Optik 126 (2015) 855–857

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

# High power Tm:YLF laser operating at 1.94 μm

Y. Ding[a], D.X. Zhang[a], W. Wang[b], B.Q. Yao[a], X.M. Duan[a,*], Y.L. Ju[a], Y.Z. Wang[a]

[a] *Key Laboratory of Tunable Laser Technology, Harbin Institute of Technology, Harbin, China*
[b] *Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun, China*

ARTICLE INFO

*Article history:*
Received 28 January 2014
Accepted 9 February 2015

*Keywords:*
VBG
Tm:YLF
Solid-state laser

ABSTRACT

We report a diode-pumped 1.94 μm Tm:YLF laser, the maximum output power of which was 50.3 W at the incident pump power of 156.9 W, corresponding to the optical-to-optical efficiency of 32.1% and slope efficiency of 41.6%. The wavelength was selected and restricted at 1940.2 nm by a volume Bragg grating (VBG) and an etalon inserted in the cavity. The laser beam quality factors $M^2$ were measured to be 1.05, 1.75 and 2.40 at the output power of 4.6 W, 26.2 W and 50.3 W respectively.

## 1. Introduction

Solid-state lasers operation around 2 μm have been developed rapidly in recent years, owing to their promising applications in the fields of LIDAR, remote sensing [1] and generation of mid-infrared lasers via optical parameter oscillators (OPOs). The commonly used rare-earth ions to generate 2 μm lasers are $Tm^{3+}$ and $Ho^{3+}$. Especially, $Ho^{3+}$-doped lasers can be resonantly pumped by $Tm^{3+}$ doped lasers operating at 1.9 μm. These configurations have the advantages of high efficiency and lower heating at room temperature, due to the inherent quantum defect between the pump and output laser photons [2,3]. Therefore, high power Tm lasers around 1.9 μm have been widely investigated [4–7]. Especially, 1.94 μm emission has a good overlap with absorption lines of Ho:YLF and Ho:LLF [8], and hence they are promising pump source of these lasers.

The mainly used bulk crystals for 1.94 μm radiation are Tm:YAP and Tm:YLF [9–12]. Tm:YAP has good thermal property (thermal conductivity of 0.11 W/(cm K)) and mechanical property (similar to YAG). Up to 50 W output has been obtained from *a*-cut composite Tm:YAP crystal [9]. However, Tm:YAP crystal, the thermal lens focal length of which is usually <100 mm [13], has thermal effects. So Tm:YAP lasers usually need better heat removing device and at the room temperature operation is not as impressive as that of the low temperature. On the other hand, the thermal focal lens effects bring much difficulty to the laser cavity design.

Tm:YLF is another attractive crystal for high power laser generation. Considering the thermal effects, it remains a promising crystal for high power 1.94 μm radiation, because the thermal focal length is usually tens or hundreds of centimeters [14]. Nevertheless, wavelength selecting elements are required to obtain 1.94 μm laser because the emission peak of Tm:YLF is 1.908 μm [2]. Up to present, as much as 28 W 1.94 μm output has been obtained in Tm:YLF slabs by Dergachev and Moulton [11] employing a Lyot filter as wavelength selecting element. In 2004, up to 30 W output of a 1.94 μm Tm:YLF laser was achieved with a volume Bragg holographic grating (VBG) in photo-thermo-refractive glass as an output coupler [12]. We have also reported a 17.3 W output of Tm:YLF laser using diode-end-pumped configuration [15].

Nevertheless, Tm:YLF is really a fragile crystal with a low thermal stress fracture limit (pump intensities over 5 kW $cm^{-2}$) [16], which limits the maximum incident pump power. In this work, we improved the fracture limit by enlarging the pump beam radius on the crystal. A total pump power of 156.9 W was focused into two rod crystals (about 39 W per end) and no fracture phenomenon was observed. This value is even comparable with that of the slab ones [11,12]. 50.3 W continuous-wave (CW) output at 1940.2 nm was obtained. To our knowledge, this is the highest power of CW 1.94 μm laser at room temperature.

