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$Ho:Sc_2SiO_5$ Saturable Absorber Passively Q-switched $Tm:YAlO_3$ Laser

BAI Bing[1] ZHU Bei-bei[1] ZHANG Bin[1] XUE Yu-chen[1]
YANG Xiao-tao[2] LI Li[1]

(1. School of Physics and Optoelectronic Engineering, Harbin Engineering University, Harbin 150001, China;
2. School of Power and Energy Engineering, Harbin Engineering University, Harbin 150001, China)

Abstract $Ho:Sc_2SiO_5$ (Ho:SSO) crystal as a new saturable absorber was firstly exploited in the passively Q-switched operation of $Tm:YAlO_3$ (Tm:YAP) laser. Under end pumping of 793 nm laser diode, Ho:SSO passively Q-switched Tm:YAP laser can generate robust microsecond pulse output at 1.88 μm wavelength. The 130 mW of average output power and 5.2 μJ of pulse energy were obtained with the pulse duration of 1.87 μs and repetition rate of 25 kHz. Further by incorporating an acousto-optic (AO) modulator, Ho:SSO-based hybrid Q-switched Tm:YAP laser was designed to compress pulse duration at hundreds of nanoseconds. The minimum pulse duration of 213 ns was achieved with the maximum pulse energy of 34 μJ at 4 kHz repetition rate. This work suggests an important application potential of Ho:SSO crystal as saturable absorber at 1.9 μm region.

Key words Ho:SSO crystal; Tm:YAP laser; passively Q-switched; hybrid Q-switched

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0 Introduction

Solid-state lasers at 1.9 μm eye-safe band have wide applications for laser ranging, remote sensing and space communication in atmosphere environment[1,2]. Tm-doped materials are the most widely used gain media to produce 1.9 μm lasing, which can be efficiently pumped by commercial laser diodes (LDs)[3-5]. Recently, a lot of Tm-doped materials were developed, such as Tm:YAP, Tm:YLF, Tm:LSO and Tm:YAG[6-9]. In particular, Tm:YAP can perform efficient operation at 1.9 μm region with linear polarization output owing to its natural birefringence[10,11]. Passively Q-switched operation can provide a simple way to obtain pulse output. Compared with actively Q-switching methods, passively Q-switching with saturable absorbers has advantages of compactness, simplicity and reliability[12-15]. Several kinds of materials, such as graphene-like two-dimensional (2D) nanomaterials, semiconductor saturable absorption mirrors (SESAMs) and Ho-doped crystals, have been used as the saturable absorbers for 1.9 μm pulse generation[16-20]. In 2017, Lan et al reported the diode-pumped continuous-wave laser operation of an *a*-cut $Tm:CaYAlO_4$ crystal in a two-mirror configuration at 1850 nm, by use of a MoS_2 saturable absorber deposited directly onto the surface of output coupler. The MoS_2 passively Q-switched laser generated a maximum output power of 490 mW with a narrowest pulse width of 0.48 μs[21]. In 2020, Sharbirin presented a $MoWS_2$ saturable absorber

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通讯作者:李立,男,汉族,博士,教授,研究方向:激光与太赫兹器件物理,E-mail:lylee_heu@hrbeu.edu.cn.

