A Dual-Crystal Cavity Ho,Tm:$GdVO_4$ Laser

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We report a 31.2 W cw diode-pumped cryogenic Ho(0.4at.%),Tm(4at.%):$GdVO_4$ laser in a dual-crystal cavity. The pumping sources are two fiber-coupled laser diodes with a fiber core diameter of 0.4 mm, both of which can supply 42 W near 802 nm. With an incident pump power of 70.3 W at 802.4 nm, a cw output power of 31.2 W at 2.05 μm is attained, corresponding to an optical-to-optical conversion efficiency of 44.4%. The M^2 factor is measured as ∼1.3 under an output power of 20 W.

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A high-power, eye-safe 2-μm laser has many important applications, such as gas sensing, wind measurement, and medical applications.[1−3] Additionally, 2 μm lasers can be applied to a nonlinear optics study such as 3–5 μm[4−6] and 8–12 μm optical parametric oscillators.[7−10] $GdVO_4$ as a host for thulium and holmium, compared with other crystals, has several advantages for diode-pump lasers.[11] The absorption cross section of Tm^{3+} in $GdVO_4$ is much stronger than that of YAG and YLF, and the absorption spectrum is broader (770–820 nm) and shifted closer to the emission wavelength of commercially available AlGaAs laser diodes. Additionally, a $GdVO_4$ crystal has a large thermal conductivity (11.7 W/m·K) which makes it easy to achieve a high-power output. Previously we *et al.* demonstrated the generation of a cw 7.9 W output at 2.05 μm with 26 W pump power in a Ho,Tm:$GdVO_4$ laser.[12] Wang *et al.*[13] reported 10.1 W of output power for the cw operation of a Tm,Ho:$GdVO_4$ laser, and 9.7 W output power for the Q-switched operation at 10 kHz. Li *et al.*[14] reported a Ho,Tm:$GdVO_4$ laser with a cw output power of 12.2 W. An average power of 11.6 W was obtained at the Q-switched mode. The pulse repetition frequency (PRF) was 10 kHz, corresponding to an optical-to-optical conversion efficiency of 38.9% and a slope efficiency of 41.4%. Sato *et al.*[15] reported a Ho,Tm:$GdVO_4$ laser working at room temperature. With a (0.3%)Ho,(3%)Tm:$GdVO_4$ crystal, an output energy of 31.2 mJ was obtained at 2.049 μm. We also obtained a 8.5 W Ho:$YALO_3$ laser at room temperature with M^2∼1.39, the pump laser was a Tm:YLF laser operating at 1.91 μm.[16]

All the Ho,Tm:$GdVO_4$ lasers previously reported operate in single crystal cavities. The maximal pump power that the single Ho,Tm:$GdVO_4$ crystal would endure was limited by its thermal effects. The maximal pump power would increase by one time for the dual-crystal cavity if the thermal effects are at the same level. Thus the maximal output power would be increased obviously and the beam quality would not become worse, which was proved by our work.

In this Letter, we focus on a high-power 2.05 μm laser with two Ho(0.4at.%),Tm(4at.%):$GdVO_4$ crystals in series. To our knowledge, an output power of 31.2 W cw Ho,Tm:$GdVO_4$ laser obtained in our work is obviously higher than the highest power 12.2 W reported before, and an M^2∼1.3 is measured under an output power of 20 W.

Figure 1 shows the experimental setup of our Ho,Tm:$GdVO_4$ laser. Either of the two fiber-coupled (fiber core diameter of 400 μm and fiber numerical aperture of 0.22) diode-lasers emits a maximal power of 42 W near 802 nm. The pump lasers were divided into four beams by two mirrors (M1 and M2) with 50% reflectivity and 50% transmission at 802.4 nm. Mirrors M3, and M4 were high reflected (HR) at 802.4 nm. The collimating lens (L1 and L2) and focusing lens (L3, L4, L5 and L6) make the ratio of image to object 2:1 and re-image the pump light into the Ho,Tm:$GdVO_4$ crystal for an optimum overlap between the pump beam and the laser beam. The dichroic mirrors M5, M6, M7 and M8 were coated at 2.05 μm with a reflectivity of greater than 99.5%, and transmission of greater than 99% at 802.4 nm. The plano-concave output coupler (M9) with a 500 mm radius of curvature was 60% reflection-coated at 2.05 μm and the physical cavity length was 260 mm. The gain medium was a codoped 0.4(at.)% Ho and 4(at.)% Tm:$GdVO_4$ crystal measuring 4 mm wide by 4 mm high by 8 mm long. Both faces were anti-reflection coated for both the laser wavelength ($R < 0.2\%$ at each end) and the pump one ($R < 0.3\%$ at each end). This crystal was wrapped in indium foil and held in a copper heat-sink connected to a small dewar filled with 350 ml liquid N_2. The windows of the dewar were water-free fused silica 2 mm in thickness and 10 mm in diameter, and AR-coated with a transmission of about

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99.5% at 2050 nm and greater than 98% at 802.4 nm.

