Optics Communications 472 (2020) 125748

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

$Tm:YVO_4$ laser intra-cavity pumped 2.1 μm Ho laser

Huawen Hu, Haizhou Huang, Jianhong Huang, Yan Ge, Lixia Wu, Wen Weng, Jinhui Li, Wenxiong Lin *

Key Laboratory of Optoelectronic Materials Chemistry and Physics, Fujian Institute of Research on the Structure of Matter, Chinese Academy of Science, Fuzhou 350002, China
University of Chinese Academy of Sciences, Beijing 100049, China

ARTICLE INFO

Keywords:
Ho laser
$Tm:YVO_4$
Intra-cavity pumped
2.1 μm laser

ABSTRACT

We firstly explored lasing properties of a 2.1 μm Ho laser intra-cavity pumped by a diode-pumped $Tm:YVO_4$ laser, which has a large absorption cross-section and broad absorption profile at 800 nm. Maximum output power of 1.42 W at 1908 nm was obtained before Ho laser with a 2 mm long $Tm:YVO_4$ crystal under absorbed common 808 nm LD power of 9.96 W. High reflection coating the output couplers at Tm laser, Ho laser oscillation with maximum output power of 954 mW at 2122 nm was achieved with corresponding beam quality factor M^2 of 1.43, which indicates a near-diffraction-limited beam propagation.

1. Introduction

Intra-cavity pumped Ho lasers (ICHL) facilitate the direct use of common 800 nm AlGaAs diode lasers (LD) for efficient 2.1 μm lasers in a compact structure, which have a variety of potential applications including medical treatment [1], countermeasures [2], macromolecule material processing [3], and nonlinear frequency conversions toward the molecular fingerprint region of 3∼14 μm [4].

Since the first demonstration by Stoneman et al. [5], ICHL had been considered as an accessible mechanism for room-temperature Ho lasers with a high conversion efficiency from absorbed diode laser to Ho laser [6]. Compared with the popular Tm laser in-band pumped Ho lasers [7–9], separated cavities for Tm laser and Ho laser were merged together, where the Tm laser was generated and confined inside the same cavity for in-band pumping the Ho laser. Unlike the traditional Tm, Ho co-doped lasers [10,11], cooling the gain media at a temperature of liquid nitrogen is un-necessary for ICHL, because the up-conversion losses of the intra-cavity Tm-doped and Ho-doped gain media are less significant than that of the Tm, Ho co-doped crystals [12].

Due to the high mechanical and thermal properties in YAG crystal [13], ICHL was firstly demonstrated in 1992 from the combination of Tm:YAG and Ho:YAG crystals with an output power of approximately 140 mW at 2.09 μm [5]. Keep the combination of Tm:YAG and Ho:YAG crystals, in 2000, Hayward et al. further increased the output power to 7.2 W with beam quality factor (M^2) of about 6 due to the significant thermal lens in YAG crystals [14]. In 2003, YLF crystal with a negative thermal lens was firstly severed as Tm-doped host of the ICHL for alleviating the thermal effects, where maximum output power of 1.6 W at 2.09 μm was obtained [15]. Although the power of the Tm:YLF ICHL was increased to 8 W with M^2 of 2.2 in 2012, conversion efficiency from LD power to Ho laser was poor, where over 135 W incident LD power was needed [16]. In 2016, a compromise between the lasing efficiency and beam quality was made in our previous works, where maximum output power of 8.03 W at 2122 nm with M^2∼2.7 was obtained in the Tm:YAG ICHL using a composite Tm:YAG crystal and the wavelength-locked LD for reduced the waste heat [17].

