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In-band pumped, high-efficiency LGS electro-optically Q-switched 2118 nm Ho:YAP laser with low driving voltage

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HIGHLIGHTS

- Two c-cut Tm:YAP crystals were utilized as pump source emitting at 1940 nm.
- The LGS crystal based on EO modulator was designed to operate in pulse-on mode with a 1/4 wave voltage of 2400 V.
- Inband pumped EO Q-switched Ho:YAP laser at 2118 nm was demonstrated using a LGS modulator.

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ABSTRACT

An in-band end-pumped LGS electro-optically (EO) Q-switched Ho:YAP laser has been investigated and demonstrated. The LGS crystal based on EO modulator was designed to operate in pulse-on mode with a 1/4 wave voltage of 2400 V, which was the lowest driving voltage at 2 μm wavelength for LGS crystal as far as we know. Under continuous-wave (CW) regime, a maximum average output power of 6.5 W was obtained from the Ho:YAP laser with a slope efficiency of 50.6% when an incident pump power was 16 W. When running in EO Q-switching regime, a maximum output power of 4 W was obtained with a single pulse energy of 1 mJ and a pulse width of 33 ns at a repetition rate of 4 kHz. At the repetition rate of 2 kHz, the maximum single pulse energy of 1.5 mJ and the shortest pulse width of 23 ns were achieved, corresponding to a pulse peak power of as high as 65 kW.

1. Introduction

2 μm pulsed lasers have many potential applications in the fields of medical treatment, radar, ranging, and so on [1,2], which are located within the eye-safety wavelength regions and weak absorption lines of atmosphere. In general, Tm^{3+} or Ho^{3+} ions doped materials are popular gain media for generating 2 μm laser. Particularly, Ho^{3+} ions doped materials can emit laser radiations near 2.1 μm, which not only benefit the practical applications keeping away from water-vapor absorption, but act as promising pump sources for optical parametric oscillators (OPOs) to generate longer wavelength especially in the case of using Zinc-Germanium Diphosphide ($ZnGeP_2$, ZGP). Additionally, in comparison with Tm lasers, in-band pumped Ho lasers have the excellent characteristics of low thermal load, high efficiency, low quantum-loss, and etc.

Ho:YAP crystals have good thermal and mechanical properties similar to those of Ho:YAG, which can quickly transfer the energy during the pumping process [3]. Moreover, different from Ho:YAG, Ho:YAP crystals have very good natural birefringence, which is more conducive to delivering highly polarized laser beam without virtual depolarization loss [4]. In addition, Ho:YAP crystals have large stimulated emission cross section (0.82×10^{-20} cm^2) and long fluorescence lifetime (6 ms) for $^5I_7 \rightarrow {}^5I_8$ transition [5,6], which are in favor of achieving high output power and large pulse energy. In particular, the Ho:YAP crystal

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has a broad absorption bandwidth near 1.9 μm with multiple absorption peaks around 1883, 1916, 1928, and 1947 nm, which are consistent with the emission spectra of Tm lasers such as Tm:YLF, Tm:YAP, Tm:fiber, and etc [7–12]. In 2009, Duan *et al.* firstly reported a Ho:YAP laser pumped by a Tm:YLF laser at room temperature with an output power of 10.2 W and a slope efficiency of 64% [11]. In 2015, a CW Ho:YAP laser pumped by a Tm-doped fiber laser delivered a maximum output power of 20.2 W, corresponding to a slope efficiency of 72% [13]. In addition, a Ho:YAP laser pumped by a Tm:YAP laser has also been reported with a maximum output power of 6.4 W, but the slope efficiency was only 25.3% [14]. Very recently, an acoustic-optical (AO) Q-switched Ho:YAP laser generated a maximum output power of 30 W with a pulse width of 45 ns and pulse repetition rate of 20 kHz [15]. Subsequently, a maximum single pulse energy of 2.7 mJ was achieved with a pulse width of 15 ns at 3 kHz from an AO Q-switched Ho:YAP laser pumped by a 1.91 μm laser diode [16]. Meanwhile, an AO Q-switched Tm, Ho:YAP laser was also reported with an average output power of 12.3 W and a maximum pulse energy of 10.3 mJ [17]. However, as for EO Q-switching operation regime, there is no report on Ho:YAP laser, to the best of our knowledge.

