Actively Q-Switching in the Intra-Cavity Pumping Mechanism for Polarized Oscillation at 2.1 \( \mu \text{m} \)

HAIZHOU HUANG\(^{1,2}\), HUAWEN HU\(^{1,3}\), YAN GE\(^{1,2}\), HONGCHUN WU\(^{1,3}\), JINHUI LI\(^{1,2}\), HUAGANG LIU\(^4\), AND WENXIONG LIN\(^{1,2}\)

\(^{1}\)Key Laboratory of Optoelectronic Materials Chemistry and Physics, Fujian Institute of Research on the Structure of Matter, Chinese Academy of Sciences, Fuzhou 35002, China
\(^{2}\)Fujian Science and Technology Innovation Laboratory for Optoelectronic Information of China, Fuzhou 350108, China
\(^{3}\)University of Chinese Academy of Sciences, Beijing 100049, China
\(^{4}\)Department of Electrical and Computer Engineering, National University of Singapore, Singapore 117576

Corresponding author: Wenxiong Lin (wxlin@fjirsm.ac.cn)

This work was supported in part by the National Key Research and Development Program of China under Grant 2018YFB0407400, in part by the Natural National Science Foundation of China (NSFC) under Grant 61875200, and in part by the National Science Foundation for Young Scientists of China under Grant 61905246.

**ABSTRACT** Q-switched and polarized Ho lasers are the ideal driving source for mid-infrared radiation via optical parametric oscillation. Although intra-cavity pumping is an efficient way to achieve the Ho laser oscillation at 2.1 \( \mu \text{m} \), which also facilitates the direct use of common diodes in a compact structure, it was demonstrated to be not suitable for Q-switching due to the saturable effect of the Ho-doped gain medium. Here, we report a RbTiOPO\(_4\) Q-switched intra-cavity pumped laser via integrating the Tm-doped and Ho-doped gain medium into a composite structure and decoupling the Tm laser from the Ho laser before it was modulated by the RbTiOPO\(_4\) crystal. The shortest pulse of 41 ns at repetition frequency of 1 kHz was obtained with a peak power of 7.5 kW. By competing with the intensified self-pulsing, the maximum pulse repetition frequency was found to reach 7 kHz, which was half the driving frequency of the electro-optical modulator. The results pave the way for achieving regular pulses from the intra-cavity pumping mechanism, which facilitates a compact, accessible and robust pulse source at 2.1 \( \mu \text{m} \).

**INDEX TERMS** Electrooptic effects, pulse modulation, holmium, solid lasers.

I. INTRODUCTION

Wavelengths above 2 \( \mu \text{m} \) are far away from the two-photon absorption bands of the famous non-oxide mid-infrared crystals such as ZnGeP\(_2\) and OP:GaAs [1]. These crystals made pulse Ho lasers with emission ranges from 2.05 to 2.1 \( \mu \text{m} \) into excellent driving sources for nonlinear frequency conversion toward the molecular fingerprint region of 3–14 \( \mu \text{m} \) [2]–[4]. In addition, Ho lasers are valuable in the real world and have been widely applied in surgeries, lidar applications, atmospheric monitoring, and so on [5]–[7].

In-band pumping of the unsensitized Ho-doped gain medium with 1.9 \( \mu \text{m} \) lasers had become a dominant way to achieve pulse operation at 2.1 \( \mu \text{m} \) for the past two decades [8]–[10], as the traditional Tm, Ho co-doped mechanism had severe upconversion losses at room temperature [11], [12].