Meanwhile, other combinations between the Tm-doped and Ho-doped gain media, such as Tm:YAG vs Ho:LuAG [18], Tm:KluW vs Ho:KLuW [19], and Tm:YAG vs Ho:SSO [20] were explored for seeking efficient LD pumped ICHLs at room temperature with a compact structure. Besides the above host media, Tm ions in vanadate crystals has smother and broader absorption band at 800 nm than in the mature YAG crystal where the peak absorption cross-section (2.5×10^{-20} cm^2 at 797.5 nm) is 4 times larger than that of Tm:YAG (6×10^{-21} cm^2 at 785 nm) [21,22]. Such absorption properties facilitate the choice of existed AlGaAs LDs and the micromation in Tm-doped gain medium for a compact ICHL. Moreover, the reduction in length of the Tm-doped gain medium benefits the alleviation in the thermal lens of the ICHL under high power pumping, especially for the vanadate hosts, which have slightly lower thermal conductivity than YAG [23].

In this letter, efficient Ho laser with maximum output power of 954 mW at 2122 nm was obtained via intra-cavity pumped by a $Tm:YVO_4$ laser. Due to the high absorption cross-section of $Tm:YVO_4$ crystal at 800 nm, above 70% incident 808 nm LD power was absorbed by the

* Corresponding author at: Key Laboratory of Optoelectronic Materials Chemistry and Physics, Fujian Institute of Research on the Structure of Matter, Chinese Academy of Science, Fuzhou 350002, China
E-mail address: wxlin@fjirsm.ac.cn (W. Lin).

https://doi.org/10.1016/j.optcom.2020.125748
Received 11 February 2020; Received in revised form 12 March 2020; Accepted 12 March 2020
Available online 16 March 2020
0030-4018/

2 mm long Tm-doped gain medium, corresponding to a conversion efficiency of 8.5% from absorbed LD power to Ho laser. It is the first presentation of a Tm-doped vanadate laser applied for the ICHL, to the best of our knowledge.

2. Experimental design and setup

Fig. 1 depicts the polarized emission spectra and absorption spectrum of a 3 at. % Tm:YVO_4 and a 0.8 at. % Ho:YAG crystals, respectively. The a-cut Tm:YVO_4 and Ho:YAG samples were cut with identical shape of 4 mm × 4 mm × 1 mm for the measurement of absorption spectrum by a UV–VIS-NIR spectrophotometer (Lambda950, Perkin Elmer INC.) with a scanning interval of 0.1 nm. Polarized emission spectra of the Tm:YVO_4 crystal were then calculated from the measured polarized absorption spectra according to the McCumber equation [24], where divergency in the spectral area away from the emission peaks was denoted [6]. As shown in Fig. 1, the main emission peaks of the Tm:YVO_4 crystal in π-polarization and σ-polarization are at approximately 1804 nm, which are away from the resonant absorption band of Ho:YAG crystal. However, the reported lasing wavelengths for Tm:YVO_4 laser with output coupling below 1% were 1.92 μm [25] and 1.94 μm [26] respectively, which were both within the absorption band of Ho:YAG with corresponding absorption cross-sections of 0.43 $\times 10^{-20}$ cm^2 and 0.28 $\times 10^{-20}$ cm^2. Hence, it is of interest for the following experiments to evaluate the true laser properties.

The schematic of the ICHL is shown in Fig. 2. The pump source was a fiber-coupled 808 nm LD with a core diameter of 400 μm and a numerical aperture of 0.22. F1 and F2 were two identical plano-convex lenses with a focal length of 35 mm, which collimated and focused the LD pump light with a waist of approximately 200 μm inside the Tm:YVO_4 crystal. The a-cut Tm:YVO_4 crystal had dimensions of 3 mm × 3 mm × 2 mm and a doped concentration of 3 at.%, which was anti-reflection (AR) coated at 808 nm and 1.9∼2.2 μm at both end surfaces. A 6 mm long Ho:YAG crystal rod with a diameter of 4 mm and doping concentration of 0.8 at.% was inserted after the Tm:YVO_4 crystal, which was AR-coated at 1.9∼2.2 μm at each end surface. Both crystals were wrapped with the indium foil before being mounted on a copper heat-sink that was cooled by the water of 16 °C. The accuracy of the water cooler is 0.1 °C.

