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Passively *Q*-switched Ho:YLF laser pumped by Tm^{3+}-doped fiber laser

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ABSTRACT

We demonstrate a compact and efficient passively *Q*-switched (PQS) Ho:YLF laser pumped by a self-made all-fiber laser. Firstly, we design and make an all-fiber laser operating at 1940 nm with a slope efficiency of 40.6%. Then, the all-fiber laser was used to pump Ho:YLF laser directly. In the CW (continues-wave) operation Ho:YLF laser, the maximum output power was 7.79 W, corresponding to the slope efficiency of 55.2%. Using Cr^{2+}:ZnS as the saturable absorber, the average power of 6.03 W was achieved with the slope efficiency of 45.9%. The shortest pulse duration was 15.6 ns and the pulse repetition frequency was 2.3 kHz at the pump power of 20.4 W. The pulse energy was a constant as 2.7 mJ when the pump power exceeded 15 W. The beam quality factor of M^2 was 1.05, indicating nearly diffraction limited beam propagation.

1. Introduction

Pulsed solid-state lasers operating at 2 μm eye-safe spectral range have become one of the most explored regions. Based on the advantages as high energy, short pulse and “atmospheric window”, 2 μm laser were broadly used in remote sensing [1], wind LIDAR [2], medicine [3,4] and pumping the optical parametric oscillators(OPOs) [5]. The pulse lasers commonly adopt the *Q*-switched technologies as actively *Q*-switched and passively *Q*-switched. It is much easier and more cost-effective for passively Q-switched lasers to achieve compact operations without the need for expensive and bulky acousto-optic or electro-optic modulators [6]. Besides, a suitable saturable absorber (SA) is crucially important for efficient PQS laser. It has been applied to several Tm-doped laser materials such as $KY(WO_4)_2$ [7], YAG [8], and YAP [9], using Cr^{2+}-doped ZnSe and ZnS crystals, PbS quantum dots, and InGaAs/GaAs semiconductor-based SAs. Compared with other SAs, Cr^{2+}:ZnS media have a series of excellent characteristics, such as the high optical damage threshold of 1.5 J/cm^2 [10] and the thermal conductivity in the cubic phase of 27 W/mK [11], which lead to a weaker thermal lens effect.

At present, the main 2 μm passively *Q*-switched laser media are Tm^{3+}-doped, Ho^{3+}-doped, and Tm^{3+},Ho^{3+}-codoped crystals. Compared with Tm^{3+}-doped media, Ho^{3+}-doped media have larger emitting cross section and longer upper laser level lifetime [12,13]. Tm,Ho co-doped media need to be operated under liquid N_2 temperature. Compared with Tm^{3+},Ho^{3+}-codoped media, the energy transition upconversion loss and reabsorption loss in Ho^{3+}-doped media were significantly decreased because there is no requirement of the sensitizing ions. So, better laser output characteristics in Ho^{3+}-doped laser can be obtained at room temperature.

Based on the effect of host material on thermology, mechanics and spectrum characteristics, the optical properties of Ho^{3+}-doped crystals crucially depend on the host materials. The host materials usually used in Ho^{3+}-doped crystals are oxide crystals (like YAP [14], YAG [15–17]) and fluoride crystals (like YLF [18], LuLF [19]). Compared with oxide crystals, the phonon energy of fluoride crystals is much lower and the related upper level lifetime is much longer, which helps to realize high energy storage and reach the laser operation condition. Ho:YLF is just a typical representation of fluoride crystal, which belongs to tetragonal system. In 2004, D. Y. Shen et al. used a tunable Tm-doped fiber laser operating at 1942 nm pumping a Ho:YLF laser. 4.8 W CW output power at 2.07 μm was obtained by 9.4 W pump power with a slope efficiency of 51% [20]. In 2006, Y. X. Bai et al. reported an efficiently Ho:YLF laser pumped by a fiber laser operating at 1941 nm. The maximum CW output power of 19 W at 2051 nm was obtained, corresponding to a slope efficiency of 64.7% [21]. In 2011, H. J. Strauss et al. realized a 330 mJ single frequency laser output pumping by a Tm:YLF laser at 1890 nm with π polarization