However, accessibility and compactness of the in-band pumped lasers was limited by the available 1.9 \( \mu \text{m} \) pump sources such as Tm-doped bulk or fiber lasers and the GaSb diode. Basically, the conventional Tm laser pumped Ho laser is a bulky cascade mechanism [13], where additional setup for the high-power Tm laser systems is required [14]. Owing to the broad emission spectrum and the significant wavelength-drift of the mid-infrared diode lasers, delicate spectral and temperature control should be considered before pumping the Ho lasers with the expensive 1.9 \( \mu \text{m} \) diode [11], [15]. Hence, inserting the Tm-doped gain medium into the cavity of the Ho laser for intra-cavity pumping was recommended, which facilitated using the existing 800 nm diodes for a compact Ho laser at room temperatures [16]–[18]. However, such a mechanism was shown to be unsuitable for achieving active Q-switching, where irregular pulse trains occurred after the acousto-optic modulator was inserted and set with the driving frequencies of 5 to 15 kHz [16]. This was attributed to the...
The pump waist radius inside the Tm-doped region was an aperture of 0.22, which was collimated and focused by two 785 nm diode with a core diameter of 400 μm. The pump source was a fiber-coupled water cooling at 16 °C. The pump source was a fiber-coupled 785 nm diode with a core diameter of 400 μm and a numerical aperture of 0.22, which was collimated and focused by two identical plano-convex lenses with a focal length of 35 mm. The pump waist radius inside the Tm-doped region was calculated to be approximately 230 μm. A plano-concave cavity consisting of the end-mirror (EM) and the output coupler (OC) was applied. EM was a plano-plano mirror coated for anti-reflection at 785 nm and high reflection (HR) at 1900 nm to 2100 nm; OC was a plano-concave mirror with a curvature of radius of 200 mm, which was coated for anti-reflection at 785 nm and high reflection (HR) at Tm laser (2000nm–2020 nm) and had a transmittance of 10% at Ho laser (2090 nm–2130 nm). A spectral filter (SF) coated to HR the Tm laser (2000nm–2020 nm) and had a transmittance of 10% at Ho laser (2090 nm–2130 nm). A spectral filter (SF) coated to HR the Tm laser (R>97%) and AR the Ho laser (T≥99.5%) was inserted intra-cavity for decoupling a Tm laser, A and the acceptable mode radii inside the thermal lens centers of the Tm-doped and Ho-doped regions; \( \sigma_{Ho}^L_{Tm} \) and \( \sigma_{Ho}^L_{Ho} \) are the absorption coefficient and gain coefficient of the Ho-doped and Tm-doped regions with lengths of \( L_{Ho} \) and \( L_{Tm} \), respectively; \( A_{Tm} \) and \( A_{Ho} \) are the mode radii inside the thermal lens centers of the Tm-doped and Ho-doped regions, \( \gamma \) is the gain coefficient \( g_{Tm} \) is the diode wavelength, \( \lambda_{Ho} = 785 \text{ nm} \) is the diode wavelength, \( \lambda_{Tm} = 2097 \text{ nm} \) is wavelength of the Tm laser, \( \alpha_{Ho} \) is the diode absorption coefficient, and \( \sigma_{Ho}^L_{Tm} \) is the diode laser power.

\[
\frac{\alpha_{Ho}^L_{Ho}}{g_{Tm}^L_{Tm}} \times \frac{\sigma_{Ho}^L_{Ho}}{\alpha_{Tm}^L_{Tm}} \times \frac{A_{Tm}}{A_{Ho}} < \gamma
\]

where \( \alpha_{Ho} \) and \( g_{Tm} \) are the absorption coefficient and gain coefficient of the Ho-doped and Tm-doped regions with lengths of \( L_{Ho} \) and \( L_{Tm} \), respectively; \( A_{Tm} \) and \( A_{Ho} \) are the mode radii inside the thermal lens centers of the Tm-doped and Ho-doped regions; \( \sigma_{Ho}^L_{Ho} \) and \( \sigma_{Tm}^L_{Tm} \) are the absorption cross section and emission cross section of the Ho-doped and Tm-doped regions, respectively, \( \gamma \) is 1 for a four-level laser and 2 for a three-level laser. Here, \( \gamma \) is 1 for creating a low Q-switching threshold. The gain coefficient \( g_{Tm} \) is

\[
g_{Tm} = \frac{\eta_{QY} P_p \lambda \beta}{L_{Ho}^\lambda_{Tm} \pi \omega_{Tm}^5 + P_p}
\]

where \( \eta_{QY} = 1.97 \) is the quantum yield of \( Tm^{3+} \) ions [22], \( P_p \) is the absorbed diode pump power, \( \lambda \beta = 785 \text{ nm} \) is the diode wavelength, \( \lambda_{Tm} = 2097 \text{ nm} \) is wavelength of the Tm laser, \( \alpha_{Ho} \) is the diode absorption coefficient, and \( \sigma_{Ho}^L_{Tm} \) is the diode laser power.