The resonator was a concave-plano cavity with a physical length of 32 mm. M1 was the concave input mirror with a 100 mm radius of curvature, which was high reflection-coated (HR) at 1.8∼2.2 μm and AR at the pump wavelength. M2 denoted the flat output couplers (OCs), which were classified as the common OCs and the narrow-band coated OCs. The common OCs were coated with transmittances of 3% and 5% at 1.9∼2.2 μm respectively. The narrow-band coated OCs HR-coated at Tm laser (1.9∼2.02 μm) had transmittances of 2%, 10%, and 20% respectively at Ho laser (2.09∼2.1 μm). The laser power was measured by a power meter (OPHIR, 30 (150) A-LP1-18), and the lasing wavelength was recorded by a mid-infrared spectrometer (771A-IR, Bristol Instruments, Inc. USA.) with a spectral resolution of 4 GHz. Beam profile of Ho laser was analyzed by a beam quality analyzer (Nanomodescan, Ophir Optronics Ltd.).

3. Experimental results and discussion

Before the ICHL, lasing property of the Tm:YVO_4 laser was analyzed as shown in Fig. 3. Maximum output powers of 1.42 W and 1.28 W were obtained at maximum absorbed LD power of 9.96 W and 10.6 W with the 3% and 5% common OCs respectively, corresponding to slope efficiencies of 27.06% and 26.26%. Evolutions in peak lasing wavelengths of the Tm laser during the power scaling processes are depicted in Fig. 3(b). Unlike the stabilized wavelength at 1917.9 nm ± 0.3 nm. With the 3% output coupler, the lasing wavelength shifted from 1915.3 nm ± 0.2 nm to 1909.5 nm ± 0.2 nm at output power around 862 mW. Using a polarizer at 1.9 μm, the switching from π-polarization

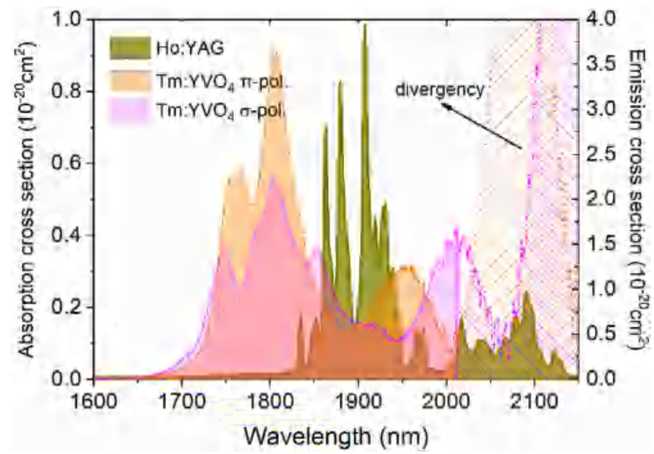

Fig. 1. The polarized emission spectra and absorption spectrum of a 3 at.% Tm:YVO_4 and a 0.8 at.% Ho:YAG crystals.

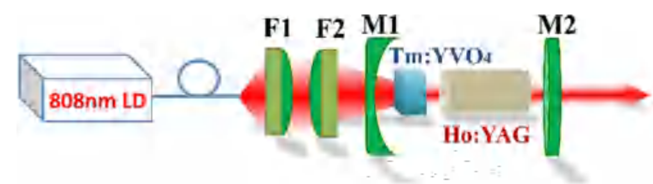

Fig. 2. Experimental setup of the ICHL.

to σ-polarization following with the obvious shift in lasing wavelength was indicated, which was attributed to the gain competition between different polarization states with the 3% output coupler. However, this phenomenon would not seriously influence the efficiency of ICHL, as both lasing wavelengths of 1909 nm and 1915 nm are within the main absorption band of the isotropous Ho:YAG gain medium (Fig. 1).