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direction (E//c-axis) [22]. However, the output performance of passively *Q*-switched Ho:YLF laser is seldom reported. Until the year of 2011, Dergachev A. reported a passively *Q*-switched Ho:YLF single-frequency laser by ring-cavity with Cr^{2+}:ZnSe SAs and the single pulse energy could reach to 0.42 mJ [23].

In this paper, we first report a Tm^{3+}-doped fiber laser directly pumping passively *Q*-switched Ho:YLF laser. The self-made Tm^{3+}-doped fiber laser was an unpolarized CW laser at 1940 nm with the slope efficiency of 40.6%. In CW Ho:YLF laser operation, output power was 7.79 W. In PQS Ho:YLF laser operation, a maximum average output power was 6.03 W. And the pulse width was 15.6 ns corresponding to the pulse repetition frequency of 2.3 kHz when the pump power at 20.4 W. The single pulse energy fluctuated around 2.7 mJ when the pump exceeded 15 W. The beam quality factor of M^2 was measured of 1.05 which was near-diffraction-limited.

2. Experimental setup

We utilized a double-cladding Tm^{3+}-doped all-fiber laser as a pump source for Ho:YLF crystal to generate 2.05 μm laser. The structure of fiber laser was depicted in Fig. 1(a). Two 793 nm Laser Diodes (LD) were employed as the pump source of the fiber laser. The laser cavity was composed of two Fiber Bragg gratings (FBGs). One of the FBGs was high reflective (HR, $R > 99.0\%$) with the central wavelength of 1940.02 nm, and the other one was partial reflective (PR, $R = 10.1\%$) with a central wavelength of 1940.00 nm. Both of the two FBGs are chirped, and the related wider spectral FWHM (full width at half maximum) of HR FBG is 2.00 nm and PR FBG is 1.00 nm at room temperature. The double-cladding Tm^{3+}-doped silica fiber (Nufern Co.) was considered as gain medium, which diameter is 25 μm and the core Numerical Aperture (NA) is 0.09. The diameter of the pure-silica inner cladding is 400 μm with 0.46 cladding NA, which is coated with a low-index polymer. The cladding absorption coefficient of the Tm^{3+}-doped fiber at 793 nm was 1.8 dB/m. A cladding stripper was designed and used to strip the light in inner cladding. The fiber output end was cleaved to 8° to eliminate the Fresnel reflection on the end facet of fiber laser. Compared with traditional 1940 nm Tm:YAP solid-state lasers [24], fiber lasers have many excellent optical characteristics, such as simplicity, tenability and compact structure and have better beam quality.

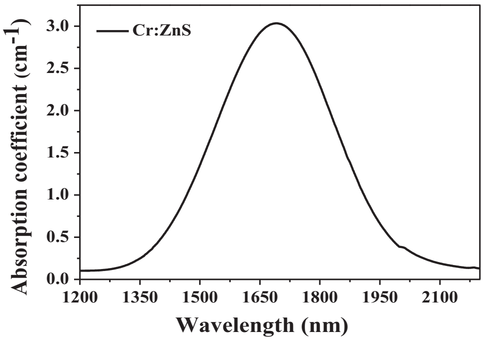

Fig. 2. The relationship between absorption coefficient of Cr^{2+}:ZnS and wavelength.

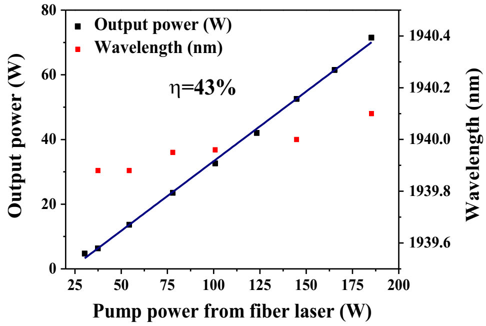

Fig. 3. The slope efficiency and wave length vs. pump power..