\[
\frac{\alpha_{Ho}^L_{Ho}}{g_{Tm}^L_{Tm}} \times \frac{\sigma_{Ho}^L_{Ho}}{\alpha_{Tm}^L_{Tm}} \times \frac{A_{Tm}}{A_{Ho}} < \gamma
\]

where \( \alpha_{Ho} \) and \( g_{Tm} \) are the absorption coefficient and gain coefficient of the Ho-doped and Tm-doped regions with lengths of \( L_{Ho} \) and \( L_{Tm} \), respectively; \( A_{Tm} \) and \( A_{Ho} \) are the mode radii inside the thermal lens centers of the Tm-doped and Ho-doped regions; \( \sigma_{Ho}^L_{Ho} \) and \( \sigma_{Tm}^L_{Tm} \) are the absorption cross section and emission cross section of the Ho-doped and Tm-doped regions, respectively, \( \gamma \) is 1 for a four-level laser and 2 for a three-level laser. Here, \( \gamma \) is 1 for creating a low Q-switching threshold. The gain coefficient \( g_{Tm} \) is

\[
g_{Tm} = \frac{\eta_{QY} P_p \lambda \beta}{L_{Ho}^\lambda_{Tm} \pi \omega_{Tm}^5 + P_p}
\]

where \( \eta_{QY} = 1.97 \) is the quantum yield of \( Tm^{3+} \) ions [22], \( P_p \) is the absorbed diode pump power, \( \lambda \beta = 785 \text{ nm} \) is the diode wavelength, \( \lambda_{Tm} = 2097 \text{ nm} \) is wavelength of the Tm laser, \( \alpha_{Ho} \) is the diode absorption coefficient, and \( \sigma_{Ho}^L_{Tm} \) is the diode laser power.

\[
\frac{\alpha_{Ho}^L_{Ho}}{g_{Tm}^L_{Tm}} \times \frac{\sigma_{Ho}^L_{Ho}}{\alpha_{Tm}^L_{Tm}} \times \frac{A_{Tm}}{A_{Ho}} < \gamma
\]

where \( \alpha_{Ho} \) and \( g_{Tm} \) are the absorption coefficient and gain coefficient of the Ho-doped and Tm-doped regions with lengths of \( L_{Ho} \) and \( L_{Tm} \), respectively; \( A_{Tm} \) and \( A_{Ho} \) are the mode radii inside the thermal lens centers of the Tm-doped and Ho-doped regions; \( \sigma_{Ho}^L_{Ho} \) and \( \sigma_{Tm}^L_{Tm} \) are the absorption cross section and emission cross section of the Ho-doped and Tm-doped regions, respectively, \( \gamma \) is 1 for a four-level laser and 2 for a three-level laser. Here, \( \gamma \) is 1 for creating a low Q-switching threshold. The gain coefficient \( g_{Tm} \) is

\[
g_{Tm} = \frac{\eta_{QY} P_p \lambda \beta}{L_{Ho}^\lambda_{Tm} \pi \omega_{Tm}^5 + P_p}
\]

where \( \eta_{QY} = 1.97 \) is the quantum yield of \( Tm^{3+} \) ions [22], \( P_p \) is the absorbed diode pump power, \( \lambda \beta = 785 \text{ nm} \) is the diode wavelength, \( \lambda_{Tm} = 2097 \text{ nm} \) is wavelength of the Tm laser, \( \alpha_{Ho} \) is the diode absorption coefficient, and \( \sigma_{Ho}^L_{Tm} \) is the diode laser power.

