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Ho:SSO solid-state saturable-absorber Q switch for pulsed Ho:YAG laser resonantly pumped by a Tm:YLF laser

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ABSTRACT

A Ho:SSO crystal was employed as an efficient saturable absorber Q switch for the pulsed Ho:YAG laser for the first time. The characteristics of the passive Q-switch Ho:YAG laser were studied with different incident pump power and different laser energy density around the Ho:SSO. The single pulsed energy varied from 8.3 μJ to 76.6 μJ with the increasing of the incident power from 2.2 W to 8.2 W. The maximum repetition rate was 42.1 kHz, and the minimum pulsed duration was 48 ns. The maximum single-pulse peak power was 1.53 kW. The output center wavelength shifted from 2090.1 nm (the continuous-wave mode) to 2091.3 nm (the passive Q-switch mode).

1. Introduction

Passive Q-switch (PQS) is no doubt one efficient approach to obtain high-power pulsed lasers, which has several obvious merits such as compact, simple and low-cost. The research on the PQS lasers in the 2-μm region has attracted a lot attentions due to its good application prospect in many areas (in instance medicine treatment and detection) [1,2]. The holmium (Ho^{3+}) ion is actually attractive for lasing in this region due its wavelength-tunable emission at ~2-μm ($^5I_7 \rightarrow {}^5I_8$ transition). A common scheme to excite Ho^{3+} is the energy transfer from Thulium (Tm^{3+}) ions, $^3F_4$ (Tm^{3+}) → $^5I_7$ (Ho^{3+}) by doping the host materials, which has a high quantum and convert efficiency [3]. Some relative researches (2-μm region lasers) have been reported, some of which adopt Tm, Ho codoped host materials and others separate Tm^{3+} and Ho^{3+} ions in independent host materials[4,5]. Merging Tm^{3+} and Ho^{3+} ions into one laser gain medium is suitable to realize a compact and simple laser system, which is only need one laser cavity and one diode laser around 0.8 μm. However, the thermal effect of the Tm,Ho codoped system maybe serious even fatal, which prefers to operate under low-temperature. So, in this work we separated the two ions into independent laser materials [6,7].

Single-doped Ho^{3+} ion PQS lasers have been demonstrated couple times using different SA. However, which is still in its early stage. In 2016, Mateos, X reported one PQS Ho:YAG ceramic lasers employing one single-walled carbon nanotubes (SWCNTs) and one Cr^{2+}:ZnSe crystal as the SA [8]. It can been seen according the comparison results, a higher repetition rate of 165 kHz was realized with the SWCNTs (the pulsed duration was 85 ns), a narrower pulsed duration of 12 ns was obtained with the Cr^{2+}:ZnSe SA (the repetition rate was 14.8 kHz). Similar work was demonstrated by Dai in the same year, in which a 41 kHz PQS Ho:YAP laser using a Cr^{2+}:ZnS SA was realized [9]. The repetition rate was 41.25 kHz with a pulsed duration of 382 ns. The graphene is also seem as an efficient SA for Ho PQS lasers. Yao reported a PQS Ho:YLF with a graphene SA in 2015, which had a maximum repetition rate of 59.2 kHz, corresponding to a minimum pulsed duration of 651.9 ns.

Sometimes, Ho ion doped host materials are also used as the SA in these 2-μm PQS lasers. In 1996, Kuo, YK demonstrated one Tm, Cr:$Y_3Al_5O_{12}$ PQS laser operating at 2.017 μm, which employed a Ho:YVO_4 crystal as the SA. In that work, a minimum pulsed duration of 45 ns corresponding to a single-pulsed energy of 3.5 mJ was obtained [10]. It indicates that, Ho ion doped crystals are potential efficient SA for the 2-μm PQS lasers. However, there is no work to report a single-doped PQS Ho laser with a Ho-doped crystal SA.