The full unpolarized pump beam from the Tm^{3+}-doped fiber laser was used to pump the solid-state oscillator crystal. The structure of passively *Q*-switched Ho:YLF laser pumped by Tm^{3+}-doped fiber laser was shown in Fig. 1(b). The Ho:YLF crystal was 50 mm in length, 5×5 mm^2 in cross section, corresponding to the doping concentration of 1.5 at%. Ho^{3+} is the gain medium which is a quasi-two level system at room temperature. The transition from $^5I_7$–$^5I_8$ can generate laser wavelength around 2 μm. A Cr^{2+}:ZnS saturable absorber produced by a post-growth diffusion method was cut into 9×10 mm^2 cross section and 3 mm thickness with small-signal transmission of about 83%. The Cr^{2+} ions were uniformly-doped with a concentration of 1.9×10^{19} at/cm^3. The

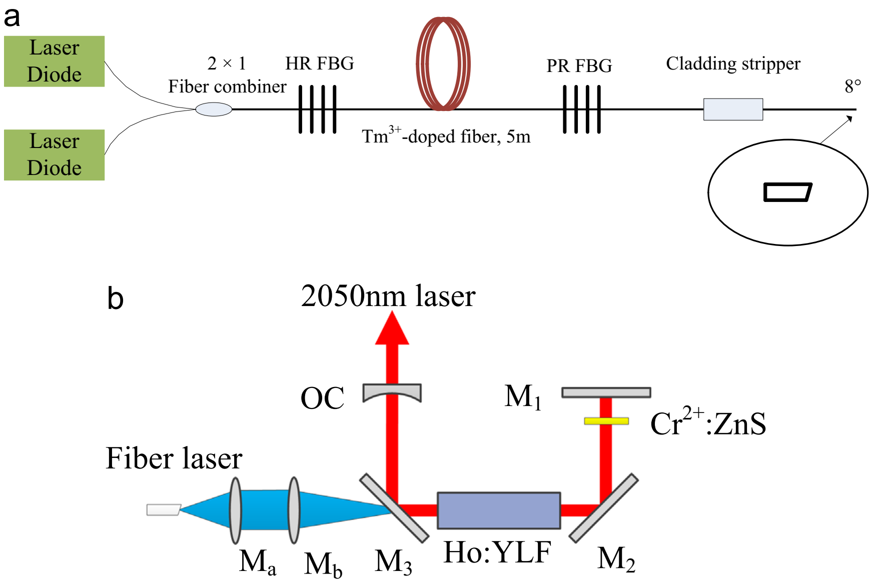

Fig.1. (a) The structure of Tm^{3+}-doped fiber laser and (b) passively *Q*-switched Ho:YLF laser.

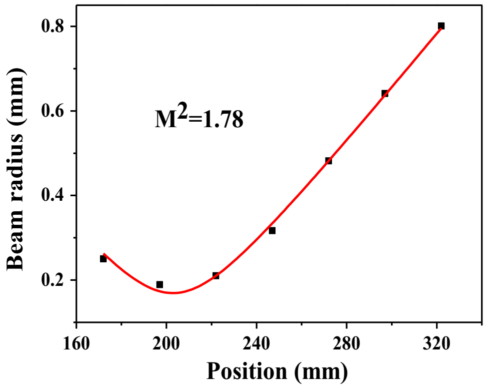

Fig. 4. The beam quality factor of M^2 of fiber laser.