\[
\frac{\alpha_{Ho}^L_{Ho}}{g_{Tm}^L_{Tm}} \times \frac{\sigma_{Ho}^L_{Ho}}{\alpha_{Tm}^L_{Tm}} \times \frac{A_{Tm}}{A_{Ho}} < \gamma
\]

where \( \alpha_{Ho} \) and \( g_{Tm} \) are the absorption coefficient and gain coefficient of the Ho-doped and Tm-doped regions with lengths of \( L_{Ho} \) and \( L_{Tm} \), respectively; \( A_{Tm} \) and \( A_{Ho} \) are the mode radii inside the thermal lens centers of the Tm-doped and Ho-doped regions; \( \sigma_{Ho}^L_{Ho} \) and \( \sigma_{Tm}^L_{Tm} \) are the absorption cross section and emission cross section of the Ho-doped and Tm-doped regions, respectively, \( \gamma \) is 1 for a four-level laser and 2 for a three-level laser. Here, \( \gamma \) is 1 for creating a low Q-switching threshold. The gain coefficient \( g_{Tm} \) is

\[
g_{Tm} = \frac{\eta_{QY} P_p \lambda \beta}{L_{Ho}^\lambda_{Tm} \pi \omega_{Tm}^5 + P_p}
\]
higher diode power. According to the thermal model for intra-cavity pumped Ho lasers [17], \( f_{\text{Ho}} \) and \( f_{\text{Tm}} \) were calculated to be 88 mm and 76 mm respectively, where the cavity mode distribution of the Tm laser is depicted in Fig. 2b. Since \( A_{\text{Tm}}/A_{\text{Ho}} \) decreased with the increased thermal lens in the Ho-doped region, the PQS tends to be well suppressed with the increased diode power, which is conducive to a stable Q-switching modulated by the EOM.

**IV. RESULTS AND DISCUSSIONS**

**A. SELF-PULSING PHENOMENON OF THE HO LASER**

Before driving the EOM, maximum continuous-wave (CW) power of 1.32 W at 2097.7 nm from the OC was obtained (Fig. 3a). Besides, the leaked laser reflected by the polarizer was measured, which had a lower threshold (5.04 W) compared with the CW laser (7.05 W). This was attributed to the first oscillation in the Tm laser from the cavity consisting of EM and SF, since that SF had a small transmittance of 4% of the Tm laser. Further confirmation was made by the side-leaked Tm laser wavelength of 2019 nm (Fig. 3c), which was reflected by the polarizer. The formation of a polarized Ho laser was achieved with a polarization extinction ratio of 23 dB in the horizontal direction, where no Ho laser signal was detected from the side leakage light. Owing to the saturable effect of the Ho-doped region which modulated the Tm laser and gain-switched the Ho laser consequently, irregular self-pulsing was observed in the CW Ho laser and the side-leakage Tm laser, respectively (Fig. 3d).

In a smaller scope of 50 \( \mu \text{s/dv} \), these trains are easily mistaken as the Q-switching signals (Fig. 4a), where the pulse repetition frequency drifted within a broad range around 30 kHz (Fig. 4b) and the pulse width drifted within a range below 1 ms (Fig. 4c) at each pulse train. Correspondingly, drifting ranges of the peak power at different diode pump powers are calculated based on Figs. 4b and 4c. As shown in Fig. 4d, the upper peak power of the random pulse increased significantly with the increased absorbed pump power, which will be high enough to interrupt the electro-optical Q-switching especially at higher driving frequency.