Here in this work, we present a PQS Ho:YAG laser employing a Ho:SSO as the SA. Up to our knowledge, it is the first time to demonstrate a single-doped PQS Ho laser with a Ho-doped crystal SA. Ho:SSO has been demonstrated as one efficient laser gain medium operating around 2-μm region [11–15]. A series of research works have been reported by our research team. Compared with the common Ho-doped crystal such as Ho:YLF and Ho:YAG, there are several outstanding superiorities for the Ho:SSO crystal host, such as large energy splitting ($\Delta E = 712\ cm^{-1}$) and high thermal conductivity. Plus, the width of the absorption and the width of emission spectrum are very large, the full width at half maximum

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(FWHM) of which are 59 nm and 193 nm respectively. It is easier to obtain the high power output for Ho:SSO laser crystal due to its high thermal conductivity. On the other hand, the SSO crystal is a special laser crystal, which has a negative refractive coefficient. It is obvious that the thermal lens effect, birefringence effects and crystallographic sites distortion can be limited by the negative refractive coefficient.

Due to the characteristic of the Ho:SSO laser crystal, we used it as the SA in the experiment to obtain a PQS Ho:YAG laser, which gives a novel application prospect to the Ho:SSO host material (Not only using as a laser gain medium but also one efficient SA for 2-μm region lasers).

2. Experimental setup

The experimental setup is schematically shown in Fig. 1, in which a simple U-shaped plane-concave cavity with a physical length of 140 mm was employed. The pump source was a diode-pumped Tm:YLF laser , whose maximum output power is 20 W at the center wavelength of 1908.3 nm. The pump beam was focused into a spot of 0.8 mm in diameter around the Ho:YAG crystal. The dichroic mirror M_1 and M_2 were plat mirrors with HR coated at 2.1 μm and high-transmission (HT) coated at 1.91 μm. The mirror M_3 was a plat mirror, which was coated HR at 2.1 μm. M_4 served as an output coupler, which was a concave mirror with curvature radius of 100 mm. A Ho:YAG crystal rod of a size Φ4 × 35 mm, with 0.8 at.% Ho^{3+} doping concentration was employed as the gain medium. Both end faces of crystal were anti-reflection (AR) coated at 1.91 μm and 2.1 μm. This Ho:YAG crystal was wrapped in indium foil and held in a copper heat-sink bonded on a thermal electric cooler (TEC) for precise temperature control. In this experiment, the temperature of Ho:SSO crystal was held at 20 °C. A 2-mm thick Ho:SSO plate (The Ho:SSO crystal doped with 0.5 at.%) with AR coating (R < 0.5% at 2.1 μm) was used as SA, whose transmissions was 89.5% at 2090 nm (the emission wavelength of the free-running Ho:YAG laser). The absorption cross section of Ho:SSO crystal was shown in Fig. 2.

It can be seen that, there are similar absorption cross sections around the pump region and the Ho:YAG emission region. In order to avoid the bleaching effect from the pump laser, M_2 was employed who had a high-transmittance at the pump wavelength. So, the residual pump power can not arrive at the Ho:SSO SA. The internal focusing lens, which had a focal length of 80 mm, was utilized to reduce the energy required to bleach the Ho:SSO SA, which was located 60 mm away from the Ho:SSO SA. The Ho:SSO SA was placed in the resonator. The beam radius inside the resonator of the Ho:SSO laser was calculated by using the well-known ABCD matrix, corresponding to |A + D|/2 value of the resonator lower than 0.2, which indicated the resonator always kept stable.

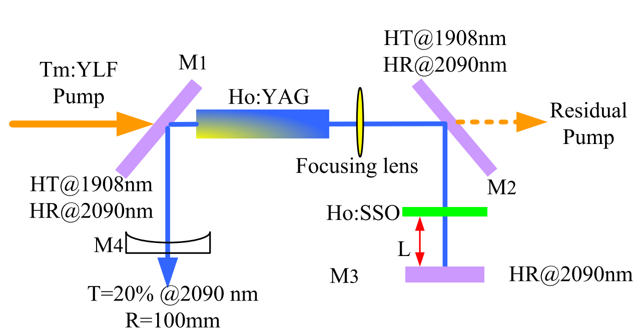

Fig. 1. Schematic diagram for the PQS Ho:SSO laser.