for passively Q-switched thulium-doped fiber laser operating at 1860 nm and 1930 nm. The $MoWS_2$ thin film was prepared as passive Q-switching element. The $MoWS_2$ passively Q-switched laser can operate at 1930 μm with a repetition rate of 66.3 kHz and pulse width of 2.1 μs. Further by employing a holmium-filter, the lasing wavelength shifted to 1860 nm while retaining maximum repetition rate of 48.9 kHz and narrowest pulse width of 2.3 μs[22]. Specifically, the graphene saturable absorbers have low damage threshold and unstable chemical properties so that they are hardly applied to high power operation[17]. The SESAMs are expensive and complex in preparation, but have fast relaxation time of intraband thermalization and interband transition which are preferable for ultrafast mode locking operation[18]. The Ho-doped crystals, including Ho:CaF_2, Ho:YVO_4 and Ho:YLF, were early used as saturable absorbers for 1.9 μm pulse laser[20,23,24]. They have high damage threshold and stability, and are suitable for the generation of high power short pulse output at sub-microsecond duration which is desirable in the lidar systems. Very recently, a new kind of holmium doped silicate crystal, Ho:Sc_2SiO_5 (Ho:SSO), was successfully prepared and showed infrared broadband absorption at 1.9 μm, high thermal conductivity and large energy splitting due to strong crystalline field[25,26]. The Ho:SSO crystal has negative refractive coefficient in thermally induced index change, which is helpful to limit thermal lens effect, crystallographic sites distortion and birefringence effects. Ho:SSO crystal has been suggested as a promising gain medium to produce 2.1 μm laser output[26-32]. However, the new Ho:SSO crystal as nonlinear saturable absorber has not been reported for passively Q-switched Tm-doped laser yet.

In the paper, Ho:SSO crystal as a new saturable absorber was firstly exploited in the passively Q-switched operation of Tm:YAP laser. In experiment, the Ho:SSO saturable absorber performed robust Q-switching operation, and the end-pumped Tm:YAP laser generated stable microsecond pulse output at 1.88 μm wavelength. Further by incorporating an acousto-optic modulator (AOM), hybrid Ho:SSO/AOM Q-switched Tm:YAP laser was designed to compress pulse duration at hundreds of nanoseconds. The Q-switched laser characteristics were discussed to support the important potential of Ho:SSO crystal as saturable absorber.

1　Experimental

Figure 1 shows the schematic of experimental setups with compact linear resonator configurations. Ho:SSO passively Q-switched Tm:YAP laser was carried out under the scheme of Fig. 1(a). Hybrid Q-switched Tm:YAP laser with Ho:SSO and AO modulator was built as the design of Fig. 1(b). A fiber-coupled LD at 793 nm wavelength was employed as the pump source with 30W of maximum output power. The core diameter of the fiber is 400 μm with a numerical aperture of 0.22. The pump beam was focused into Tm:YAP crystal by a couple of lenses with high transmission at 780-800 nm. The *c*-cut Tm:YAP laser crystal with 3 at.% dopant has the dimension of $3\times3\times8$ mm^3. Both end faces of the crystal were anti-reflection coated at both 1.9 μm and 793 nm bands. The crystal was wrapped in indium foil and mounted in a water-cooled copper heat sink with a constant temperature of 293 K for heat dissipation. A 0.5 at.% doped Ho:SSO crystal was used as saturable absorber, with the dimension of $5\times5\times30$ mm^3. The 48% initial transmission of the Ho:SSO sample was measured by a 1.9 μm laser source. Note that the long crystal

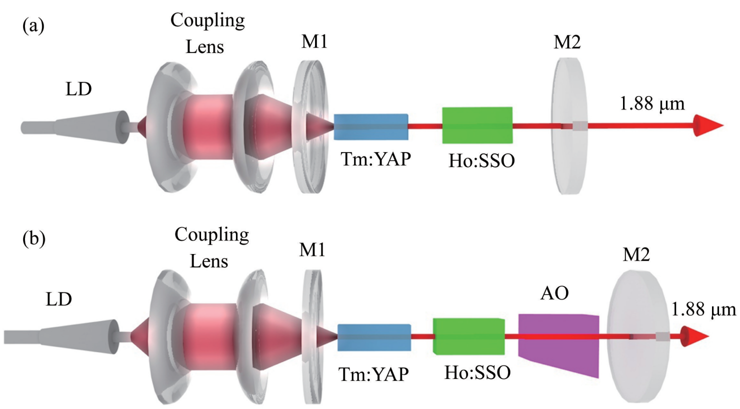

Figure 1　Schematic of experimental setups (a) Ho:SSO passively Q-switched Tm:YAP laser; (b) Hybrid Q-switched Tm:YAP laser with Ho:SSO and AO modulator