Fig. 4(a) shows the power curves of the ICHL. In the ICHL experiment, three different narrow-band coated OCs were applied to optimize lasing efficiency of the Ho laser. With the optimal output coupling of 10%, the maximum output power of 954 mW at 2122.1 nm was obtained corresponding to the highest slope efficiency of 17.3%. Effectiveness of the Tm:YVO_4 laser pumped ICHL was verified as the maximum Ho laser power was 67% of the maximum Tm laser power of 1.42 W. Slightly decrement in Ho laser efficiency was obtained with the 20% OC, where maximum output power of 706 mW at 2090.8 nm was achieved corresponding to a slope efficiency of 14.6% owing to the good confinement in Tm laser with the narrow-band coated output coupler. Poor lasing efficiency with the 2% output coupler was 5.8%, which attributed to the fact that transmittance of the output coupler was away from the optimal value for Ho:YAG and its isostructural gain medium [27–29]. As is shown in Fig. 4(b), beam quality at each maximum output powers with the 2%, 10%, and 20% OCs were measured to be with M^2 of 1.10, 1.43, and 1.25 respectively, which indicate a near-diffraction-limited beam propagation. For intra-cavity pumped Ho lasers, the beam quality is mainly influenced by the thermal lens of the gain media, especially the Tm:YVO_4 crystal with a significant higher quantum defect and higher absorption coefficient to the pump light. However, the thermal lens effect was associated with the incident LD pump power. As the incident LD pump power of 10% OC is higher than other OCs at each maximum output power, a thermal diopter on the Tm:YVO_4 decreased, which resulted in the increase of thermal lens effect and the slightly poor beam quality. Alleviating the thermal lens effect by bonding the Tm:YVO_4 crystal with another un-doped YVO_4 crystal, which could further improve the beam quality and output power.

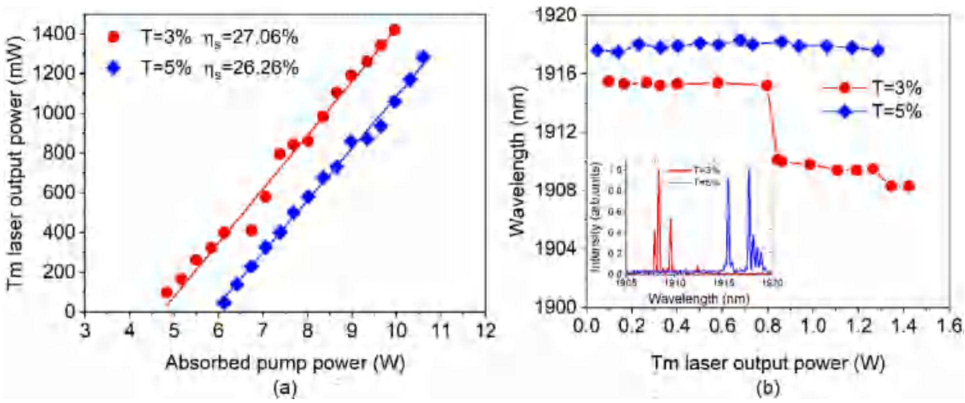

Fig. 3. (a) Output power of the Tm laser versus absorbed pump power and the corresponding slope efficiencies (η_s) with different common OCs; (b) Wavelengths of the Tm laser versus the output powers with different common OCs (Insert: lasing spectrum of the $Tm:YVO_4$ laser at maximum output powers with the 3% and 5% OCs, respectively).

