Diode-pumped single frequency Tm,Ho:YLF laser at room temperature

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A diode-pumped single frequency Tm,Ho:YLF laser operating at an eye-safe wavelength of 2 μm has been developed. Temperature of the laser crystal was controlled at room temperature with a thermoelectric cooler. The line-width narrowing elements were two solid uncoated fused silica etalons whose thicknesses were 1 and 0.1 mm, respectively. Continuous wave single frequency power of 113 mW was obtained.

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Solid-state lasers operating in 2-μm waveband are the subject of much interest[1−8], as this is an eye-safe waveband that offers the possibility of atmospheric propagation for applications such as range-finding, coherent laser radar, and atmospheric sensing. Coherent detection techniques require a single frequency laser source. Izawa *et al.* carried out the experiments on the lasing performance of Tm,Ho:YLF microchip laser with an external etalon, and achieved an output power of 27 mW in single-mode operation[9]. Shen *et al.* demonstrated acousto-optically induced unidirectional operation of a Ho:YAG ring laser pumped by a Tm-doped silica fibre laser, and obtained 3.7-W single-frequency output at 2114 nm for 8.8-W incident pump power at 1905 nm[10]. The increasing demands for high power lasers operating in eye-safe spectral regions have fostered renewed interest in crystals co-doped with Tm and Ho to be used as active media in laser diodes pumped solid-state lasers. With these crystals, 2-μm lasers can be realized through the transition from the first excited state $^5I_7$ to the ground state $^5I_8$ of Ho^{3+} ions. Sensitization of these ions occurs via energy transfer from Tm^{3+} ions, which can be efficiently optically pumped with commercially available high power laser-diode. A laser diode pumped, all solid state, 2-μm laser is of interest because of its compact size, all-solid-state design, a narrower spectral line width, good beam quality, and high conversion efficiency. Up to present, yttrium aluminum garnet (YAG) and yttrium lithium fluoride (YLF) have been recognized as two of the most interesting crystals for efficient laser operation[11]. For our experiments YLF was selected over YAG because of its predicted lower up-conversion losses. The up-conversion rate for diode-pumped Tm,Ho:YLF is 5×10^{-18} cm^3/s, which is five times smaller than the value of 2.4×10^{-17} cm^3/s for Tm,Ho:YAG reported in Ref. [12].

This letter demonstrates single longitudinal mode operation of a laser diode pumped Tm,Ho:YLF laser at 2.067 μm. A single mode, narrow bandwidth master oscillator is necessary for coherent Doppler applications, which might include civilian wind shear detection or global wind speed measurements from a satellite.

Figure 1 shows a schematic diagram of the experimental setup. A plano-concave resonator was employed to make the system very simple and compact with a cavity length of 45 mm. When the polarization direction of pump beam is paralled to c axial direction of the YLF crystal, the pump band is at 792 nm, the energy extraction occurs at 2067 nm. Since the YLF crystal is a uniaxial crystal, two orientations of electric field polarization are needed to characterize the dipole-allowed transitions of Tm ions. Both the pump and laser cross sections are considerably enhanced in the π polarization, so we should specify the preferred orientation of the laser element in any optical arrange.

The Tm,Ho:YLF crystal 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. 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. This laser beam then is focused onto the Tm,Ho:YLF crystal using a lens with a 50-mm focal length. With this arrangement the pumping beam can be focused to a spot size of approximately 100×100 (μm) at the entrance face of the laser crystal. The total transmission efficiency of the beam-reshaping system is about 91% at 792 nm. The crystal from II-VI corporation has do-pant concentrations of 6%, 0.4% Ho with dimension of $5 \times 5 \times 2.5$ (mm). The polished faces of crystal are parallel. The crystal was coated with high reflectance at 2 μm, and an anti-reflectance at 792 nm at the entrance end. To efficiently remove the heat generated with pump power from the crystal, the crystal was wrapped with indium foils and held in brass heat sink.

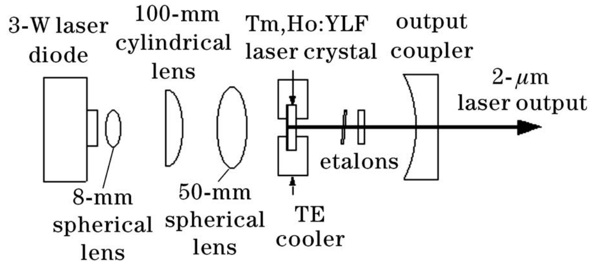

Fig. 1. Schematic of the single Tm,Ho:YLF laser.