As an alternative of AO Q-switch, EO modulator also plays an important role in generating narrow pulse duration and high peak power due to its fast switching speed, excellent stability and high extinction ratio. The crystals such as $LiNbO_3$ (LN), $La_3Ga_5SiO_{14}$ (LGS) and $RbTiOPO_4$ (RTP) have been successfully employed as EO modulators in many diode-pumped solid-state Tm lasers. In 2016, a diode-pumped EO Q-switched Tm:YAG slab laser based on RTP modulator generated a pulse energy of 7.5 mJ and a pulse width of 58 ns [18]. In 2018, our group reported a diode-wing-pumped LN EO Q-switched Tm:LuAG laser with a maximum pulse energy of 10.8 mJ and a minimum pulse width of 52 ns at a repetition rate of 100 Hz [19]. In 2019, a LGS EO Q-switched Tm:YAP laser was demonstrated with an output power of 2.79 W and a pulse width of 5 ns at a repetition rate of 200 kHz [20]. In 2013, a 14 ns, 550 mJ Ho:YLF laser was achieved by using a RTP modulator and pumped by a 100 W Tm:fiber laser, but the working temperature was 80 K which was realized by cryogenic cooling [21]. Among the above mentioned EO crystals, LN crystal has low optical damage threshold (~100 MW/cm^2), and the piezoelectric ring effect usually happens at frequencies above 1 kHz. RTP crystal has natural birefringence, so two mutually orthogonal crystals are normally employed, resulting in a complicated configuration [20]. LGS has promising virtues including non-hygroscopicity, high optical damage threshold of 950 MW/cm^2 and broad transmission spectral range, although it suffers from the high 1/4 wave driving voltage of up to 5 kV, which is caused by the small electro-optic coefficient (2.3×10^{-12} m/V) [22]. Moreover, there is no report on application of LGS as EO modulator in Q-switched Ho-doped laser at room temperature as far as we know.

In this paper, a highly efficient LGS EO Q-switched Ho:YAP laser resonantly pumped by a Tm:YAP laser was realized at room temperature for the first time, to the best of our knowledge. By designing the aspect ratio of LGS crystal, the 1/4 wave driving voltage for EO modulator was reduced to 2400 V. When a pump power of 16 W was employed, a maximum CW output power of 6.5 W was obtained, corresponding to a slope efficiency of up to 50.6%. The EO Q-switched Ho:YAP laser was investigated under different repetition rates. Under Q-witching operation, a maximum output power of 4 W was achieved with a pulse width of 33 ns at a repetition rate of 4 kHz. At the repetition rate of 2 kHz, a maximum output energy of 1.5 mJ and a minimum pulse width of 23 ns were generated, corresponding to a maximum peak power of 65 kW.

2. Experimental setup

The experimental setup of the EO Q-switched Ho:YAP laser is schematically shown in Fig. 1, in which a simple L-shaped plano-

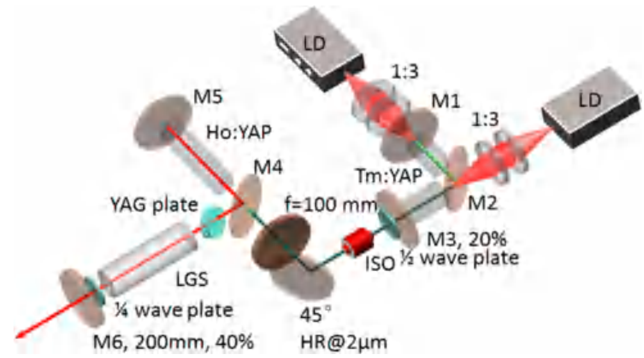

Fig. 1. Experimental setup of EO Q-switched Ho:YAP laser.