**B. EXPLORING THE ACTIVELY Q-SWITCHING**

Starting the EOM and setting the driving frequency (DF) between 1 kHz and 5 kHz, a regular pulse train occurred at an absorbed diode power around 7.3 W (Fig. 1b). Figure 5a depicts the evolution in average Ho laser power with the increased pump power, where the maximum output power of 711 mW was obtained at a DF of 5 kHz. Decreasing the DF from 5 kHz to 1 kHz, the fitted slope efficiency decreased slightly from 13% to 11.4%, owing to the saturation in the power curve under the low DF. This saturation was caused by the increased EOM period for energy storage, where severe thermal lensing in the Ho-doped region occurred due to the intensified nonradiative transition [8]. Hence, the maximum average output powers were saturated...
FIGURE 5. Q-switching properties of the Ho laser at driving frequencies between 1 kHz and 5 kHz. (a) The evolutions in average output power and pulse frequency; (b) the evolutions in pulse width; (c) the calculated peak power.

FIGURE 6. Q-switching properties of the Ho laser at a driving frequency between 7 kHz and 14 kHz. (a) The evolutions in average output power and pulse frequency; (b) the evolutions in pulse width; (c) the calculated peak power (the shaded region denotes the estimated self-pulsing region in Fig. 4c).

At 318 mW and 352 mW, respectively, under the DF of 1 kHz and 2 kHz. Although a higher DF is conducive to relieving the thermal lens and increasing the output power, the half-frequency was observed at DFs of 4 kHz and 5 kHz, where the pulse repetition frequency (PRF) became half of the DF at the beginning of a stable pulse train. After increasing the diode power to 9.6 W and 10.2 W, respectively, for the DFs of 4 kHz and 5 kHz, the PRF could follow the DF. However, the half-frequency remained unchanged during the Q-switching processes at DFs between 7 kHz and 14 kHz (Fig. 6a, see Fig. 7a also for the pulse train at a DF of 14 kHz). Hence, this half-frequency is attributed to the insufficient accumulated pump intensity of the Tm laser at each EOM period, especially under low diode power or at the high DF. Neither a one-third DF frequency, nor a one-quarter DF frequency, was observed in a stable pulse train at DFs above 7 kHz, where the formation of these pulses is considered to be prohibited by the above twice EOM losses at each pulse period.

Before a stable pulse train, there existed a transition area where standard deviation (SDEV) of the PRF and the pulse width decreased from hundreds of Hz to below 1 Hz and from tens of nanoseconds to below 5 ns, respectively, as shown by the error bars in Figs. 5(a), 5(b), 6(a), and 6(b). With the measured PRF and pulse width, the evolutions in peak power of the Ho laser under different DFs are depicted in Figs. 5(c) and 6(c). Maximum peak power of 7.5 kW was obtained at PRF of 1 kHz, which corresponds to the shortest pulse with width of 41 ns. Compared with the smooth evolution in the pulse width, a step change occurred at the transition point between the half frequency and the full frequency of the DF, which was followed by a decrement in the peak power (Fig. 5c). Non-stable pulse behavior (the same as Fig. 3c was observed at a DF of 14 kHz when the diode power was increased above 10.2 W. Together with the observed threshold powers for stable Q-switching at different DFs (Figs. 5a and 6a), these are attributed to the competition between a regular pulse and the self-pulsing. Peak power of the Q-switching pulse should overwhelm that from random self-pulsing under the same pump power for a regular pulse train (Figs. 6c). However, the calculated peak powers from a regular pulse at PRF of 7 kHz (Fig. 7c) already fell within the estimated self-pulsing region (Fig. 6c). Hence, it was a challenge to obtain regular pulses at higher PRFs above 7 kHz, where the thermal stability of the current experimental configuration would need to be improved to achieve higher output power with shorter pulse widths to suppress the synchronously intensified self-pulsing.

Pulse delay with an increased DF was observed (Figs. 5b–5d), where the time separation between the falling edge of the driving signal and the front edge of the laser pulse increased from 350 ns at a DF of 1 kHz, to 610 ns at a DF of 7 kHz, at corresponding maximum output powers.
In conclusion, actively Q-switching in the intra-cavity pumping mechanism, the output wavelength was stabilized at a power of 720 mW at PRF of 6 kHz (Fig. 7e). During the Q-switching process, the output wavelength was stabilized at 2097.3±0.5 nm (Fig. 7f).

