LD pumped 2-μm CW laser from Tm,Ho:GdVO$_4$

Baoquan Yao (姚宝权), Xingbao Zhang (张兴宝), Yuezhu Wang (王月珠),
Wanjun He (贺万俊), Yufeng Li (李玉峰), and Youlun Ju (鞠有伦)

Institute of Opto-Electronics, Harbin Institute of Technology, Harbin 150001

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A set of fiber-coupled continuous wave (CW) diode lasers has been used to pump Tm, Ho:GdVO$_4$ and generate 2.048-μm laser radiation at liquid nitrogen temperature. The optical-optical efficiencies of 25%, output power of 3.5 W, and pumping threshold of 838 mW have been obtained and compared with those from Tm, Ho:YLF under identical experimental conditions.

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It is known that the Ho laser on the $^5I_7 \rightarrow {}^5I_8$ transition in Ho^{3+} ions emitting at 2 μm is an eye-safe laser, which has potential use in various applications such as atmospheric remote sensing including Doppler lidar wind sensing, water vapour profiling by differential absorption lidar, and so on. In recent years, attempts have been made by different research groups to generate highly coherent laser radiation at 2 μm. For this purpose, flashlamp and diode (continuous wave (CW) and quasi-CW) pumping schemes have been utilized to produce the 2-μm laser radiation in Tm,Ho:YAG[1], Tm,Ho:YLF[2], Tm,Ho:GdVO$_4$[3], Tm,Ho:LuLF, and Tm,Ho:LuAG[4] crystals. In our laboratory, we have performed experiments to generate 2-μm laser radiation on the $^5I_7 \rightarrow {}^5I_8$ transition using Tm,Ho:YLF[5,6] and Tm,Ho:GdVO$_4$ pumped by CW diode laser. The operation of 2-μm laser has been demonstrated in Tm,Ho:GdVO$_4$, but with an efficiency of only 3.4%[3]. This low efficiency was assumed to result from damaged coatings. Whereas the 25% optical-optical conversion efficiency and 3.5-W output power were obtained in our laboratory. Compared with the results of Tm,Ho:YLF under identical experimental conditions, the laser efficiency from Tm,Ho:GdVO$_4$ was found to be much higher than that from Tm,Ho:YLF. In this paper, we report our observation on the performance of the 2-μm laser from Tm,Ho:GdVO$_4$ due to the $^5I_7 \rightarrow {}^5I_8$ transition pumped by a set of CW fiber-coupled diode laser.

The experimental configuration is shown in Fig. 1. A CW 15-W fiber-coupled laser diode was used to end-pump the laser crystal. Adjusting diode temperature up to 20 °C, so that the emission wavelength of the diode is tuned to 792 nm in order to pump the Tm^{3+} transition ($^3H_6 \rightarrow {}^3F_4$) in Tm,Ho co-doped crystal. The 1-m-long optical fiber carrying the pump radiation has a core diameter of 400-μm and a numerical aperture of 0.22. The Tm,Ho:GdVO$_4$ and Tm,Ho:YLF crystal (5 mm thick, 5 mm wide, 10 mm long) used in the present study have the Tm and Ho ion concentrations of 0.5 at.-% and 5 at.-%, respectively. The crystal was end-pumped at 792 nm and the laser emission was observed along the end of the laser crystal. The pumped end of the crystal was high-reflection coated at 2 μm (R = 99%) and high-transmission coated at 792 nm (T >96%). The achromatic lens of 50- and 30-mm focal length were used to focus the diode laser beam, resulting in a focused spot of 300 μm on the crystal. Three different output couplers with transmission values of 20%, 30%, and 40% at 2 μm were used in our study. The pump input end of Tm,Ho:GdVO$_4$ crystal served as the plane high reflector. A spherical output coupling mirror with radius of curvature of −300 mm is placed at 150-mm geometrical distance from the flat mirror (pump entrance facet of the crystal). A monochrometer (WDG50) with a 300-line/mm grating blazing at 2 μm was used to scan the spectra in the wavelength range of 660 nm to 2 μm. The laser output power at 2 μm was measured with a calibrated power meter (LPE-1A).