length has effect on the laser performance involving the increase of pump threshold and the reduction of laser output efficiency. Ho:SSO crystal was wrapped in indium foil and placed in another water-cooled copper heat sink with constant temperature of 286 K for heat dissipation. The input plane mirror (M_1) was anti-reflection coated at 780-800 nm ($R<0.5\%$) on one surface. The other surface was high-reflection coated at 1.9 μm band ($R>99.8\%$), meanwhile with high transmission ($T>99.8\%$) at 780-800 nm. The output coupler (M_2) is a plan-concave mirror with a curvature radius of 150 mm, which was coated at 1.9 μm band with 98% reflectance. Note that in Fig. 1(a), the Ho:SSO saturable absorber was placed in a resonator with 140 mm cavity length. In Fig. 1(b), the hybrid Q-switched Tm:YAP laser has a shared resonator with 145 mm cavity length for passively and actively Q-switched operation. The AOM was anti-reflection coated at 1.9 μm band on both faces and driven at 1-90 kHz radio frequency. The laser output was measured by a Coherent Field Maxll laser power meter and an InGaAs photo diode. The pulse trains were recorded by a 500 M digital oscilloscope. The spectra were monitored by an infrared monochromator with 0.1 nm resolution.

2 Results and discussion

Firstly, Ho:SSO passively Q-switched operation in an end-pumped Tm:YAP laser was implemented with the scheme of Fig. 1(a). As shown in Fig. 2, the laser output powers versus pump powers were measured. The laser cavity and the position of Ho:SSO saturable absorber were optimized in experiment. Under the absorbed pump power of 15.4 W, the output power of 130 mW was obtained experimentally. The slope efficiency was evaluated about 5% with linear fitting. The power threshold is around 12.6 W, which is higher than the threshold (~1.6 W) of continuous wave operation without Ho:SSO saturable absorber. Note that the output power of continuous wave Tm:YAP laser was measured to be 4.9 W under 14 W pump absorption power, with a slope efficiency of 40%. This indicates the notable insertion loss of Ho:SSO crystal, which results from the strong linear absorption limited by the preparation process of new silicate crystal and long crystal length. Under the maximum output of 130 mW, the pulse duration was measured to be around 1.87 μs with little temporal fluctuation. Figure 3 shows the typical pulses train in Ho:SSO passively Q-switched operation. Beyond the pump threshold, a train of output pulses with full depth of modulation was observed constantly, with the repetition rate varying with the pump power. As shown in Fig. 3, the robust Q-switched pulses were recorded by a digital oscilloscope under the maximum output of 130 mW. The repetition rate is about 25 kHz and the pulse profiles are highly symmetric in temporal shape.

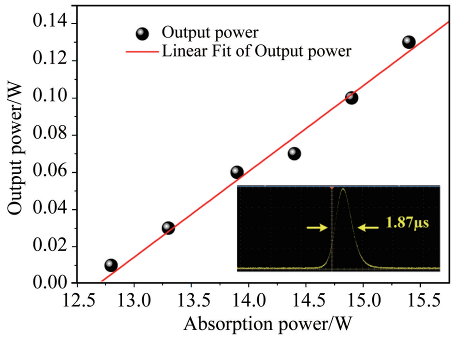

Figure 2 The laser output power versus pump power in passively Q-switched Tm:YAP laser. The inset: single pulse profile recorded by digital oscilloscope, with 1.87 μs duration at maximum output power of 130 mW

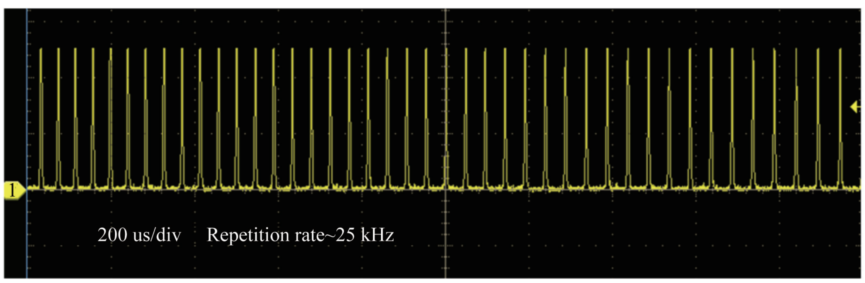

Figure 3 The temporal profiles of output pulse trains recorded by digital oscilloscope, with a repetition rate of 25 kHz at maximum output power of 130 mW