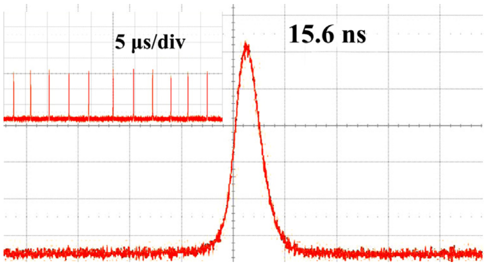

Fig. 6. Typical expanded shape of a single pulse.

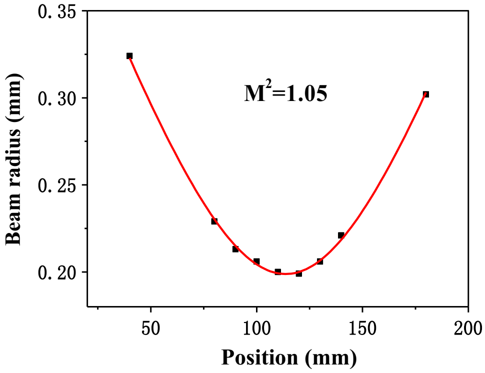

Fig. 7. The beam quality factor of M^2 the insert was a train of output pulses at 20.4 W.

polycrystalline ZnS material was produced by the CVD method. The absorption coefficient of Cr^{2+}:ZnS was measured in Fig. 2. The Cr^{2+}:ZnS saturable absorber was also mounted in a copper heat sink which was cooled by water at 290 K.

The pump from fiber laser was delivered to Ho:YLF laser cavity by two lens(M_a, $f=500$ mm and M_b, $f=200$ mm). The pump beam radius was converted to 0.5 mm, which was matched to dimension of Ho:YLF crystal. M_1, M_2 and M_3 were cavity mirrors, and all of the mirror radii were 20 mm. 45° dichroic mirror M_2 and M_3 were coated with 1.94 µm anti-reflection coatings ($T>95\%$) and 2.05 µm high-reflection coatings ($R>99\%$). M_1 was a flat mirror with a high reflectivity at 2.05 µm. OC was an output coupling mirror with a curvature radius of 400 mm, corresponding to the transmittance of 49% @ 2.05 µm. The laser cavity length was 160 mm. The distance between OC and M_3 was 40 mm, M_3 to M_2 was 80 mm, M_2 to M_1 was 40 mm, and the Cr^{2+}:ZnS saturable absorber was placed 10 mm to M_1. The polycrystalline Cr^{2+}:ZnS was mounted in a copper heat sink which was cooled by water at 290 K. The laser cavity was stable by ABCD matrix calculation.