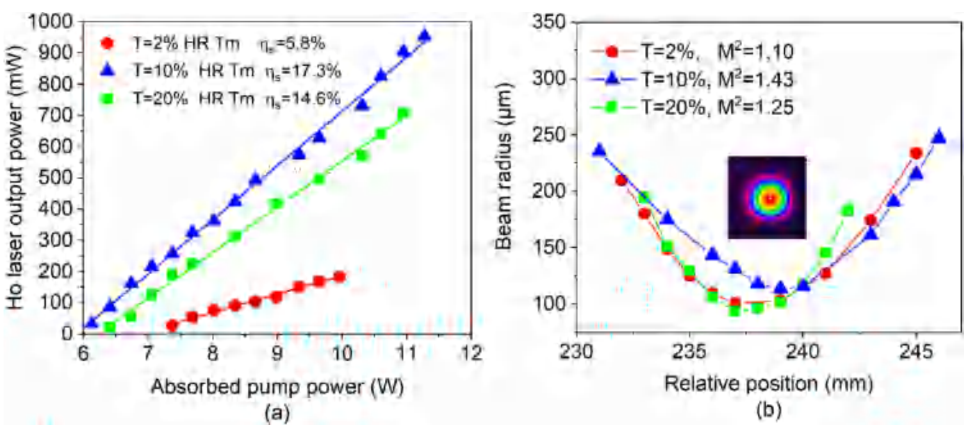

Fig. 4. (a) Output power of the Ho laser versus absorbed pump power of the $Tm:YVO_4$ laser and the corresponding slope efficiencies (η_s) at different narrow-band coated OCs, where stability at the maximum power of 954 mW was 0.5% within 30 min; (b) Beam quality of the intra-cavity pumped Ho:YAG laser at the maximum output power with different narrow-band coated OCs (Insert: 2D beam Profiles of T = 10%.).

Fig. 5 shows the evolutions in the laser spectrum with different narrow-band coated OCs, where each ten measured lasing spectra were averaged in every data point for presenting the real-time undated spectrum on the software interface. Peak lasing wavelengths during power scaling processes of ICHL were stabilized at 2122.2 nm ± 0.2 nm, 2122.2 nm ± 0.1 nm, and 2090.7 nm ± 0.1 nm with the 2%, 10%, and 20% OCs, respectively. Due to the higher cavity loss, shorter wavelength at approximately 2090 nm was obtained with the 20% output coupler (Fig. 5(c)). As shown in Fig. 5(b), slight leakage in Tm laser at the threshold of the ICHL was observed, where the Tm laser wavelength was at around 1955 nm. We attributed this to the higher gain for both Tm laser and Ho laser with the 10% output coupler compared with other output couplings.

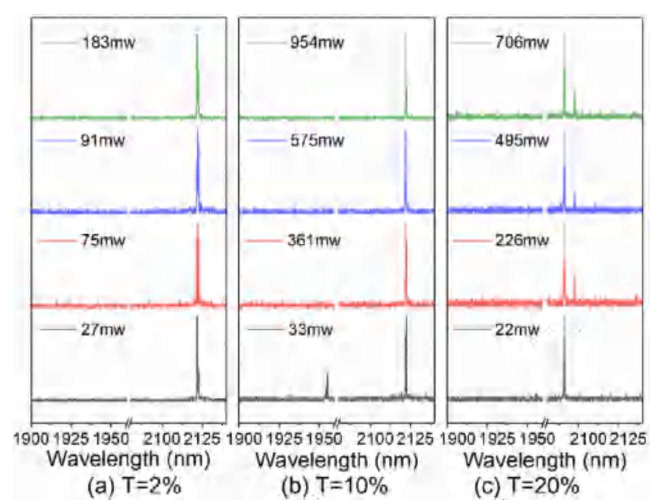

Fig. 5. Dependences of wavelength on output power and different narrow-band coated OCs for the Ho laser.

