300 mm. The cavity length was kept as short as 80 mm.

Figure 2 shows the threshold power of Tm,Ho:YLF increasing with the increase of crystal temperature. This is caused by more thermal population in laser lower level at higher temperature, so that more pumping power is needed for achieving population inversion. The measured threshold is 0.16 W compared with 0.2 W by theoretical calculation. The smaller re-absorption loss at 77 K, large stimulated emission cross section of 15×10^{-20} cm^2, and long upper level lifetime of about 6 ms contribute to lower threshold power. The value of $1 + f_l/f_u$ (f_l and f_u are Bolezman factors) decreases with decreasing temperature[7], approaching unit at 77 K, which implies that the laser system of Tm,Ho:YLF is similar to four-level one as Nd-doped laser.

The dependence of output power of Tm,Ho:YLF laser on input LD power is shown in Fig. 3. The maximum CW power of 3.6 W at 2.051 μm is achieved under pumping power of 13.6 W, corresponding to optical-optical conversion efficiency of 26%, and the slope efficiency is larger than 30%, compared with 38% by calculation. High quantum conversion efficiency of approaching 2 caused by Tm^{3+} ions cross relaxation and fast energy transferring between Tm^{3+} and Ho^{3+} lead to higher optical-optical conversion efficiency in Tm,Ho:YLF laser. No power saturation occur in this experiment because of the lower pumping power density (3.5 kW/cm^2) and good matching between the pump mode and laser mode. In the experiment of Ref. [6], because single strip LD was used, the pump beam diameter is about 0.2 mm, leading to bad laser mode matching and lower optical-optical conversion efficiency, and the power saturation occurred when the pumping power was higher than 1.3 W corresponding to pumping power density of approaching 5 kW/cm^2. There is no great difference to slope efficiency using 23% and 40% output coupling. To lower the intracavity intensity and reduce the potential for damage to the intracavity optics, the high transmissivity output coupler ($T \approx 40\%$) is used.

The estimated cavity loss is 8% by using different output coupler of 10%, 23%, and 40%. The cavity loss include re-absorption of Tm,Ho:YLF, reflectivity loss of dewar windows and crystal end faces.

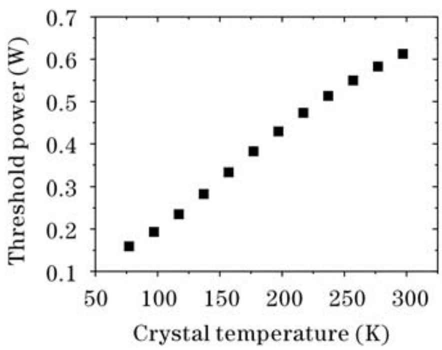

Fig. 2. Threshold power of Tm,Ho:YLF versus crystal temperature.

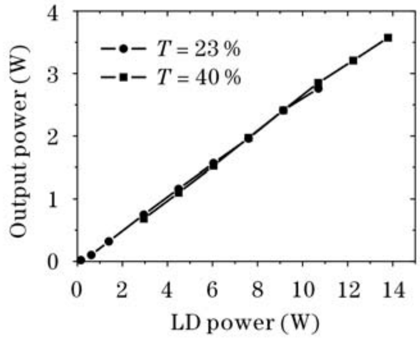

Fig. 3. Output power of Tm,Ho:YLF laser versus LD pumping power.

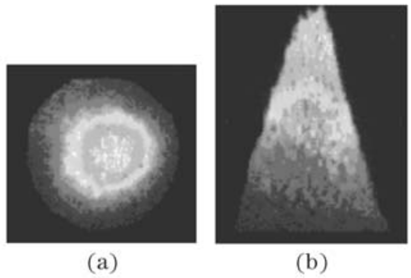

Fig. 4. Spatial profile of Tm,Ho:YLF laser. (a) Two-dimensional (2D) profile, (b) three-dimensional (3D) profile.

The beam profile of Tm,Ho:YLF laser is taken by Pyrocam I infrared camera, as shown in Fig. 4. The output transversal mode is TEM_{00} one with Gaussian distribution according to the image.

Green fluorescence was observed in the Tm,Ho:YLF crystal with the pumping light focused into it, and the brightness became darker at the center of fluorescence when the laser radiation was produced, which was like annular eclipse. The green light comes from the population transition from $^5I_7$ to $^5S_2$, then to ground level.

In this experiment, 3.6-W CW Tm,Ho:YLF laser has been demonstrated at the temperature of 77 K. For higher power and conversion efficiency in the future, it is needed to optimize the co-doped Tm^{3+}, Ho^{3+} concentration, crystal length, resonator parameter, and the collimating-focusing optics of pumping laser. The work is still in progress.

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