V. CONCLUSION

In conclusion, actively Q-switching in the intra-cavity pumping mechanism has been demonstrated here for realizing polarized pulse radiation at 2.1 μm, which was shown to be impossible due to the saturable effect of the Ho-doped gain medium. Regular pulse trains with PRF from 1 kHz to 7 kHz were obtained after suppressing the inherent self-pulsing caused by the saturable effect of the Ho-doped gain medium, where the shortest pulse, with a width of 41 ns and a peak power of 7.5 kW was obtained. In addition, half-frequency and pulse delay with the increased DF were observed due to the insufficient energy accumulation during the shorter pulse period at a higher DF. The results pave the way for achieving regular pulses from the intra-cavity pumping mechanism, which facilitates a compact, accessible, and robust pulse source at 2.1 μm.

REFERENCES

[1] P. G. Schunemann, “New nonlinear crystals for the mid-infrared,” in Proc. Nonlinear Opt., Honolulu, HI, USA, 2017, paper NTu2A.1.
[2] J. Zhang, K. F. Mak, N. Nagl, M. Seidel, D. Bauer, D. Sutter, P. Pervak, F. Krausz, and O. Pronin, “Multi-nW, few-cycle mid-infrared continuum spanning from 500 to 2250 cm⁻¹,” Light-Sci. Appl., vol. 7, p. 17180, Feb. 2018.
[3] S. Das, “Optical parametric oscillator: Status of tunable radiation in mid-IR to IR spectral range based on ZnGeP₂ crystal pumped by solid-state lasers,” Opt. Quantum Electron., vol. 51, no. 3, p. 47, Feb. 2019.
[4] D. Sanchez, M. Hemmer, M. Baudisch, S. L. Cousin, K. Zawilski, P. Schunemann, O. Chalus, C. Simon-Boisson, and J. Biegert, “7 μm, ultrafast, sub-millijoule-level mid-infrared optical parametric chirped pulse amplifier pumped at 2 μm,” Optica, vol. 3, no. 2, pp. 147–150, Feb. 2016.
[5] S. Hein, R. Petzold, R. Suarez-Ibarrola, P.-F. Müller, M. Schoenthaler, and A. Miernik, “Thermal effects of Ho: YAG laser lithotripsy during retrograde intrarenal surgery and percutaneous nephrolithotomy in an ex vivo porcine kidney model,” World J. Urol., vol. 38, no. 3, pp. 753–760, Mar. 2020.
[6] K. Mizutani, S. Ishii, M. Aoki, H. Iwai, R. Otsuka, H. Fukuoaka, T. Isikawa, and A. Sato, “2 μm Doppler wind lidar with a Tm: Fiber-laser-pumped Ho: YLF laser,” Opt. Lett., vol. 43, no. 2, pp. 202–205, Jan. 2018.
[7] T. F. Refaat, U. N. Singh, J. Yu, M. Petros, R. Remus, and S. Ismail, “Double-pulse 2-μm integrated path differential absorption lidar airborne validation for atmospheric carbon dioxide measurement,” Appl. Opt., vol. 55, no. 15, pp. 4232–4246, May 2016.
[8] L. Dai, C. Liu, X. Han, L. Wang, Y. Shao, and Y. Xu, “Effect of Ho²⁺ and Tm⁶⁺ concentration on UV-VIS-NIR and upconversion luminescence in Ho: Tm: LiNbO₃ crystals,” J. Alloys Compounds, vol. 771, pp. 960–963, Jan. 2019.
[9] M. Park, A. Tyazhev, P. Loiko, R. Soulard, J.-L. Doualan, L. Guillermot, A. Braud, T. Godin, P. Camy, and A. Hideur, “Passively mode-locked diode-pumped Tm, Ho: LiYF₄ laser,” Laser Phys. Lett., vol. 17, no. 4, p. 7, Apr. 2020.