4. Conclusion

In conclusion, ICHL at 2.1 μm has been demonstrated via intra-cavity pumped by a common 808 nm LD pumped $Tm:YVO_4$ laser. Due to the high absorption and emission cross-sections of Tm ion in vanadate gain medium, maximum output power of 1.42 W at 1908 nm could be obtained with a 2 mm long disk-shape $Tm:YVO_4$ gain medium before exploring the ICHL. High reflection coating the output coupler at the lasing band of the $Tm:YVO_4$ laser, ICHL with maximum output power of 954 mW at 2122 nm was obtained, which was 67% of the maximum Tm laser power. It is the first presentation of a Tm-doped vanadate laser applied for achieving the ICHL, which benefits the direct use of the existed AlGaAs LDs for a compact, accessible Ho laser due to the broad absorption band and high absorption cross-section of such type of gain media. Further improvement in the performance of Ho laser is expected via optimizing the dopant concentration of Tm and Ho ions and direct producing a more efficient $Tm:YVO_4$ gain module by bonding the $Tm:YVO_4$ crystal with another un-doped YVO_4 crystal, opening up a range of potential 2.1 μm high power applications.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Huawen Hu: Visualization, Validation, Writing - original draft. **Haizhou Huang:** Methodology, Funding acquisition, Formal analysis. **Yan Ge:** Supervision. **Lixia Wu:** Investigation. **Wen Weng:** Funding acquisition. **Jinhui Li:** Resources. **Wenxiong Lin:** Conceptualization, Writing- review & editing.

Acknowledgments

This work is supported by The National Key Research and Development Program of China (Grant No. 2017YFB1104500); Natural National Science Foundation of China (NSFC) (61875200), and China Postdoctoral Science Foundation (2018M642575).

References

[1] V.A. Vinnichenko, A.A. Kovalenko, V.A. Arkhipova, I.V. Yaroslavsky, G.B. Altshuler, Comparison of a blue diode laser with Ho:YAG, Tm fiber, and KTP lasers for soft tissue ablation, in: 2018 International Conference Laser Optics, ICLO, 2018, p. 467.

[2] I. Elder, Performance requirements for countermeasures lasers, Proc. SPIE 7836 (2010) 783605.

[3] I. Mingareev, F. Weirauch, A. Olowinsky, L. Shah, P. Kadwani, M. Richardson, Welding of polymers using a 2 μm thulium fiber laser, Opt. Laser Technol. 44 (2012) 2095.

[4] J. Zhang, K. Fai Mak, N. Nagl, M. Seidel, D. Bauer, D. Sutter, V. Pervak, F. Krausz, O. Pronin, Multi-mW, few-cycle mid-infrared continuum spanning from 500 to 2250 cm^{-1}, Light Sci. Appl. 7 (2018) 17180.

[5] R.C. Stoneman, L. Esterowitz, Intracavity-pumped 2.09 μm Ho:YAG laser, Opt. Lett. 17 (1992) 736.

[6] M. Eichhorn, Quasi-three-level solid-state lasers in the near and mid infrared based on trivalent rare earth ions, Appl. Phys. B 93 (2008) 269.

[7] T. Zhao, F. Wang, D.Y. Shen, High-power Ho:YAG laser wing-pumped by a Tm:fiber laser at 1933 nm, Appl. Opt. 54 (2015) 1594.

[8] E. Ji, Q. Liu, Z. Hu, P. Yan, M. Gong, High-power, high-energy Ho:YAG oscillator pumped by a Tm-doped fiber laser, Chin. Opt. Lett. 13 (2015) 121402.

[9] Y.J. Shen, B.Q. Yao, X.M. Duan, G.L. Zhu, W. Wang, Y.L. Ju, Y.Z. Wang, 103 W in-band dual-end-pumped Ho:YAG laser, Opt. Lett. 37 (2012) 3558.

[10] L. Li, X. Yang, L. Zhou, W. Xie, Y. Wang, Y. Shen, Y. Yang, W. Yang, W. Wang, Z. Lv, X. Duan, M. Chen, Active/passive Q-switching operation of 2 μm Tm, Ho:YAP laser with an acousto-optical Q-switch/MoS_2 saturable absorber mirror, Photon. Res. 6 (2018) 614.

[11] B.Q. Yao, G. Li, P.B. Meng, G.L. Zhu, Y.L. Ju, Y.Z. Wang, High power diode-pumped continuous wave and Q-switch operation of Tm, Ho:YVO_4 laser, Laser Phys. Lett. 7 (2010) 857.

[12] G. Rustad, K. Stenersen, Modeling of laser-pumped Tm and Ho lasers accounting for upconversion and ground-state depletion, IEEE J. Quantum Electron. 32 (1996) 1645.