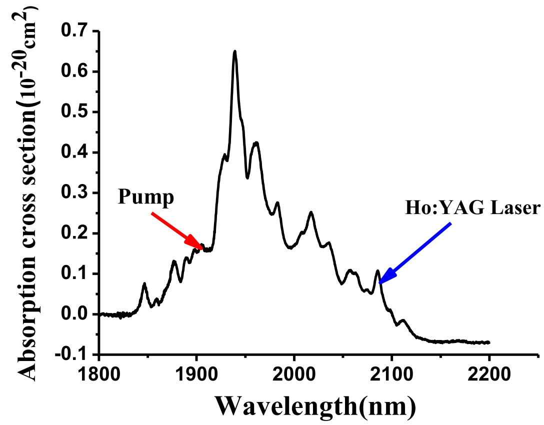

Fig. 2. Absorption cross section of Ho:SSO crystal.

3. Experimental result and discussion

Fig. 3 shows the output characteristics of free-running continuous-wave (CW) without the Ho:SSO SA with different output couplers. The output average power of Ho:SSO laser in the experiment was measured by a Coherent power meter. From the figure we can conclude that, higher slope efficiency can be obtained employing a output coupler with higher transmittance. In this experiment, a maximum slope of 62.4% was demonstrated when the *T* was 30%. However, the laser threshold will be higher with a high-transmittance output mirror. The maximum output CW power was 4.5 W under the incident power of 8.2 W, corresponding a optical-optical efficiency of 54.8%.

Fig. 4 shows the output characteristics of PQS with the Ho:SSO SA. In this experiment, we changed the distance between the SA and M_3 to test the performance of the PQS Ho:YAG laser. It can been seen from the figure that, the slope efficiency became obviously lower in the PQS mode, which maybe caused by the extra loss from the focusing lens and the Ho:SSO SA, whose transmittance was 89.5% at the emission wavelength of the Ho:YAG laser. The extra loss also increased the laser operation threshold. The maximum output average energy was 3.11 W, under the incident pump power of 8.2 W when the repetition rate was 43.8 kHz. The laser energy density around the SA can also affect the laser performance, which had been demonstrated in the experiment by changing the distance of *L* (distance between SA and M_3). The highest slope efficiency appeared when *L* is 15 mm, which is 50.1%. It seemed that, the laser performance was very sensitive to the laser energy density around the SA. When the L was 10

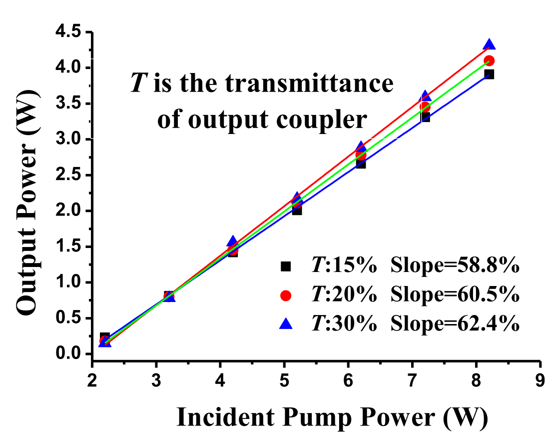

Fig. 3. Output characteristics curve of the free-running Ho:YAG laser.

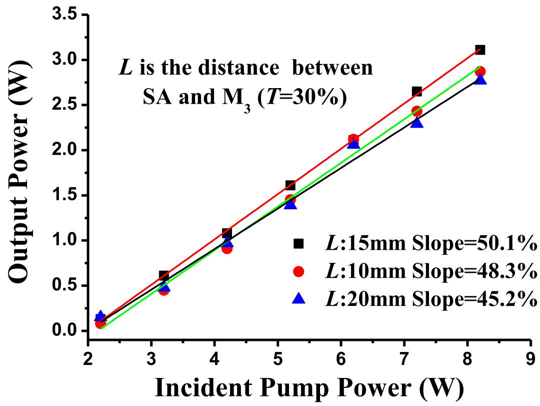

Fig. 4. Output characteristics curve of the PQS Ho:YAG laser.

mm and 20 mm, the slope efficiency were 48.3% and 45.2%, respectively.

The repetition rate of the PQS Ho:YAG laser increased as the incident pump power. The maximum repetition frequency was 42.1 kHz, when the incident pump power was 8.2 W and *L* was 15 mm, corresponding to a single pulse energy of 76.6 μJ. It can be seen from the Fig. 5, the single pulse energy of the PQS Ho:YAG laser also increased with the incident pump power . At the same time, the laser repetition and pulse energy vary with the value of *L*, which means that the laser energy density affect the laser repetition rate. In this experiment, it was indicated that higher repetition rate can be obtained with higher laser energy density. The same situation occurred on the laser slope efficiency.