[10] J. Tang, E. Li, F. Wang, W. Yao, C. Shen, and D. Shen, “High-power ho: YAP laser with 107 w of output power at 2117 nm,” IEEE Photon. J., vol. 12, no. 2, pp. l-1–l-7, Apr. 2020.
[11] E. Ji, Q. Liu, M. Nie, X. Cao, X. Fu, and M. Gong, “High-slope-efficiency 2.06 μm Ho: YLF laser in-band pumped by a fiber-coupled broadband diode,” Opt. Lett., vol. 41, no. 6, pp. 1237–1240, Mar. 2016.
[12] P. A. Budni, M. L. Lemons, J. R. Mosto, and E. P. Chicklis, “High-power/high-brightness diode-pumped 1.9-μm thulium and resonantly pumped 2.1-μm holmium lasers,” IEEE J. Sel. Topics Quantum Electron., vol. 6, no. 4, pp. 629–635, Jul. 2000.
[13] S. Lamrini, P. Koopmann, M. Schäfer, K. Scholle, and P. Fuhrberg, “Efficient high-power ho: YAG laser directly in-band pumped by a GaSb-based laser diode stack at 1.9 μm,” Appl. Phys. B, Lasers Opt., vol. 106, no. 2, pp. 315–319, Feb. 2012.
[14] B.-R. Zhao, B.-Q. Yao, C.-P. Qian, G.-Y. Liu, Y. Chen, R.-X. Wang, T.-Y. Dai, and X.-M. Duan, “231 W dual-end-pumped Ho: YAG MOPA system and its application to a mid-infrared ZGP OPO,” Opt. Lett., vol. 43, no. 24, pp. 5985–5992, Dec. 2018.
[15] A. Berrou, T. Tbachi, and M. Eichhorn, “High-energy resonantly diode-pumped Q-switched Ho³⁺: YAG laser,” Appl. Phys. B, Lasers Opt., vol. 120, no. 1, pp. 105–110, Jul. 2015.
[16] M. Schellhorn, A. Hirth, and C. Kieleck, “Ho: YAG laser intracavity pumped by a diode-pumped Tm: YLF laser,” Opt. Lett., vol. 28, no. 20, pp. 1933–1935, Oct. 2003.
[17] H. Huang, S. Liu, J. Li, Z. Lin, Y. Ge, S. Dai, J. Deng, and W. Lin, “Manipulating the wavelength-drift of a Tm laser for resonance enhancement in an intra-cavity pumped Ho laser,” Opt. Express, vol. 26, no. 5, pp. 5758–5768, Mar. 2018.
[18] X. Duan, L. Li, Z. Zheng, B. Yao, Z. Zou, D. Jiang, and L. Su, “Efficient intracavity-pumped Ho: SS-OA laser with cascaded in-band pumping scheme,” Infr. Phys. Technol., vol. 94, pp. 7–10, Nov. 2018.
[19] H. Huang, H. Hu, Z. Lin, J. Deng, J. Huang, H. Zheng, J. Li, and W. Lin, “Antisotropic thermal analyses of a high efficiency Tm: YAP slab laser and its intra-cavity pumping for Ho lasers,” Opt. Express, vol. 28, no. 14, pp. 20930–20942, Jul. 2020.
[20] X. Yang, H. Huang, D. Shen, H. Zhu, and D. Tang, “2.1 μm Ho:LaAG ceramic laser intracavity pumped by a diode-pumped Tm: YAG laser,” Chin. Opt. Lett., vol. 12, no. 12, p. 121405, Dec. 2014.
[21] Y. K. Kao and Y. A. Chang, “Numerical study of passive Q-switching of a Tm: YAG laser with a Ho: YLF solid-state saturable absorber,” Appl. Opt., vol. 42, no. 9, pp. 1685–1691, Mar. 2003.
Y. Li, W. Chen, H. Lin, D. Ke, G. Zhang, S. Zhu, and Z. Chen, “Comparative investigation of diode-wing-pumped tm: Y$_3$Al$_5$O$_{12}$ laser between composite and non-composite crystal,” Opt. Laser Technol., vol. 63, pp. 132–136, Nov. 2014.