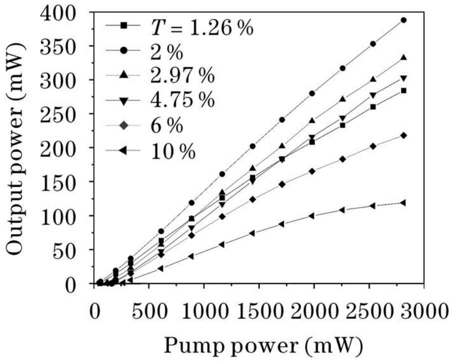

Fig. 2. Output power as a function of the incident pump power with different transmission output couplers.

Temperature of the heat sink was held at a constant 293 K with a thermoelectric cooler. The resonator was then completed with a concave output coupler.

Without the intra-cavity etalons, we performed several experiments with various output coupler transmissions of 1.26%, 2%, 2.97%, 4.74%, 6%, and 10% at 2 μm. The radii of curvature of these output couplers are 51.8 mm. Figure 2 shows the results of the output power as a function of the incident pump power at room temperature. The best performance was achieved with the 2% mirror. The highest output power of 388 mW was obtained under the pump power of 2810 mW with the 2% output coupler, which corresponds to a slope efficiency of 14%. Slope efficiency can reach a maximum at a relatively low value of the transmission of the output coupler and then decrease thereafter. With the traditional four level laser system, the slope efficiency increases asymptotically towards a maximum value as the transmission value of the output coupler increases. However, in Tm Ho laser systems, with the transmission value of the output coupler increasing, higher population densities in the Ho $^5I_7$ manifold are required to achieve threshold. Higher population densities in the Ho $^5I_7$ manifold lead to increased up-conversion and therefore decreased slope efficiency. Thus a decrease in the slope efficiency at higher transmission values of the output couplers implies larger up-conversion rates. The best performance was achieved with the 2% mirror, so that only the results obtained with this mirror are presented in the following. The output spectrum of the free-running laser was measured on a monochromator to be centered at 2.067 μm and to be linearly polarized parallel to the laser crystal c axis. To investigate its longitudinal mode structure, the output of the laser was interrogated using a scanning Fabry-Perot (F-P) interferometer. The free-running laser typically ran on approximation seven longitudinal modes.

To achieve single frequency operation, two solid, uncoated fused silica etalons were used to control and tune the laser wavelength by angle tuning the etalons. The two etalons had thicknesses of 0.1 and 1 mm, respectively. The 0.1-mm etalon was placed in a standard mirror mount allowing a two-axis rotation of the etalon and was mounted at a foxed angle in the cavity. The 1-mm etalon was placed in a second two-axis mount allowing continuous angle tuning by hand. The single frequency operation of the Tm,Ho:YLF laser was measured with a diagnostic air-gap scanning F-P interferometer. The

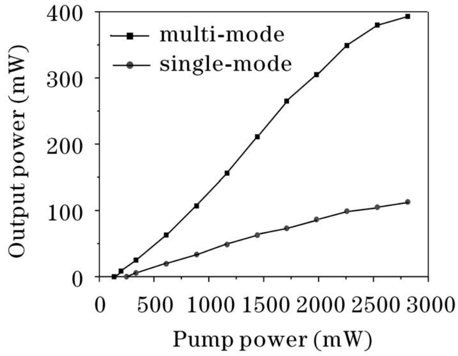

Fig. 3. Output power performance of multi-mode and single-mode at room temperature.

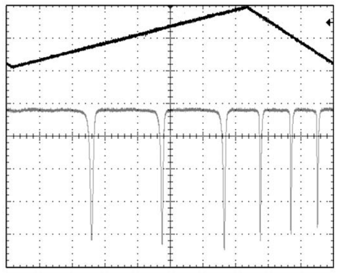

Fig. 4. F-P spectrum of the single frequency Tm,Ho:YLF laser.

collimated continuous output of the Tm,Ho:YLF laser was transmitted through the F-P interferometer, and the transmitted intensity was detected by a 9-V biased PbS detector. The electronic signal from the detector was fed into a digital oscilloscope through a preamplifier. Figure 3 plots the single frequency output power as a function of pump power, and the maximum power is 113 mW. Figure 4 is a typical output signal from the scanning F-P interferometer for a free spectral range of 4 GHz, the upper trace is the F-P ramp voltage and the lower trace is the voltage of the PbS detector measuring the Tm,Ho:YLF laser transmission through the F-P interferometer. As can be seen, the laser operated on a single longitudinal mode. By changing the angle of the 1-mm-thick etalon, it was found that the wavelength of the single longitudinal mode could be tuned over a range of approximation 6 nm.

In conclusion, a diode-pumped single frequency Tm,Ho:YLF laser has been demonstrated, When the crystal temperature is at 293 K, the laser threshold pump power is 250 mW, the maximum continuous wave single frequency output power is 113 mW. The single frequency laser may be used as a seed laser for either a larger oscillator or an amplifier.

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