concave cavity with a physical length of 180 mm has been employed. For the Tm:YAP laser as pump source, two *c*-cut crystals were utilized with Tm^{3+} ions doping concentration of 3 at.% and dimensions of $3 \times 3 \times 10$ mm^3. Each crystal was pumped by two fiber-coupled laser diodes (LDs) emitting at 792 nm with fiber core diameter of 200 μm and numerical aperture of 0.22, respectively. The pump light was focused into Tm:YAP crystals with beam radii of nearly 300 μm by using 1:3 coupling lenses. The Tm:YAP laser resonator had a cavity length of 60 mm. M1 (AR@792 nm, HR@1850–2150 nm) was a plane input mirror and M2 (R > 99.5% at 1.9 μm and T ~ 95% at 792 nm) was a flat 45° dichroic mirror. The output coupling rate of the plane output mirror M3 was 20% at 1850–2150 nm. For the Ho:YAP laser, the output Tm laser beam was focused into the Ho:YAP crystal with a spot size of about 250 μm through a plano-convex lens with a focal length of 100 mm, that was AR coated in a broad band of 1.65–3.0 μm. The *a*-cut Ho:YAP crystal used in the experiment was 0.3 at.% Ho^{3+} ions doped with dimensions of $4 \times 4 \times 40$ mm^3, both surfaces of which were anti-reflection (AR) coated from 1.9 to 2.1 μm. All the laser crystals were wrapped with indium foil and placed in copper block cooled at 15 °C with water. M4 (R > 99.5% at 2.1 μm and T ~ 95% at 1.99 μm) was a flat 45° dichroic mirror. To increase the absorption efficiency, flat mirror M5 was high reflectivity (HR) coated at 1850–2150 nm, and the residual pump light was recycled into the Ho:YAP crystal. An optical isolator (ISO) combined with λ/2 wave plate was employed to prevent the pump laser light from returning into the Tm:YAP laser system. The output coupler coated with 40% transmission at 2.1 μm was a concave mirror with a curvature radius of 200 mm.

The LGS EO modulator employed in the experiment was designed in pulse-on mode, which consisted of polarizer, LGS crystal and 1/4 wave plate. In order to enhance the degree of polarization under high pump power, two 0.5 mm-thick uncoated YAG plates were inserted into the cavity at Brewster angle (61°) and acted as the polarizers. Combined with a 1/4 wave plate, the round-trip oscillation was blocked. A *z*-cut LGS crystal with dimensions of $4 \times 4 \times 48$ mm^3 was polished for both surfaces. The LGS crystal had a transmission of 95% at 2.1 μm, but was uncoated. The EO modulator operated in transverse-field regime and the laser beam propagated along z axis of the LGS crystal. According to the quarter-wave voltage formula $V_{\lambda/4} = \lambda/4\pi n_0^3 \gamma_{11}(l/d)$ [20], and parameters $\lambda = 2.1$ μm, $n_0 = 1.86$, $\gamma_{11} = 2.3 \times 10^{-12}$ m/V and $l/d = 12$, the quarter-wave voltage was theoretically estimated to be $V_{\lambda/4} = 2956$ V. From the theoretical result, it can be seen that the aspect ratio of 12:1 greatly reduces the driving voltage required for Q-switching. In the experiment, the practical $V_{\lambda/4}$ was artificially set to be only 2400 V, less than the theoretical value. In such a way, the relatively small $V_{\lambda/4}$ would increase the intra-cavity loss, however, a low quarter-wave voltage is also much desired for practical application, which of course should firstly assure the stable oscillation of the laser. The quarter-wave voltage was supplied by a Pockels cell driver with a rise time of 20 ns (QBU-BT-5020, OEM Tech, The Republic of Belarus). The temporal pulse characteristics were detected by a fast InGaAs

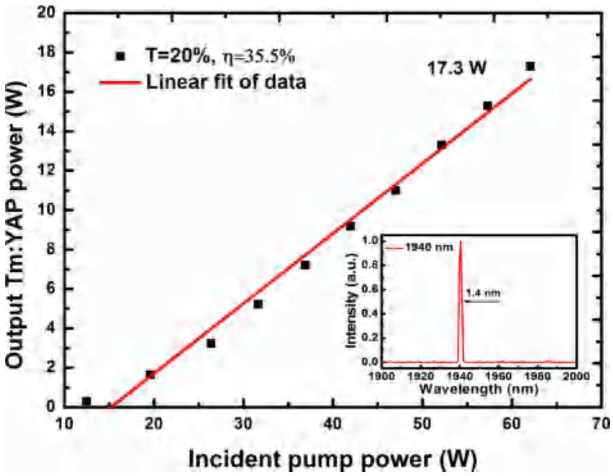

Fig. 2. Output powers of CW Tm:YAP laser. Inset: Output spectrum.