Figure 4 shows the experimental data of the pulse duration and repetition rate versus the pump power, as well as single pulse energy versus pump power. The results of Fig. 4 (a) indicate that the pulse duration varies from 6.0 μs down to 1.87 μs with the pump power increasing from 12.8 W to 15.4 W. Meanwhile, the repetition rate increases from 9.3 kHz to 25 kHz. Figure 4(b) shows the increase of single pulse energies with the pump power. The maximum pulse energy of 5.2 μJ was achieved under the pump power of 15.4 W.

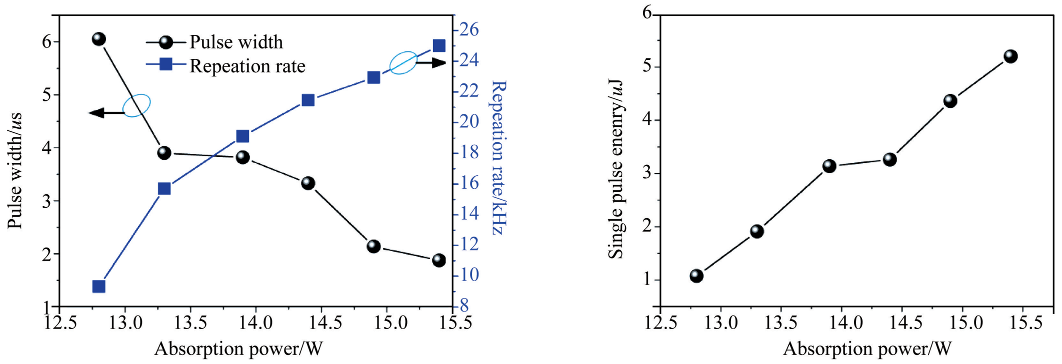

Figure 4　**The experimental data of (a) the pulse duration and repetition rate versus the pump power and (b) single pulse energy versus pump power**

Figure 5 shows the spectra measurement of laser output and beam profile. The results show that the Ho:SSO passively Q-switched Tm:YAP laser operated at 1.88 μm with the spectra width of 1.6 nm. Compared to the continuous wave Tm:YAP laser without Ho:SSO saturable absorber, the lasing wavelength of passively Q-switched operation made a notable shift away from the central wavelength of Tm:YAP gain spectra. This is closely associated with the absorption property of Ho:SSO at 1.9 μm region[26]. The beam profile measurement as shown by the inserts indicates good quality of fundamental transverse mode TEM00 in the operation.

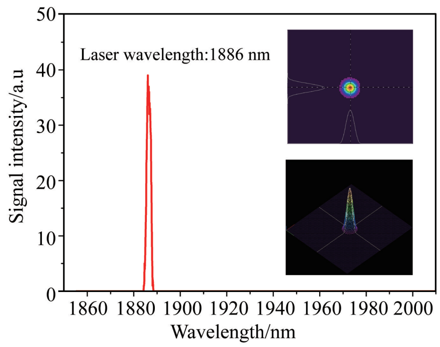

Figure 5　**The spectra measurement of laser output centered at** 1886 **nm. The insets: two and three dimensional profile of output laser beam**