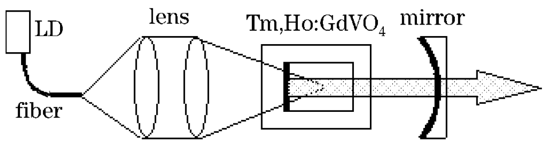

Fig. 1. Schematic diagram of the experimental setup.

At liquid nitrogen temperature, 2.048-μm laser operation was achieved with fiber-coupled diode end-pumped 5% Tm, 0.5% Ho:GdVO$_4$ laser. The output power of 3.5 W has been obtained at pump power of 14 W with optical-optical conversion efficiency of 25% and pump power threshold of 838 mW, which is higher than the threshold of Tm:GdVO$_4$ laser[7], because the up-conversion in double-doped materials is greater than in single-doped thulium materials. The thresholds are 670 and 790 mW, respectively, when pumping at 797 and 806 nm[8]. The dependence of the threshold on pump wavelength is slightly due to the broad absorption spectrum of Tm (770−820 nm, see Fig. 2)[3] in GdVO$_4$.

The output laser power versus pump power is shown in Fig. 3 with different transmission values of output couplers. The highest output power achieved from the Tm, Ho:GdVO$_4$ was 3.5 W under the condition of the transmission of the output coupler was 20%. The output power is linear to the input power. The track does not curve and saturate, and the thermal effect is not apparent in low power region. But green fluorescence was observed in up-conversion process, which derives from the $^5S_2 \rightarrow {}^5I_8$ transition in Ho^{3+} ions emitting at 539−550 nm and the $^5F_4 \rightarrow {}^5I_8$ transition in Tm^{3+} ions emitting at 534−546 nm.

The optical-to-optical efficiency versus input pump power versus is shown in Fig. 4. From the figure, we can see that the efficiency increases rapidly in low power

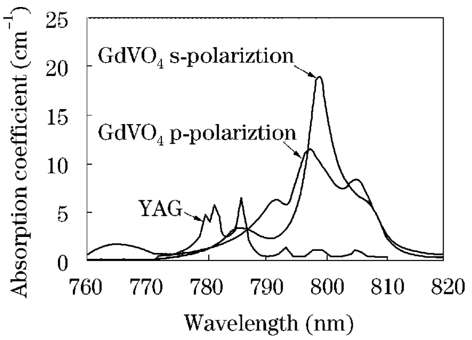

Fig. 2. Absorption spectra of 5.7% Tm, 0.36% Ho:YAG and 5% Tm, 0.5% Ho:GdVO$_4$[3].

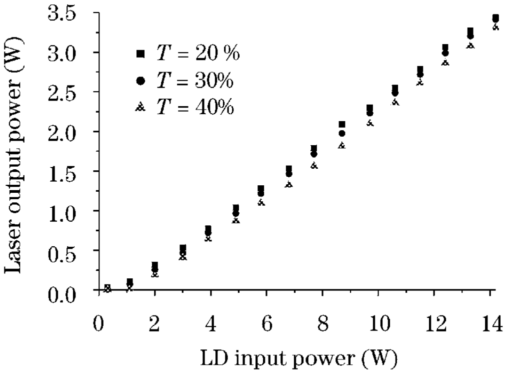

Fig. 3. Output power versus pump power at different transmission values T.