M. Eichhorn, “Quasi-three-level solid-state lasers in the near and mid infrared based on trivalent rare Earth ions,” Appl. Phys. B, Lasers Opt., vol. 93, nos. 2–3, pp. 269–316, Nov. 2008.

J. J. Degnan, “Theory of the optimally coupled Q-switched laser,” IEEE J. Quantum Electron., vol. 25, no. 2, pp. 214–220, Feb. 1989.

HAIZHOU HUANG was born in Guangdong, China, in 1990. He received the B.S. degree in opto-electronic information engineering from Jinan University, Guangzhou, China, in 2013, and the Ph.D. degree from the University of Chinese Academy of Sciences, Beijing, China, in 2018. He is currently a Postdoctoral Researcher with the Key Laboratory of Optoelectronic Materials Chemistry and Physics, Fujian Institute of Research on the Structure of Matter, Chinese Academy of Sciences, Fuzhou, China. His research interests include mid-infrared laser technology and nonlinear optics.

HUAWEN HU was born in Jiangxi, China, in 1994. He received the B.S. degree in optical engineering from Nanchang University, Nanchang, China, in 2018. He is currently pursuing the master’s degree in optical engineering with the University of Chinese Academy of Sciences, Beijing, China. He carries out research with the Key Laboratory of Optoelectronic Materials Chemistry and Physics, Fujian Institute of Research on the Structure of Matter, Chinese Academy of Sciences, Fuzhou, China. His research interests include solid-state lasers and nonlinear optics.

YAN GE was born in Jiangxi, China, in 1984. She received the B.S. and master’s degrees from Northwest University, Xi’an, China, in 2005 and 2008, respectively. She is currently a Senior Engineer with the Key Laboratory of Optoelectronic Materials Chemistry and Physics, Fujian Institute of Research on the Structure of Matter, Chinese Academy of Sciences, Fuzhou. Her research interests include solid-state laser, nonlinear optics, and laser processing and applications.

HONGCHUN WU was born in Jiangxi, China, in 1981. He received the B.S. and master’s degrees from Fujian Normal University, Fuzhou, China, in 2004 and 2007, respectively. He is currently a Senior Engineer with the Key Laboratory of Optoelectronic Materials Chemistry and Physics, Fujian Institute of Research on the Structure of Matter, Chinese Academy of Sciences, Fuzhou. His research interests include lens design, solid-state laser, and nonlinear optics.

JINHUI LI was born in Fujian, China, in 1980. He received the B.S. degree from the Nanjing University of Aeronautics and Astronautics, Nanjing, China, in 2003, and the master’s degree from Fuzhou University, Fuzhou, China, in 2017. He is currently a Senior Engineer with the Key Laboratory of Optoelectronic Materials Chemistry and Physics, Fujian Institute of Research on the Structure of Matter, Chinese Academy of Sciences, Fuzhou. His research interest includes mechanical engineering and design.

HUAGANG LIU was born in Anhui, China, in 1981. He received the B.S. and Ph.D. degrees from Tianjin University, Tianjin, China, in 2005 and 2010, respectively. He was an Associate Professor with the Key Laboratory of Optoelectronic Materials Chemistry and Physics, Fujian Institute of Research on the Structure of Matter, Chinese Academy of Sciences, Fuzhou. He is currently a Research Fellow with the Faculty of Engineering, National University of Singapore. His current research interests include nonlinear optics and laser micro/nano machining.

WENXIONG LIN was born in Fujian, China, in 1966. He received the B.S. degree from Shanghai Jiao Tong University, Shanghai, China, in 1988, and the master’s and Ph.D. degrees from the Fujian Institute of Research on the Structure of Matter (FJIRSM), Chinese Academy of Sciences (CAS), Fuzhou, China. He is currently a Professor and an Associate Director of FJIRSM, CAS. He has authored or coauthored more than 80 articles in scientific researches. His research interests include solid-state lasers, nonlinear optics, laser applications, and additive manufacturing. He received two national science and technology prizes.

* * *