When *L* was 10 mm, the output energy was 8 μJ around the laser threshold, which reached 71.4 μJ with the incident pump power of 8.2 W. The increase of the single pulse with the absorbed pump power was not linear, which changed a little when the incident pump power was larger than 6 W. When *L* was 20 mm the repetition rate changed from 8.6 kHz to 36.2 kHz, corresponding to the single pulse energy from 13.2 μJ to 73.8 μJ.

The pulsed duration of the PQS Ho:YAG laser was measured in the experiment. The pulsed duration decreased with the increasing of the incident pump power. In this experiment, the minimum pulsed duration was 48 ns under the incident pump power of 8.2 W, which was corresponding to a repetition rate of 42.1 kHz. It can also be found that, there were different pulsed duration with different laser energy density. With the highest laser energy density (L = 15 mm), we got the shortest pulsed duration. The output peak power was also calculated in this work, which was shown in Fig. 6(b). The peak power increased as the increasing of the incident pump power. The maximum peak power was 1.53 kW under an 8.2 W incident power.

Fig. 7 shows the typical Q-switch pulse trains of PQS Ho:YAG laser. It can be found from Fig. 7 that the output pulses always showed good stability. As shown in Fig. 7, the pulse repetition rate was 42.1 kHz, corresponding to a 48 ns pulsed duration under the incident pump power of 8.2 W. The detail of the pulse trains was given in the inset of Fig. 7. Furthermore, we measured the temporal trace of the PQS Ho:YAG laser, which was also shown inset of Fig. 7.

The CW and PQS Ho:YAG laser spectrum recorded by Spectrum Analyzer (BRISTOL INSTRUMENTS 721) at the incident pump power of 8.2 W was shown in Fig. 8. As can be seen from Fig. 8, the CW laser operated at a center wavelength of 2090.1 nm, which shifted to 2091.3 nm in the PQS mode. The photo-diode used in

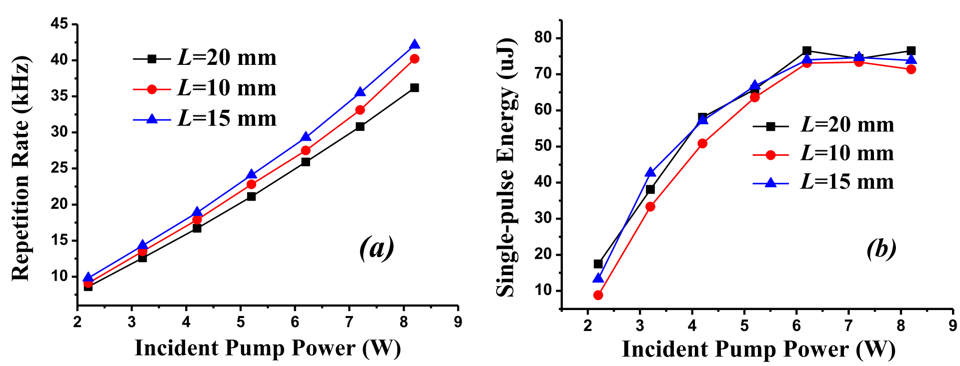

Fig. 5. (a) Repetition frequency; (b) Pulse energy as a function of incident pump power.

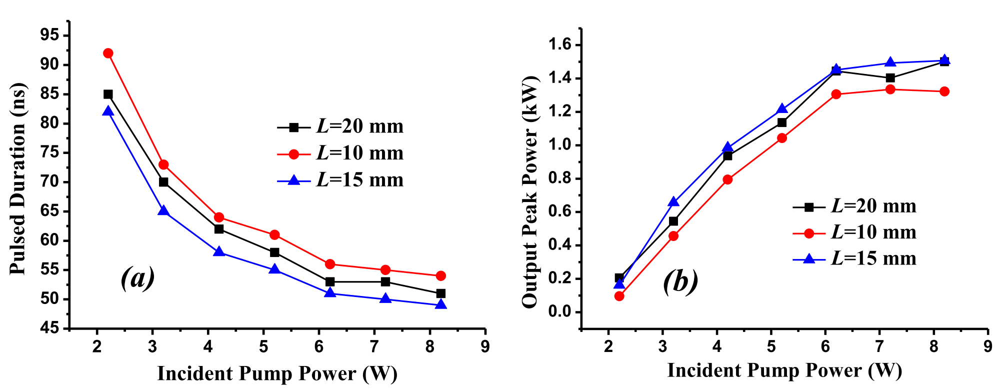

Fig. 6. (a) Pulsed duration; (b) Peak power as a function of incident pump power.