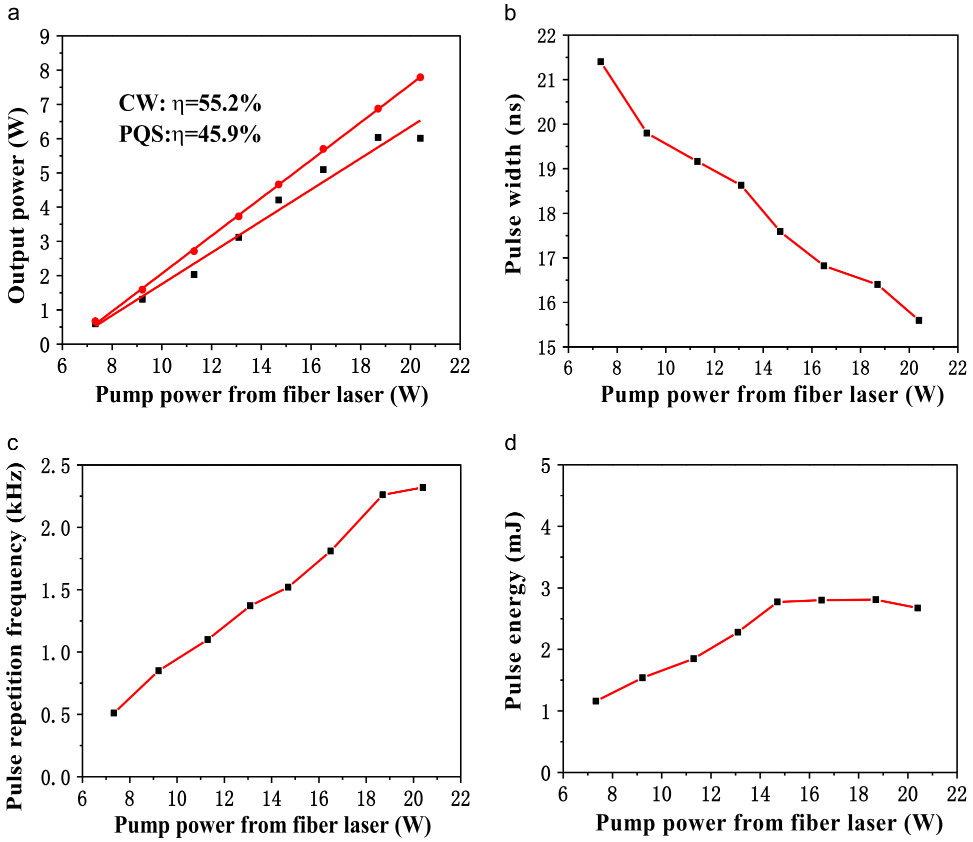

Fig. 5. (a) Output power of CW and PQS operation vs. pump power from fiber laser (b) Pulse width vs. pump power from fiber laser (c) Pulse repetition frequency (PRF) vs. Pump power from fiber laser (d) Pulse energy vs. pump power from fiber laser.

3. Experimental results and discussion

3.1. Fiber laser

With a maximum pump power of 77.9 W, 23.5 W laser output power was obtained from the all-fiber laser. The slope efficiency was 40.6%, corresponding to an optical efficiency of 30.2%. The laser wavelength was measured to be 1939.95–1940.05 nm, as shown in Fig. 3. The wavelength was increased weakly with the pump power increasing and became 1940 nm when the output power was around 20 W. The beam quality factor of M^2 was 1.78 which was measured by 90/10 knife-edge method at the total incident pump power as shown in Fig. 4.

3.2. Ho:YLF laser

We measured the CW and PQS output power vs. the pump power from fiber laser respectively, as shown in Fig. 5(a). In CW operation, 7.79 W output power was obtained with the slope efficiency of 55.2%, corresponding to the optical efficiency of 38.2%. In PQS operation, the average power was increased linearly with the pump power except for over 6.03 W, corresponding to the pump power of 20.4 W. The slope efficiency was 45.9% by linear fitting, corresponding to the optical efficiency of 32.2%. The relation curve between laser pulse width and pump power was shown in Fig. 5(b). 21.4 ns *Q*-switched pulse width was obtained at the beginning of the pulse formation. With the pump power increasing, the pulse width turned narrow gradually. When the pump power reached 20.4 W, 15.6 ns *Q*-switched pulse width was obtained.

The pulse repetition frequency (PRF) variation tendency with the pump power was shown in Fig. 5(c). With the pump power increasing, the pulse repetition frequency increased from 0.5 kHz to 2.3 kHz. The output single pulse width at maximum pump power was shown in Fig. 6, and the insert was the pulse trains. The variation tendency between *Q*-switched single pulse energy and pump power was shown in Fig. 5(d). The solid-state laser generated 1.2 mJ *Q*-switched pulse energy when the pump power was low. With the pump power increasing, the pulse energy presented a tendency of augment. When the pump power exceeded 15 W, the *Q*-switched pulse energy fluctuated around the 2.7 mJ with no obvious upward or downward trend. The beam quality factor of M^2 was measured of 1.05 by 90/10 knife-edge method at the total incident pump power of 20 W, as shown in Fig. 7, which indicated the output beam was close to fundamental TEM_{00}.