## 2. Experimental setup

The experimental setup of the dual crystal 1.94 μm Tm:YLF laser is shown in Fig. 1. The whole cavity was consisted of three 45° dichroic mirrors, a VBG as high reflector and the output coupler with the transmission of 40% and the curve radius of 200 mm. The diffraction efficiency of the VBG was more than 99% reflection at 1940.2 nm (at 22 °C in air) with a FWHM of less than 1 nm. A 0.5 mm-thickness YAG etalon was inserted into the cavity to restrict the laser wavelength at 1940.2 nm in order to avoid spiking in the

---

* Corresponding author. Tel.: +86 0451 86412720; fax: +86 0451 86412720.
*E-mail address:* xmduan@hit.edu.cn (X.M. Duan).

http://dx.doi.org/10.1016/j.ijleo.2015.02.032
0030-4026/

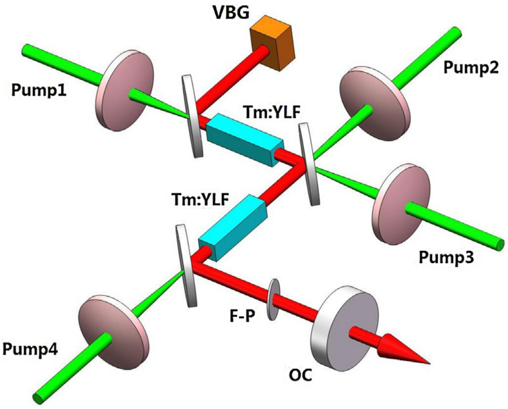

**Fig. 1.** Experimental setup of Tm:YLF laser.

Tm:YLF laser output caused by the water vapor absorption near 1.94 μm.

Compared with Tm:YAP, the main limit of high power operation of Tm:YLF laser is the thermal stress fracture of the crystal, which restricts the maximum incident pump power at the end face of the crystal. This shortcoming is more severe for 1.94 μm operation, because the conversion efficiency is lower than that of 1.91 μm and more heat will be deposit in the crystal at the same pump power. To avoid this problem, slab crystals, instead of rod crystals, were employed in most of the former works [11,12]. For rod crystals, a power-scaling method is lowering the doping concentration of $Tm^{3+}$, which leads to less heat deposited per unit length due to the weaker pump absorption and reduced energy-transfer up-conversion [17]. Meanwhile, the length of the crystal should be increased to maintain the total gain of the media at the same level. So a longer crystal with lower concentration will endure higher pump power and have similar slope efficiency, although the laser threshold will increase a little. In this work, we employed two 3 at.% $Tm^{3+}$ doped YLF rod crystals. Both of the a-cut Tm:YLF crystals had a size of 3 mm × 3 mm × 16 mm. The crystals were wrapped with Indium foil and clamped in a cooper heat sink which was cooled at 17 °C by a thermoelectric controller (TEC).

A dual-end-pump configuration was utilized here. The pump sources were four fiber-coupled (core diameter of 400 μm and numerical aperture of 0.22) 40 W laser diodes centered at 792.3 nm. Each pump light was collimated and then focused into the crystals, forming a waist radius of 500 μm. In fact, a simple way to increase the fracture limit was enlarging the pump waist in the crystal properly. So we set the pump waist as 500 μm (greater than 400 μm in [15]) in order to further increase the maximum incident pump power.

The physical cavity length of the Tm:YLF laser resonator was approximately 140 mm. From ABCD matrix theory, it can be calculated that the average laser beam radius at the two crystals were about 250 μm and 300 μm respectively, which indicated that the ratios of the pump beam to oscillating laser beam were about 2:1 and 1.67:1 respectively. However, the negative thermal lens effect of Tm:YLF made the oscillating laser beam radius increase at high pump powers, and hence the match between pump beam and laser beam will get better. At the pump power of 150 W, the ratio was calculated to be about 1.35:1 and 1.2:1.

## 3. Results and analysis

Fig. 2 depicts the output power with respect to the incident pump power. The power meter used in the experiment was a Coherent PM150. Output power of 50.3 W was obtained under an incident pump power of 156.9 W, corresponding to a slope efficiency of 41.6% and an optical-to-optical conversion efficiency of 32.1%. The output power was not further increased by the limits of the available pump power. The slope efficiency did not decrease at high pump power and no signs of fracture were observed. The conversion efficiency was at the same level as the former works on Tm:YLF laser [15], while the maximum pump power (about 39 W per end) increased significantly.