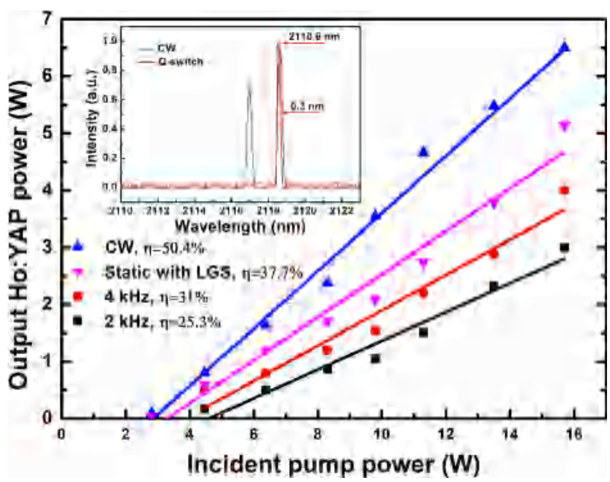

Fig. 3. Output characteristics of CW and EO Q-switched Ho:YAP laser. Inset: Output spectra.

photodetector (EOT, ET-5000, USA) and recorded in a digital oscilloscope (1 GHZ band width, Tektronix DPO 7102, USA).

3. Results and discussions

A small pump beam radius of about 200 μm was once tried for the Tm:YAP laser, but the output power saturation happened, which much

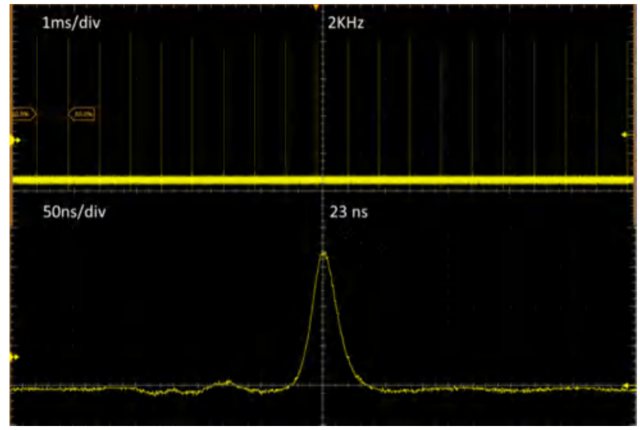

Fig. 5. The temporal pulse train and single pulse shape of EO Q-switched Ho:YAP laser obtained at the repetition rate of 2 kHz.

limited the increase of the output power. Therefore, the pump beam radius for the Tm:YAP crystal was increased to about 300 μm. The Tm:YAP laser output powers as function of incident pump powers are shown in Fig. 2. The threshold pump power was about 15 W and the output powers linearly increased with the pump powers. When the incident pump power was 62 W, a maximum output power of 17.3 W was obtained with the output coupling rate of 20%. The corresponding slope efficiency was 35.5%, and the optical-to-optical conversion efficiency was 28%. After the ISO, the available pump power for the Ho:YAP crystal was 16 W, indicated a transmission loss of about 7.5%. The output spectrum of the Tm:YAP laser was measured by using a laser spectrometer (APE WaveScan, APE Inc.). As shown in the inset part of Fig. 2, the center wavelength was 1940 nm with a full width at half-maximum (FWHM) of 1.4 nm.