4. Conclusion

In this paper, the Tm^{3+}-doped fiber laser pumped passively *Q*-switched Ho:YLF laser with a U-shaped laser cavity at room temperature was demonstrated. Firstly, we made an all-fiber laser operating at 1940 nm. The slope efficiency was 40.6%, corresponding to the optical efficiency of 30.2%. The output wavelength was from 1939.95 nm to 1940.05 nm with a beam quality factor of M^2 of 1.78 at the total incident pump power. Then the fiber laser was utilized to pump solid-state Ho:YLF laser directly. In CW operation, 7.79 W output power was obtained with a slope efficiency of 55.2%, corresponding to the optical efficiency of 38.2%. In PQS operation, 6.03 W average output power was obtained by inserting a Cr^{2+}:ZnS SA into the laser cavity. The output wavelength was 2.05 μm with the slope efficiency of 45.9%, corresponding to the optical efficiency of 32.2%. The pulse width was from 21.4 ns to 15.6 ns with the pump power increasing. The pulse repetition frequency was increased up to 2.3 kHz at the pump power of 20.4 W. The single pulse energy was almost a constant of 2.7 mJ when the pump exceeded 15 W. Furthermore, the laser beam profile was measured of 1.05 which was near-diffraction-limited.

Acknowledgments

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Reference

[1] R.M. Mihalcea, M.E. Webber, D.S. Baer, R.K. Hanson, G.S. Feller, W.B. Chapman, Diode-laser absorption measurements of CO_2, H_2O, N_2O and NH_3 near 2.0 μm, Appl. Phys. B 67 (3) (1998) 283–288.

[2] S.W. Henderson, C.P. Hale, J.R. Magee, M.J. Kavaya, A.V. Huffaker, Eye-safe coherent laser radar system at 2.1 μm using Tm,Ho:YAG lasers, Opt. Lett., 16, (1991) 773–775.

[3] R.L. Blackmon, J.R. Case, S.R. Trammell, P.B. Irby, N.M. Fried, Fiber-optic manipulation of urinary stone phantoms using holmium:YAG and thulium fiber lasers, J. Biomed. Opt. 18 (2) (2013) 028001.

[4] M. Freebody, Fiber Lasers at the Cutting Edge of Surgery, Biophotonics S (2013) http://www.photonics.com/Article.aspx?PID&equal;1&VID=108&IID=681&Tag=Features&AID=53575.

[5] C. Kieleck, A. Berrou, B. Donelan, B. Cadier, T. Robin, M. Eichhorn, 6.5 W $ZnGeP_2$ OPO directly pumped by a *Q*-switched Tm^{3+}-doped single-oscillator fiber laser, Opt. Lett. 40 (6) (2015) 1101–1104.

[6] X.L. Zhang, L. Yu, S. Zhang, L. Li, J.Q. Zhao, J.H. Cui, Diode-pumped continuous wave and passively *Q*-switched Tm,Ho:LLF laser at 2 μm, Opt. Express, 21, (2013) 12629–12634.

[7] L.E. Batay, A.N. Kuzmin, A.S. Grabtchikov, V.A. Lisinetskii, V.A. Orlovich, A. A. Demidovich, A.N. Titov, V.V. Badikov, S.G. Sheina, V.L. Panyutin, M. Mond, S. Kück, Efficient diode-pumped passively *Q*-switched laser operation around 1.9 μm and self-frequency Raman conversion of Tm-doped $KY(WO_4)_2$, Appl. Phys. Lett. 81 (16) (2002) 2926–2928.

[8] M. Mond, E. Heumann, G. Huber, S. Kuck, V.I. Levchenko, V.N. Yakimovich, V.E. Shcherbitsky, V.E. Kisel, N.V. Kuleshov, Passive *Q*-switching of a diode-pumped Tm: YAG laser by Cr^{2+}:ZnSe. Lasers and Electro-Optics Europe, CLEO/Europe, IEEE, CA7-5-WED, 2003.