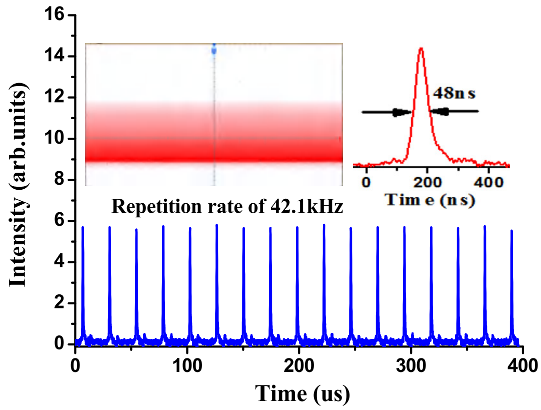

Fig. 7. Pulse trains of the PQS Ho:YAG laser. Inset, profile of the pulse.

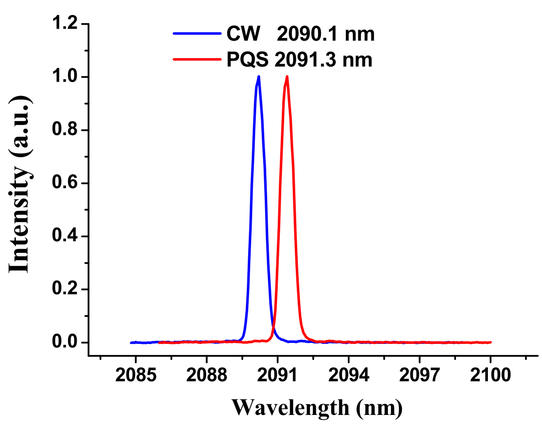

Fig. 8. Output spectra of the CW and PQS Ho:YAG laser.

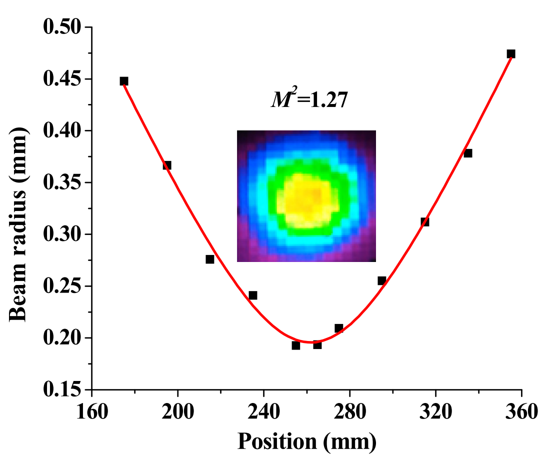

Fig. 9. The beam radius of the PQS Ho:YAG laser. Inset: typical 2D beam profiles.

this manuscript was made by the Electro-Optics Technology (EOT, ET-5000F), whose work bandwidth was more than 12.5 GHz. Both of the increase/decrease time were 28 ps. A DPO7000C oscilloscope was used in this work, which is made by the Tektronix company. The bandwidth of the oscilloscope was 12.5 GHz, and the sampling rate was 100G/s. The resolution of the measurement system can be estimated less than 40 ps.

Fig. 9 shows the measured beam radius under the maximum PQS output power at various distances. The transverse output beam profile was measured by using the 90/10 knife-edge technique. The M^2 factor is calculated to be 1.27, and this indicated the output beam was close to TEM_{00} mode. The inset in Fig. 9 is the transverse output beam profile obtained in the near field at the highest pump power, which was captured by a Spiricon Pyrocam I pyroelectric camera.