With the Tm:YAP laser as pump source, the output powers of Ho:YAP lasers are shown in Fig. 3. First, the output laser power characteristics under CW regime without EO modulator in the cavity were investigated (marked as regular triangle symbol). It can be seen that the CW Ho:YAP laser output powers increased almost linearly with the incident pump power. Under an incident pump power of 16 W, a maximum output power of 6.5 W was obtained with a corresponding slope efficiency of 50.4%, which indicated that the Tm:YAP laser was an efficient pump source of Ho:YAP laser. The single-pass absorbance to the 1940 nm pump light of Ho:YAP crystal was also measured to be about ~60% under non-lasing condition. By using the crystal with higher Ho^{3+} doping concentration, the laser slope efficiency could be further increased. As shown in Fig. 3 (inset), the emission spectrum under CW operation shows multi-mode regime centered at about

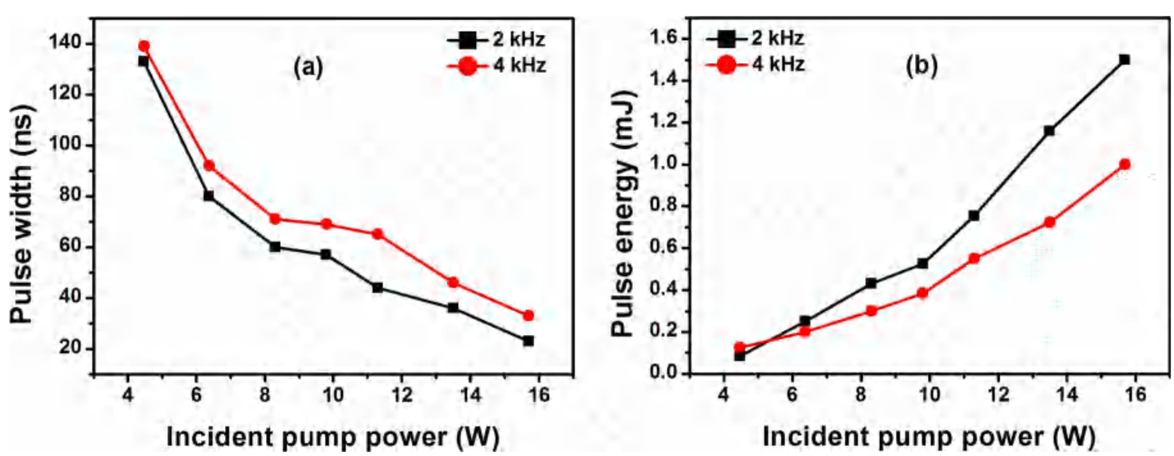

Fig. 4. (a) Pulse widths and (b) pulse energies of EO Q-switched Ho:YAP laser under different pump powers and repetition rates.

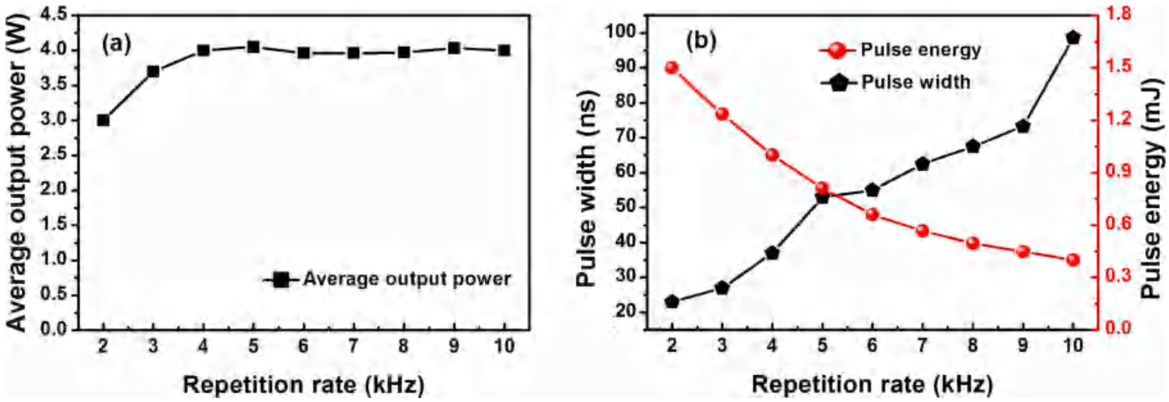

Fig. 6. (a) Average output powers and (b) pulse widths and pulse energies of EO Q-switched Ho:YAP laser versus repetition rates under the incident pump power of 16 W.