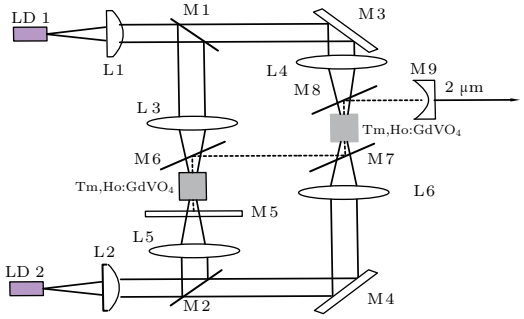


Fig. 1. The experimental setup.

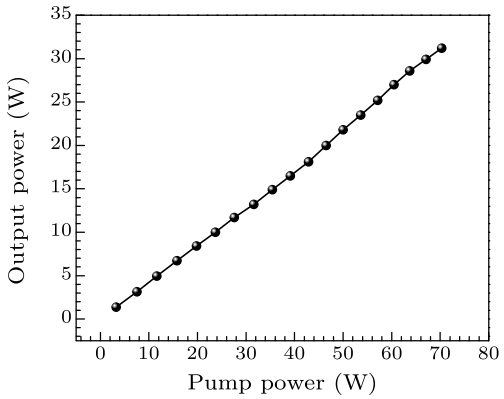


Fig. 2. The output power of the Ho,Tm:GdVO4 laser.

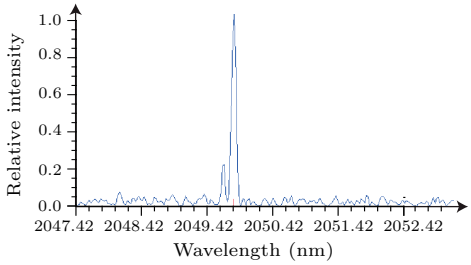


Fig. 3. Emission wavelengths of the Ho,Tm:$GdVO_4$ laser.

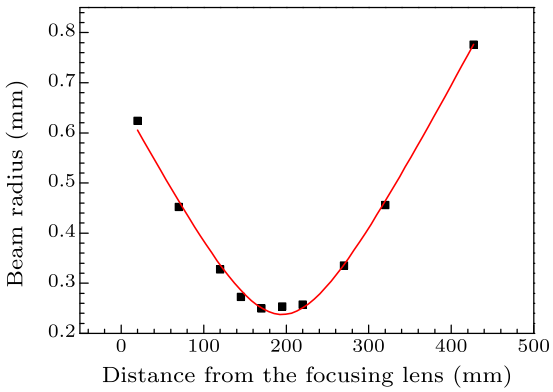


Fig. 4. The beam radius of the Ho,Tm:$GdVO_4$ laser at the 20 W output power level.

The dependence of the output power of the Ho,Tm:$GdVO_4$ laser on the input LD power is shown in Fig. 2. The maximum cw power of 31.2 W (measured by Coherent PM30) at 2.05 μm was achieved at a pump power of 70.3 W, corresponding to an optical-optical conversion efficiency of 44.4%. The variation of the power is less than 1%. The laser wavelength was measured by an EXFOWA-650 spectrum analyzer combined with an EXFO WA-1500 wavemeter (4-GHz spectral resolution), as shown in Fig. 3. Figure 4 shows the beam radius for the Ho,Tm:$GdVO_4$ laser at different distances from the focusing lens at the 20 W output power level, which was measured using the traveling knife-edge method.[17] The M^2 factor of the Ho,Tm:$GdVO_4$ laser was measured to be ∼1.3 at an output power of 20 W.

In this work, the Ho,Tm:$GdVO_4$ laser operated in a dual-crystal cavity. The M^2 factor of the Ho, Tm : $GdVO_4$ laser is near diffraction-limited and the output power of 31.2 W is obviously higher than the highest power of 12.2 W reported previously. Both the output power and beam quality are impressive due to the weak thermal effects by use of the dual-crystal cavity. A similar frame was also used in our Tm:YLF laser. An output power of 48.1 W was obtained at 1.91 μm in the Tm:YLF laser with an M^2 factor of ∼1.2 at an output power of 29 W.

In summary, we have demonstrated a 31.2 W diode-pumped cw cryogenic Ho(0.4at.%), Tm(4at.%) : $GdVO_4$ laser operating at 2.05 μm by using a dual-crystal cavity, the optical-optical conversion efficiency is 44.4%. The M^2 factor of the Ho,Tm:$GdVO_4$ laser was measured to be ∼1.3 at the output power of 20 W. The dual-crystal cavity is proved to be effective in improving the output power and beam quality synchronously.

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