[13] J. Zhang, F. Schulze, K.F. Mak, V. Pervak, D. Bauer, D. Sutter, O. Pronin, High & power, High & efficiency Tm:YAG and Ho:YAG thin-disk lasers, Laser Photonics Rev. 12 (2018) 1700273.

[14] R.A. Hayward, W.A. Clarkson, D.C. Hanna, High-power diode-pumped room-temperature Tm:YAG and intracavity-pumped Ho:YAG lasers, in: Advanced Solid State Lasers, in: OSA Technical Digest Series, 2000, MB8.

[15] M. Schellhorn, A. Hirth, C. Kieleck, Ho:YAG laser intracavity pumped by a diodepumped Tm:YLF laser, Opt. Lett. 28 (2003) 1933–1935.

[16] G.L. Zhu, X.D. He, B.Q. Yao, Y.Z. Wang, Ho:YAP laser intra-cavity pumped by a diode-pumped Tm:YLF laser, Laser Phys. 23 (2013) 015002.

[17] H. Huang, J. Huang, H. Liu, J. Li, S. Dai, W. Weng, W. Lin, Efficient 2122 nm Ho:YAG laser intra-cavity pumped by a narrowband-diode-pumped Tm:YAG laser, Opt. Lett. 41 (2016) 3952.

[18] X. Yang, H. Huang, D. Shen, H. Zhu, D. Tang, 2.1 μm Ho:LuAG ceramic laser intracavity pumped by a diode-pumped Tm:YAG laser, Chin. Opt. Lett. 12 (2014) 121405.

[19] J.M. Serres, P.A. Loiko, X. Mateos, K.V. Yumashev, N.V. Kuleshov, V. Petrov, U. Griebner, M. Aguiló, F. Díaz, Ho:KLuW microchip laser intracavity pumped by a diode-pumped Tm:KLuW laser, Appl. Phys. B 120 (2015) 123.

[20] X. Duan, L. Li, L. Zheng, B. Yao, Z. Zou, D. Jiang, L. Su, Efficient intracavity-pumped Ho:SSO laser with cascaded in-band pumping scheme, Infrared Phys. Technol. 94 (2018) 7.

[21] K. Ohta, H. Saito, M. Obara, Spectroscopic characterization of Tm^3+:YVO_4 crystal as an efficient diode pumped laser source near 2000 nm, J. Appl. Phys. 73 (1993) 3149.

[22] H.Z. Huang, J.H. Huang, H.G. Liu, S.T. Dai, W. Weng, H. Zheng, Y. Ge, J.H. Li, J. Deng, W.X. Lin, High-efficiency Tm-doped yttrium aluminum garnet laser pumped with a wavelength-locked laser diode, Laser Phys. Lett. 13 (2016) 095001.

[23] Y. Sato, T. Taira, The studies of thermal conductivity in $GdVO_4$, YVO_4, and $Y_3Al_5O_{12}$ measured by quasi-one-dimensional flash method, Opt. Express 14 (2006) 10528.

[24] D.E. McCumber, Einstein relations connecting broadband emission and absorption spectra, Phys. Rev. 136 (1964) A954.

[25] J.J. Zayhowski, J. Harrison, C. Dill, J. Ochoa, Tm:YVO_4 microchip laser, Appl. Opt. 34 (1995) 435.

[26] H. Saito, S. Chaddha, R.S.F. Chang, N. Djeu, Efficient 1.94-μm Tm^3+ laser in YVO_4 host, Opt. Lett. 17 (1992) 189.

[27] A. Berrou, T. Ibach, M. Eichhorn, High-energy resonantly diode-pumped Q-switched Ho^3+:YAG laser, Appl. Phys. B 120 (2015) 105.

[28] K. Scholle, P. Fuhrberg, In-band pumping of high-power ho:yag lasers by laser diodes at 1.9 μm, in: Conference on Lasers and Electro-Optics, Optical Society of America, 2008, CTuAA1.

[29] 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.