Further by incorporating an AOM, hybrid Ho:SSO/AOM Q-switched Tm:YAP laser was designed to compress pulse duration at hundreds of nanoseconds[5,33]. Note that the introduction of AOM active element can improve the Ho:SSO Q-switched Tm:YAP operation due to the fast acousto-optic switching regime. This is helpful to obtain short pulse output at 1886 nm and keep stable inherently by the absorption property of Ho:SSO crystal[26]. The hybrid Q-switched operation was implemented with the scheme of Fig. 1(b). The experimental data of average output power, pulse energy and pulse width are summarized in Fig. 6. As shown in Fig. 6(a), the slope efficiencies of average output power were linearly fitted to be 2.0 %, 2.2%, 2.4% at various AOM frequencies of 4 kHz, 5 kHz and 6 kHz, respectively. The pump thresholds in the hybrid Q-switched operation were around 16.8 W. The maximum output power of 140 mW was obtained under the pump power of 19.1 W, with the pulse duration of 213 ns. In Fig. 6(b), single pulse energies were plotted as a function of pump power at various AOM frequencies. The maximum pulse energy of 34 μJ was obtained at the AOM frequencies of 4 kHz. Note that the increase of AOM frequency from 4 kHz to 6 kHz resulted in the reduction of output pulse energy. Meanwhile, the pulse durations were measured with the variation of pump power at different AOM frequencies, as shown in Fig. 6(c). The results suggest that a low modulation frequency is helpful to suppress pulse duration. The minimum pulse width of 213 ns was achieved at 4 kHz repetition rate. This indicates that with the help of an AOM, Ho:SSO-based hybrid Q-switched laser can produce short pulses at hundreds of nanoseconds. Additionally, the lasing spectra were monitored in experiment, which kept the same wavelength at 1.88 μm as that shown in Fig. 5.

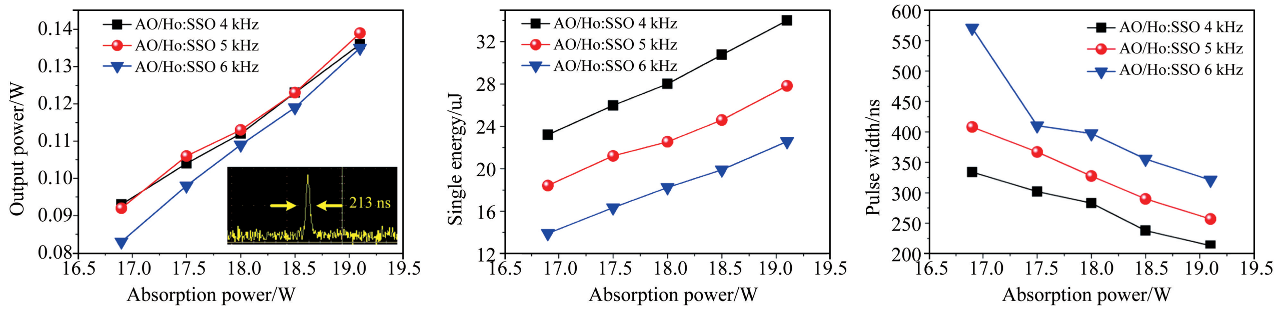

Figure 6 (a) The output laser power; (b) single pulse energy; (c) the pulse duration versus pump power at various AOM frequencies in hybrid Q-switched Tm:YAP laser. The inset: single pulse profile recorded by oscilloscope at maximum output

It is worth pointing out that under the hybrid Q-switching operation, the active Q-switching can restrict high repetition rate of Ho:SSO passive Q-switching and its dependence on pump power. This is helpful to improve pulse energy. Meanwhile, the fast acoustic-optic response of AOM element can restrict the Q-switching duration, which is helpful to suppress the pulse width. In the active Q-switching experiment without Ho:SSO saturable absorber, the reduction of cavity absorption losses resulted in the decrease of pump threshold and the increase of pulse energy. The threshold of pump absorption power was measured to be 3.6 W, which is much lower than that of hybrid Ho:SSO/AOM Q-switching operation about 16.8 W. But the pulse duration was not shortened notably. The lasing wavelength did not keep stable at 1886 nm any more, and made a notable shift towards long wavelength with poor wavelength stability due to the lack of Ho:SSO absorption stabilization regime[26]. Thereby this indicates that Ho:SSO crystal has positive effect on improving the Q-switching wavelength stability; and it cooperates with active Q-switching to narrow the pulse width, showing the advantages of hybrid Q-switching schemes[5].