[9] B.Q. Yao, Y. Tian, G. Li, Y.Z. Wang, InGaAs/GaAs saturable absorber for diode-pumped passively *Q*-switched dual-wavelength Tm:YAP lasers, Opt. Express, 18, (2010) 13574–13579.

[10] D.M. Simanovskii, H.A. Schwettman, H. Lee, A.J. Welch, Midinfrared optical breakdown in transparent dielectrics, Phys. Rev. Lett. 91 (10) (2003) 107601.

[11] E. Sorokin, N. Tolstik, K.I. Schaffers, I.T. Sorokina, Femtosecond SESAM-modelocked Cr:ZnS laser, Opt. Express 20 (27) (2012) 28947–28952.

[12] 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. Quant. Electron. 6 (4) (2000) 629–635.

[13] A. Dergachev, P.F. Moulton, High-power, high-energy Ho:YLF laser pumped with Tm:fiber laser, Advanced Solid-State Photonics © 2005, OSA/ASSP 2005, pp. 608–612.

[14] X.T. Yang, X.Z. Ma, W.H. Li, Continuous-wave operation of a room-temperature Ho: YAP laser pumped by a Tm:YAP laser, Optik 25 (15) (2014) 3943–3945.

[15] J. Kwiatkowski, J.K. Jabczynski, W. Zendzian, L. Gorajek, M. Kaskow, High repetition rate, *Q*-switched Ho:YAG laser resonantly pumped by a 20 W linearly polarized Tm: fiber laser, Appl. Phys. B 114 (3) (2014) 395–399.

[16] Y.L. Ju, T.Y. Dai, X.M. Duan, Y.J. Shen, B.Q. Yao, Wang Y.Z. Continuous-wave, and Q-switched operation of a Ho:YAG ring laser in-band pumped at 1908 nm, Laser Phys. 23 (2014) 045808.

[17] T.Y. Dai, Y.L. Ju, B.Q. Yao, Y.J. Shen, W. Wang, Y.Z. Wang, Injection-seeded Ho:YAG laser at room temperature by monolithic nonplanar ring laser, Laser Phys. Lett. 9 (10) (2012) 716–720.

[18] H.J. Strauss, D. Preussler, M.J.D. Esser, W. Koen, C. Jacobs, Collett OJP, C. Bollig, 330 mJ single-frequency Ho:YLF slab amplifier, Opt. Lett. 38 (7) (2013) 1022–1024.

[19] J.W. Kim, J.I. Mackenzie, D. Parisi, S. Veronesi, M. Tonelli, W.A. Clarkson, Efficient in-band pumped $Ho:LuLiF_4$ 2 μm laser, Opt. Lett. 35 (3) (2010) 420–422.

[20] D.Y. Shen, J. Sahu, W.A. Clarkson, Efficient holmium-doped solid-state lasers pumped by a Tm-doped silica fiber laser, Proc. SPIE 5620 (2004) 46–55.

[21] Y.X. Bai, M. Petros, J.R. Yu, P. Petzar, B. Trieu, S. Chen, H. Lee, U. Singh, Highly efficient operation of Tm:Fiber laser pumped Ho:YLF laser, OSA/ASSP 2006, TuB7.

[22] H.J. Strauss, D. Preussler, M.J.D. Esser, W. Koen, C. Jacobs, O.J.P. Collett, C. Bollig, 330 mJ, 2 μm, single frequency, Ho:YLF slab amplifier Advanced Solid-State Photonics(ASSP) 2011, ATuA4.

[23] A. Dergachev, Pulsed single-frequency, ring laser with a holographic output coupler, Opt. Express 19 (7) (2011) 6797–6806.

[24] L. Han, B.Q. Yao, X.M. Duan, S. Li, T.Y. Dai, Y.L. Jun, Y.Z. Wang, High power slab Tm: YAP laser dual-end-pumped by fiber coupled laser diodes, Opt. Quant. Electron., 47, (2015) 1055–1061.