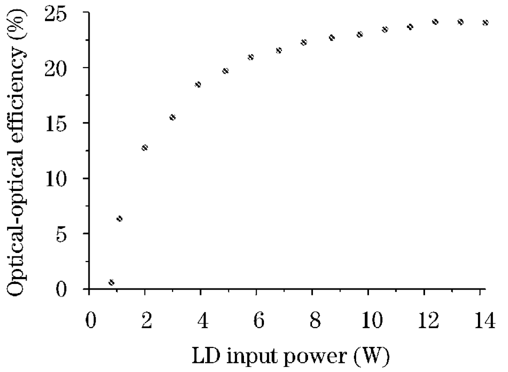

Fig. 4. Conversion efficiency versus pump power.

region. When the power is higher than 5 W the efficiency increases slowly. The maximal output power is 3.5 W and the corresponding optical-to-optical efficiency is 25%, which is much higher than the previously reported data (3.4%)[3]. The output power versus the input pump power at different LD temperatures is shown in Fig. 5. The experimental results indicate that the output power is not affected by LD temperature remarkably, and show the advantage of broad absorption bandwidth of Tm,Ho:GdVO$_4$ crystal.

Under the same experimental conditions, the optical-to-optical efficiency and threshold pump power were observed for Tm,Ho:GdVO$_4$ and Tm,Ho:YLF. The results are listed in Table 1. It can be seen clearly from this table that the threshold pump power of Tm,Ho:GdVO$_4$ is higher than that of Tm,Ho:YLF, but the efficiencies (η) and output powers P_{max} are very similar.

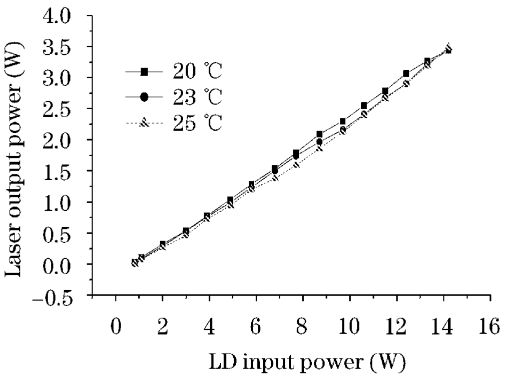

Fig. 5. Output power versus pump power at crystal temperatures of 20, 23, and 25 °C.

Table 1. Comparison between 2-μm Ho,Tm:GdVO$_4$ and Ho,Tm:YLF Lasers

	η (%)	P_{max} (W)	Threshold (mW)
Ho,Tm:GdVO$_4$	25	3.5	838
Ho,Tm:YLF	28	4	325

In conclusion, the Tm,Ho:GdVO$_4$ crystal is a promising candidate for LD-pump, compact, all solid state, 2-μm laser material. The high thermal conductivity of GdVO$_4$ (10 W·m^{-1}·K^{-1} at 300 K) is very favourable for efficient cooling of the crystal, and the absorption cross section of thulium in GdVO$_4$ is considerably stronger and broader than in YAG and YLF. The broad emission spectrum (1.9–2.1 μm) allows for tuning the laser wavelength and generating short pulses. We have studied the low temperature laser performance of Tm,Ho:GdVO$_4$ pumped with a set of fiber-coupled CW diode lasers and monitored the 2.048-μm laser emission. The results from Tm,Ho:GdVO$_4$ have been compared with those from Tm,Ho:YLF at similar experimental conditions. The threshold of Tm,Ho:GdVO$_4$ laser is higher than Tm,Ho:YLF laser, and the optical-to-optical efficiencies are similar.

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References

1. T. Y. Fan, G. Huber, and R. L. Byer, IEEE J. Quantum Electron. **24,** 924 (1988).
2. B. T. Mcguckin, T. Robert, and Menzies, IEEE J. Quantum Electron. **28,** 1025 (1992).
3. P. J. Morris, W. Luthy, and H. P. Weber, Opt. Commun. **111,** 493 (1994).
4. V. Sudesh and K. Asai, J. Opt. Soc. Am. B **20,** 1829 (2003).
5. Y. Z. Wang and X. L. Zhang, Chin. Opt. Lett. **1,** 281 (2003).
6. B. Q. Yao and L. Q. Dong, Acta Opt. Sin. (in Chinese) **24,** 79 (2004).
7. C. P. Wyss and W. Luthy, Opt. Commun. **153,** 63 (1998).
8. C. P. Wyss, W. Luthy, H. P. Weber, Appl. Phys. B **67,** 545 (1998).