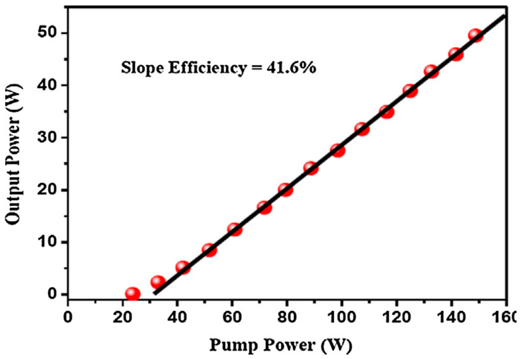

**Fig. 2.** The output power of Tm:YLF laser.

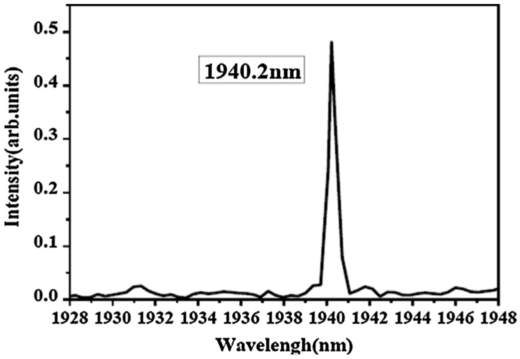

**Fig. 3.** The laser spectra of 1.94 μm Tm:YLF laser.

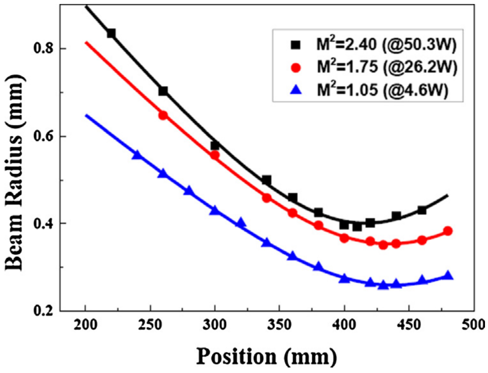

**Fig. 4.** The beam quality factor $M^2$ measurement of Tm:YLF laser.

The laser wavelength was measured by an EXFO WA-650 spectrum analyzer combined with an EXFO WA-1500 wave-meter (4-GHz spectral resolution). The result in Fig. 3 shows a wavelength peak at 1940.2 nm and the FWHM line width is less than 0.2 nm.

The beam quality of the output laser was also measured in traveling knife-edge method. The $M^2$ factors at the output power of 4.6 W, 26.2 W and 50.3 W were calculated to be 1.05, 1.75 and 2.40 respectively (shown in Fig. 4). The beam radius increased with respect to the output power, meanwhile, the location of the beam waist was shifted, which both indicated that the negative thermal lens effect had obvious impacts.

## 4. Conclusions

We demonstrated a diode-end-pumped dual crystal Tm:YLF laser working at 1.94 μm. The maximum output power was 50.3 W at the pump power of 156.9 W. To our knowledge, this is the highest power of CW 1.94 μm laser at room temperature currently. The wavelength was restricted at 1940.2 nm by a VBG and an etalon. The beam quality factor $M^2$ was measured to be 1.05, 1.75 and 2.40 at the output level of 4.6 W, 26.2 W and 50.3 W respectively.

## Acknowledgements

This work is supported by the National Natural Science Foundation of China (No. 61308009), the Fundamental Research funds for the Central University (Grant No. HIT.NSRIF.2014044), and the Science Fund for Outstanding Youths of Heilongjiang Province (JQ201310).