2118 nm. When the LGS EO modulator was placed in the cavity, the output powers of the static Ho:YAP laser were recorded (marked as inverted triangle symbol in Fig. 3). Due to the insertion loss of EO modulator, the maximum output power was reduced to 5 W with the corresponding slope efficiency of 37.7%. Then oscillation was shut down by rotating 1/4 wave plate, and Q-switching operation was realized when the quarter-wave voltage was supplied to drive the LGS crystal. At a repetition rate of 4 kHz, a maximum output power of 4 W was obtained with a slope efficiency of 31% (circle symbol). The corresponding pulse width was 30 ns, and the single pulse energy was 1 mJ. To increase the pulse peak power, the repetition rate was decreased to 2 kHz. Under the maximum pump power, an output power of 3 W was realized with a slope efficiency of 25.3% (square symbol). A single pulse energy of 1.5 mJ was achieved with the shortest pulse width of 23 ns, which approximated the rise time of Pockels cell driver, and limited the further shortening of the pulse. Fig. 4 shows the corresponding relationships between the pulse widths, single pulse energies and incident pump powers at repetition rates of 2 kHz and 4 kHz. At the repetition frequency of 2 kHz, the pulse width decreased from 130 ns to 23 ns and the single pulse energy increased from 0.1 mJ to 1.5 mJ. The corresponding temporal pulse train and single pulse shape obtained at the repetition rate of 2 kHz were shown in Fig. 5, and the pulse-to-pulse amplitude fluctuation was measured to be about 5%. At higher repetition rates, the output Q-switched pulse stability would slightly get worse, which was induced by the relatively long fluorescence lifetime 6 ms of Ho:YAP crystal. However, the pulse stability could be enhanced by increasing the pump power intensity. The very little fluctuation following the single pulse profile in the bottom part of Fig. 5 was induced by the noise originating from the electrical signal for EO modulator. When the repetition frequency was set at 4 kHz, the pulse duration was increased to be 33 ns, and the maximum single pulse energy was reduced to be 1 mJ. The inset part of Fig. 3 also records the output spectrum of the EO Q-switched Ho:YAP laser. The center wavelength was 2118.6 nm with a FWHM of 0.3 nm. Due to the insertion loss of the electro-optic modulator, the laser mode with relatively small gain was suppressed compared with the CW case, thus the loss induced spectrum narrowing effect occurred.

Under the maximum incident pump power of 16 W, the output characteristics of EO Q-switched Ho:YAP laser were also investigated under different repetition frequencies as shown in Fig. 6. The average output powers increased from 3 W to 4 W with repetition rates varying from 2 kHz to 4 kHz. However, the average output powers were almost invariable when the repetition rate exceeded 4 kHz until 10 kHz. Under the same pump power, the single pulse energies decreased from 1.5 mJ to 0.4 mJ while the pulse durations increased from 23 ns to 99 ns with the repetition rates increasing from 2 kHz to 10 kHz.

4. Conclusions

In conclusion, an in-band pumped LGS EO Q-switched Ho:YAP laser was demonstrated for the first time, to the best of our knowledge. The EO modulator was designed to operate in pulse-on mode with a relatively low 1/4 wave voltage of 2400 V. A maximum CW output power of 6.5 W was obtained from the Ho:YAP laser with a slope efficiency of 50.6%. Under EO Q-switching regime, a maximum output power of 4 W was obtained with a single pulse energy of 1 mJ and a pulse width of 33 ns at a repetition rate of 4 kHz. At the repetition rate of 2 kHz, the maximum single pulse energy of 1.5 mJ and the shortest pulse width of 23 ns were obtained, corresponding to a pulse peak power of as high as 65 kW. The experimental results well indicate that LGS modulator can operate under comparably low driving voltage and generate nanosecond pulses with high peak powers and pulse energies for Ho-doped lasers at 2.1 μm.

5. Founding

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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.

References

[1] X.M. Duan, B.Q. Yao, Y.J. Zhang, C.W. Song, L.L. Zheng, Y.L. Ju, Y.Z. Wang, Diode-pumped high efficient Tm:YLF laser output at 1908 nm with near-diffraction limited beam quality, Laser Phys. Lett. 5 (5) (2008) 347–349 https://iopscience.iop.org/article/10.1002/lapl.200810002.