3 Conclusions

In conclusion, we have presented that Ho:SSO crystal can be used as saturable absorber to perform passively Q-switching operation in Tm:YAP laser at 1.9 μm region. Under end pumping of 793 nm laser diode, Ho:SSO passively Q-switched Tm:YAP laser generated robust pulse output at 1.88 μm wavelength. The maximum output power and pulse energy were obtained about 130 mW and 5.2 μJ, respectively, with the pulse duration of 1.87 μs and repetition rate of 25 kHz. Furthermore, hybrid Ho:SSO/AOM Q-switched Tm:YAP laser was designed to compress pulse duration. The minimum pulse width of 213 ns was achieved with the pulse energy of 34 μJ at 4 kHz repetition rate. This work shows an important application potential of Ho:SSO crystal as saturable absorber.

References

[1] Singh U N, Walsh B M, Yu J, et al. Twenty years of Tm:Ho:YLF and LuLiF laser development for global wind and carbon dioxide active remote sensing[J]. Opt Mater Express, 2015, 5(4): 827-837.

[2] 杨亚铃,杨克建,赵圣之,等. 2 μm 波段锁模固体激光研究进展[J]. 聊城大学学报(自然科学版), 2019, 32(2): 22-33.

[3] Li J, Yang S H, Zhao C M, et al. High efficient single-frequency output at 1991 nm from a diode-pumped Tm:YAP coupled cavity[J]. Opt Express, 2010, 18(12): 12161-12167.

[4] Liu J J, Zhang C, Zhang Z, et al. 1886-nm mode-locked and wavelength tunable Tm-doped CaF_2 lasers[J]. Opt Lett, 2019, 44(1): 134-137.

[5] Li L J, Yang X N, Zhou L, et al. Active/passive Q-switched operation of 2 μm Tm, Ho: YAP laser with an acousto-optical Q-switch/MoS_2 saturable absoraber mirror[J]. Photon Res, 2018, 6(6): 614-619.

[6] Cole B, Goldberg L. Highly efficient passively Q-switched Tm: YAP laser using a Cr: ZnS saturable absorber[J]. Opt Lett, 2017, 42(12): 2259-2262.

[7] Faoro R, Kadankov M, Parisi D, et al. Passively Q-switched Tm: YLF laser[J]. Opt Lett, 2012, 37(9): 1517-1519.

[8] Feng T L, Zhao S Z, Yang K J, et al. Diode-pumped continuous wave tunable and graphene Q-switched Tm: LSO lasers[J]. Opt Lett, 2013, 21(21): 24665-24673.

[9] Lai K S, Phua P B, Wu R F, et al. 120-W continuous-wave diode-pumped Tm: YAG laser[J]. Opt Lett, 2000, 25(21): 1591-1593.

[10] Stoneman R, Esterowitz L. Efficient 1.94 μm Tm: YALO laser[J]. IEEE J Sel Top Quantum Electron, 1995, 1(1): 78-81.

[11] Elder I, Payne M. Lasing in diode-pumped Tm: YAP, Tm, Ho: YAP and Tm, Ho: YLF[J]. Opt Commun, 1998, 145(1-6): 329-339.

[12] 王强国，崔娜，姚勇平，等. 基于 MoS_2 可饱和吸收的 Nd：$ScYSiO_5$晶体调 Q 激光特性研究[J]. 聊城大学学报(自然科学版)，2019，32(5)：32-36.

[13] Li L J, Yao B Q, Song C W, et al. Continuous wave and AO Q-switch operation Tm, Ho: YAP laser pumped by a laser diode of 798 nm[J]. Laser Phys Lett, 2009, 6(2): 102-104.

[14] Zu Y Q, Zhang C, Wu Y J, et al. Graphene oxide for diode-pumped Tm: YLF paasively Q-switched laser at 2 μm[J]. Chin Opt Lett, 2018, 16(2): 020013.

[15] Yu J R, Trieu B C, Modlin E A, et al. 1 J/pulse Q-switched 2 μm solid-state laser[J]. Opt Lett, 2016, 31(4): 462-464.

[16] 郭波，欧阳秋云，李施，等. 基于石墨烯三元复合材料的双波长孤子激光器[J]. 中国激光，2017，44(7)：0703012.