## References

[1] J.L. Yang, Y.L. Tang, J.Q. Xu, Development and applications of gain-switched fiber lasers, Photonics Res. 1 (1) (2013) 52–57.
[2] P.A. Budni, M.L. Lemons, J.R. Mosto, E.P. Chicklis, High power/high-brightness diode-pumped 1.9 μm thulium and resonantly pumped 2.1 μm holmium lasers, IEEE J. Sel. Top. Quantum Electron. 6 (2000) 629–634.
[3] B.Q. Yao, X.M. Duan, L. Ke, Y.L. Ju, Y.Z. Wang, G.J. Zhao, Q-switched operation of an in-band-pumped Ho:LuAG laser with kilohertz pulse repetition frequency, Appl. Phys. B 98 (2010) 311–315.
[4] P.F. Moulton, G.A. Rines, E.V. Slobodtchikov, K.F. Wall, G. Frith, B. Samson, A.L.G. Carter, Tm-doped fiber lasers: fundamentals and power scaling, IEEE J. Sel. Top. Quantum Electron. 15 (2009) 85–92.
[5] M. Schellhorn, High-power diode-pumped Tm:YLF laser, Appl. Phys. B 91 (2008) 71–74.
[6] E.C. Honea, R.J. Beach, S.B. Sutton, J.A. Speth, S.C. Mitchell, J.A. Skidmore, M.A. Emanuel, S.A. Payne, 115 W Tm:YAG diode-pumped solid-state laser, IEEE J. Quantum Electron. 33 (1997) 1592–1600.
[7] M. Schellhorn, S. Ngcobo, C. Bollig, High-power diode-pumped Tm:YLF slab laser, Appl. Phys. B 94 (2009) 195–198.
[8] B.M. Walsh, N.P. Barnes, B.D. Bartolo, Branching ratios, cross sections, and radiative lifetimes of rare earth ions in solids: application to $Tm^{3+}$ and $Ho^{3+}$ ions in $LiYF_4$, J. Appl. Phys. 83 (1998) 2772–2787.
[9] A.C. Sullivan, G.J. Wagner, D. Gwin, R.C. Stoneman, A.I.R. Malm, High power Q-switched $Tm:YAlO_3$ lasers, in: Advanced Solid-State Photonics, OSA Technical Digest, Paper WA7, Optical Society of America, 2004.
[10] R.C. Stoneman, L. Esterowitz, Efficient 1.94 μm Tm:YALO laser, IEEE J. Sel. Top. Quantum Electron. 1 (1995) 78–81.
[11] A. Dergachev, P.F. Moulton, High-power, high-energy diode-pumped Tm:YLF-Ho:YLF-ZGP laser system, in: J. Zayhowski (Ed.), Advanced Solid-State Photonics. OSA Trends in Optics and Photonics, Paper 137, vol. 83, Optical Society of America, 2003.
[12] A. Dergachev, P.F. Moulton, V. Smirnov, L. Glebov, High power CW Tm:YLF laser with a holographic output coupler, in: Conference on Lasers and Electro-Optics/International Quantum Electronics Conference and Photonic Applications Systems Technologies, Technical Digest (CD), Paper CThZ3, Optical Society of America, 2004.
[13] B. Yao, Y. Tian, W. Wang, G. Li, Y. Wang, Analysis and compensation of thermal lens effects in Tm:YAP lasers, Chin. Opt. Lett. 8 (2010) 996–999.
[14] O.N. Eremekin, N.A. Egorov, N.G. Zakharov, A.P. Savikin, V.V. Sharkov, Investigating a thermal lens in a Tm:YLF crystal under intense diode pumping, J. Opt. Technol. 76 (2009) 676–679.
[15] B.Q. Yao, P.-B. Meng, G. Li, Y.-L. Ju, Y.-Z. Wang, Comparison of Tm:YLF and Tm:YAP in thermal analysis and laser performance, J. Opt. Soc. Am. B 28 (2011) 1866–1873.
[16] J.I. Mackenzie, S. So, D.P. Shepherd, W.A. Clarkson, Comparison of laser performance for diode-pumped Tm:YLF of various doping concentrations, in: Advanced Solid-State Photonics, OSA Trends in Optics and Photonics, Paper 202, Optical Society of America, 2005.
[17] S. So, J.I. Mackenzie, D.P. Shepherd, W.A. Clarkson, J.G. Betterton, E.K. Gorton, A power-scaling strategy for longitudinally diode-pumped Tm:YLF lasers, Appl. Phys. B 84 (2006) 389–393.