[2] L. Wei, L. Xiao, L. Hang, J.Y. Wu, K.Q. Wang, ZGP optical parametric oscillator pumped by Tm:YAP Laser, Chinese J. Lasers 39 (7) (2012) 0702006 http://en.cnki.com.cn/Article_en/CJFDTotal-JJZZ201207005.htm.

[3] Y.J. Shen, B.Q. Yao, X.M. Duan, Y.L. Ju, Y.Z. Wang, Q-switched operation of a-cut Ho:$YAlO_3$ laser pumped by a diode-pumped 1.91 μm thulium laser, Laser Phys. 22 (4) (2012) 661–663.

[4] B.Q. Yao, L.L. Zheng, X.T. Yang, T.H. Wang, X.M. Duan, G.J. Zhao, Q. Dong, Judd-Oflet analysis of spectrum and laser performance of Ho:YAP crystal end-pumped by 1.9-μm Tm:YLF laser, Chinese Phys. B. 18 (03) (2009) 1009–1013.

[5] B.Q. Yao, X. Mi, L.L. Duan, Y.L.Ju. Zheng, Y.Z. Wang, G.J. Zhao, Q. Dong, Continuous-wave and Q-switched operation of a resonantly pumped Ho:$YAlO_3$

laser, Opt. Express 16 (19) (2008) 14668–14674.
[6] H.B. Premkumar, B.S. Ravikumar, D.V. Sunitha, H. Nagabhushana, S.C. Sharma, M.B. Savitha, R.P.S. Chakradhar, Investigation of structural and luminescence properties of Ho^{3+} doped $YAlO_3$ nanophosphors synthesized through solution combustion route, Spectrochim. Acta Part A Mol. Biomol. Spectrosc. 115 (2013) 234–243.
[7] 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 125 (15) (2014) 3943–3945 https://www.sciencedirect.com/science/article/pii/S0030402614003337.
[8] R.L. Zhou, Y.L. Ju, W.G.L. Zhu, Y.Z. Wang, Acousto-optic Q-switched operation Ho:YAP laser pumped by a Tm-doped fiber laser, Chin. Phys. Lett. 28 (7) (2011) 074210 https://iopscience_iop.gg363.site/article/10.1088/0256-307X/28/7/074210/meta.
[9] X.T. Yang, X.Z. Ma, W.H. Li, Y. Liu, Q-switched Ho:YAlO3 laser pumped by Tm:YLF laser at room temperature, Laser Phys. 21 (12) (2011) 2064–2067 https://link_springer.gg363.site/article/10.1134/S1054660X11210262.
[10] C. Yao, X.T. Yang, W.H. Li, A high efficiency Ho:$YAlO_3$ laser pumped by Tm:YLF laser with a Volume Bragg Grating, Laser Phys. 22 (3) (2012) 499–502 https://link_springer.gg363.site/article/10.1134/S1054660X12030267.
[11] X.M. Duan, B.Q. Yao, G. Li, T.H. Wang, X.T. Yang, Y.Z. Wang, G.J. Zhao, Q. Dong, High efficient continuous wave operation of a Ho:YAP laser at room temperature, Laser Phys. Lett. 6 (4) (2009) 279–281 https://onlinelibrary_wiley.gg363.site/doi/abs/10.1002/lapl.200810130.
[12] L.J. Li, X.N. Yang, L. Zhou, W.Q. Xie, Y.F. Bai, G.C. Ye, Y.J. Shen, Z.W. Lv, H. Zhang, M.H. Chen, Y.Q. Yang, W.L. Yang, X.M. Duan, BN as a saturable absorber for a passively mode-locked 2 μm solid-state laser, Physica Status Solidi (RRL)–Rapid Res. Lett. 13 (3) (2019) 1800482.
[13] T. Yu, G. Bai, Z.G. Yang, W.B. Chen, 20.2W CW 2.118 μm Ho:$YAlO_3$ laser pumped by 1915 nm Tm-doped fiber laser, Proc. of SPIE 9466 (2015) 94660U-1 https://www.spiedigitallibrary.org/conference-proceedings-of-spie/9466/94660U/202W-CW-2118%CE%BCm-Ho-YAlO3-laser-pumped-by-1915nm/10.1117/12.2177643.short?SSO=1.