[17] Wang Q, Teng H, Zou Y W, et al. Graphene on SiC as a Q-switcher for a 2 μm laser[J]. Opt Lett, 2012, 37(3): 395-397.

[18] Luan C, Yang K, Zhao J, et al. Diode-pumped mode-locked Tm: LuAG laser at 2 μm based on GaSb-SESAM[J]. Opt Lett, 2017, 42(4): 839.

[19] 王江，汪太进，刘思聪，等. 基于 Langmuir-Blodgett 技术制备的二硫化钨可饱和吸收体在调 Q 固体激光器中的研究[J]. 聊城大学学报(自然科学版)，2019，32(5)：15-18.

[20] Kuo Y K, Birnbaum M. Ho: YVO_4 solid-state saturable-absorber Q switch for a 2-μm Tm, Cr: $Y_3Al_5O_{12}$ laser[J]. Appl Opt, 1996, 35(6): 881-884.

[21] Lan J, Zhang X, Zhou Z, et al. Passively Q-switched Tm: $CaYAlO_4$ laser using a MoS_2 saturable absorber[J]. IEEE Photon Technol Lett, 2017, 29(6): 515-518.

[22] Sharbirin A S, Ahmad H, Ismail M F. Q-switched thulium-doped fiber laser at 1860 nm and 1930 nm using a holmium-doped fiber as an amplified spontaneous emission filter[J]. Opt Laser Technol, 2020, 123: 105908.

[23] Kuo Y K, Birnbaum M, Unlu Ferruh, et al. Ho: CaF_2 solid-state saturable-absorber Q switch for the 2-μm Tm, Cr: $Y_3Al_5O_{12}$ laser[J]. Appl Opt, 1996, 35(15): 2576-2579.

[24] Kuo Y K, Birnbaum M. Numerical study of passive Q switching of a Tm: YAG laser with a Ho: YLF solid-state saturable absorber[J]. Appl Opt, 2003, 42(9): 1685-1691.

[25] 李璇，麻尉蔚，马凤凯，等. Ho^{3+}掺杂 Sc_2SiO_5激光晶体生长与光谱性能研究[J]. 人工晶体学报，2014，43(6)：1327-1331.

[26] Yang X T, Yao B Q, Ding Y, et al. Spectral properties and laser performance of Ho: Sc_2SiO_5 crystal at room temperature[J]. Opt Express, 2013, 21(26): 32566-32571.

[27] Yang X T, Zhong W W, Zhao C X, et al. Narrow linewidth continuous wave Ho: SSO laser with Fabry-Perot etalons[J]. Opt Rev, 2015, 22(6): 893-896.

[28] Yang X T, Liu L, Xie W Q. Passively Q-switched Ho: SSO laser by use of a Cr^{2+}: ZnSe saturable absorber[J]. Chin Phys Lett, 2017, 34(2): 023201.

[29] Yang X T, Mu Y L, Zhao N B. Ho: SSO solid-state saturable-absorber Q switch for pulsed Ho: YAG laser resonantly pumped by a Tm: YLF laser[J]. Opt Laser Technol, 2018, 107: 398-401.

[30] Duan X M, Zhang W S, Li L J, et al. Electro-optically cavity-dumped Ho: SSO laser with a pulse width of 3.6 ns and linewidth of 70 pm[J]. Laser Phys, 2018, 29(1): 1-5.

[31] Duan X M, Li L J, Zheng L H, et al. Efficient intracavity-pumped Ho: SSO laser with cascaded in-band pumping scheme[J]. Infrared Phys Technol, 2018, 94: 7-10.

[32] Zhang W S, Duan X M, Li L J. High power Ho: SSO laser resonantly pumped by a FBG-locked Tm fiber laser at 1940.3 nm[J]. Optik, 2018, 175: 340-343.

[33] Wu C T, Ju Y L, Ke L, et al. Diode-pumped actively Q-switched Tm: YAG ring laser operation at room temperature[J]. Laser Phys, 2010, 20(6): 1279-1283.

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