4. Conclusion

In summary, Ho:SSO crystal is employed as a saturable absorber Q switch for the passive Q-switch pulsed Ho:YAG. Presented here is the first time for Ho:SSO crystal to be a saturable absorber Q switch. It indicates that, the Ho:SSO can be used not only as a kind of laser gain medium, but also as a saturable absorber Q switch for pulsed 2-um lasers. A maximum output peak energy of 1.53 kW was obtained in the passive Q-switch Ho:YAG laser, corresponding to a repetition of 42.1 kHz and a pulsed duration of 48 ns. The incident pump power had a direct influence in the characteristics of the passive Q-switch Ho:YAG laser as well as the laser energy density around the saturable absorber Q switch.

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References

[1] M. Gower, Industrial applications of laser micromachining, Opt. Exp. 7 (2) (2000) 56–62.
[2] Z.X. Jiao, G.Y. He, J. Guo, B. Wang, High average power 2μm generation using an intracavity PPLN optical parametric oscillator, Opt. Lett. 37 (1) (2012) 64–68.
[3] M. Schellhorn, A. Hirth, Modeling of intracavity-pumped quasi-three- level lasers, IEEE J. Quantum Electron. 38 (11) (2002) 1455–1459.
[4] A.S. Kurkov, E.M. Sholokhov, A.V. Marakulin, L.A. Minashina, Dynamic behavior of laser based on the heavily holmium doped fiber, Laser Phys. Lett. 7 (2010) 587.
[5] L.J. Li, B.Q. Yao, Z.G. Wang, X.M. Duan, G. Li, Y.Z. Wang, Q-switched Ho:$YAlO_3$ laser pumped by Tm:YLF laser at room temperature, Laser Phys. 20 (2010) 205.
[6] X.M. Duan, B.Q. Yao, L. Ke, Y.L. Ju, Y.Z. Wang, 3.5 W continuous wave Ho:LSO laser at room temperature, Laser Phys. Lett. 6 (2009) 715.
[7] G. Galzerano, M. Marano, S. Longhi, E. Sani, A. Toncelli, M. Tonelli, P. Laporta, Sub-100-ps amplitude-modulation mode-locked Tm–Ho: BaY2F8 laser at 2.06 μm, Opt. Lett. 28 (21) (2003) 2085.
[8] R. Lan, P. Loiko, X. Mateos, Y. Wang, J. Li, Y. Pan, S.Y. Choi, M.H. Kim, F. Rotermund, A. Yasukevich, Passive Q-switching of microchip lasers based on Ho:YAG ceramics, Appl. Opt. 55 (18) (2016) 4877–4887.
[9] T.Y. Dai, X.G. Xu, X.L. Li, B.Q. Yao, Z. Cui, Y.L. Ju, Y.Z. Wang, 41 kHz repetition rate passively Q-switched Ho:YAP laser with Cr:ZnS as a saturable absorber, Optik 127 (11) (2016) 4844–4847.
[10] B.Q. Yao, X.L. Li, Z. Cui, T.Y. Dai, S. Bai, H.Y. Yang, X.M. Duan, Y.L. Ju, High-repetition rate passively Q-switched Ho:YLF laser with graphene as a saturable absorber, Opt. Eng. 54 (7) (2015) 076105.
[11] X.T. Yang, Y. Shi, X.M. Duan, L.H. Zheng, J. Xu, Performance of acousto-optically Q-switched Ho:SSO laser pumped by a Tm: YAP laser, Opt. Eng. 54 (3) (2015) 36105–36109.
[12] X.T. Yang, B.Q. Yao, Y. Ding, X. Li, G. Aka, L.H. Zheng, J. Xu, Spectral properties and laser performance of Ho:Sc_2SiO_5 crystal at room temperature, Opt. Exp. 21 (2013) 32566–32571.
[13] X.T. Yang, L. Liu, W.Q. Xie, Passively Q-switched Ho:SSO laser by use of a Cr^{2+}: ZnSe saturable absorbe, Chin. Phys. Lett. 34 (2) (2017) 024201.
[14] X.T. Yang, W.Q. Xie, L. Liu, L.J. Li, Compact intra-cavity pumped low-threshold passively Q-switched Ho:Sc_2SiO_5 laser by a LD-pumped Tm:YAP laser at room temperature, Laser Phys. Lett. 14 (8) (2017) 85806.
[15] X.T. Yang, P. Zhang, L. Liu, W.Q. Xie, A resonantly pumped single-longitudinal mode Ho:Sc_2SiO_5 laser with two fabry-perot etalons, Appl. Sci. 7 (5) (2017) 434.