[14] Z. Cui, X.M. Duan, B.Q. Yao, J. Li, X.L. Li, T.Y. Dai, C.Y. Li, Y.B. Pan, Resonantly pumped 2.118 μm Ho:YAP laser Q-switched by a Cr^{2+}:ZnS as a saturable absorber, Laser Phys. Lett. 12 (2015) 105002.
[15] T. Yu, X. Ye, Z. Yang, et al., All fiber thulium-doped fiber laser pumped Q-switched Ho:YAP laser//Fourth International Symposium on Laser Interaction with Matter, Int. Soc. Opt. Photon. 10173 (2017) 101731M https://www.spiedigitallibrary.org/conference-proceedings-of-spie/10173/101731M/All-fiber-thulium-doped-fiber-laser-pumped-Q-switched-Ho/10.1117/12.2268326.short.
[16] X.M. Duan, L.J. Li, Y.J. Shen, B.Q. Yao, Efficient Ho:YAP laser dual end-pumped by a laser diode at 1.91 μm in a wing-pumping scheme, Appl. Phys. B 124 (9) (2018) 179 https://link_springer.gg363.site/article/10.1007/s00340-018-7053-3.
[17] L.J. Li, X.N. Yang, L. Zhou, W.Q. Xie, Y.F. Bai, G.C. Ye, Y.J. Shen, Z.W. Lv, H. Zhang, M.H. Chen, Y.Q. Yang, W.L. Yang, X.M. Duan, Active/passive Q-switching operation of 2 μm Tm, Ho:YAP laser with an acousto-optical Q-switch/Mo_S2 saturable absorber mirror, Photon. Res. 6 (2018) 614–619 https://www.osapublishing.org/prj/abstract.cfm?uri=prj-6-6-614.
[18] L. Jin, P. Liu, H.T. Huang, X. Liu, D.Y. Shen, Short pulse diode-pumped Tm:YAG slab laser electro-optically Q-switched by $RbTiOPO_4$ crystal, Opt. Mater. 60 (2016) 350–354 https://www.sciencedirect.com/science/article/abs/pii/S0925346716304165.
[19] L. Guo, S.Z. Zhao, T. Li, K.J. Yang, W.C. Qiao, D.C. Li, G.Q. Li, S.Y. Zhang, J.T. Bian, L.H. Zheng, L.B. Su, J. Xu, Diode-wing-pumped electro-optically Q-switched 2 μm laser with pulse energy scaling over ten millijoules, Opt. Express 26 (2018) (2018) 17731–17738 https://www.osapublishing.org/abstract.cfm?uri=oe-26-13-17731.
[20] S.H. Ma, D.Z. Lu, H.H. Yu, H.J. Zhang, X.K. Han, Q.M. Lu, C.Q. Ma, J.Y. Wang, Langasite electro-optic Q-switched 2 μm laser with high repetition rates and reduced driven voltages, Opt. Commun. 447 (15) (2019) 13–17 https://www.sciencedirect.com/science/article/abs/pii/S0030401819303062.
[21] H. Fonnum, E. Lippert, M.W. Haakestad, 550 mJ Q-switched cryogenic Ho:YLF oscillator pumped with a 100 W Tm:fiber laser, Opt. Lett. 38 (11) (2013) 1884–1886 https://www.osapublishing.org/abstract.cfm?uri=ol-38-11-1884.
[22] Y.C. Li, Q.P. Wang, S.J. Zhang, X.Y. Zhang, Z.J. Liu, Z.F. Jiang, Z.J. Liu, S.T. Li, A novel $La_3Ga_5SiO_{14}$ electro-optic Q-switched Nd:LiYF (Nd:YLF) laser with a Cassegrain unstable cavity, Opt. Commun. 244 (1) (2005) 333–338 https://www.sciencedirect.com/science/article/abs/pii/S0030401804009514.