High-Power Continuous-Wave and Acousto-Optical Q-Switched Ho:$(Sc_{0.5}Y_{0.5})_2SiO_5$ Laser Pumped by Laser Diode *

Xiao-Ming Duan(段小明)[1**], Guang-Peng Chen(陈广鹏)[1], Ying-Jie Shen(申英杰)[2], Li-He Zheng(郑丽和)[3], Liang-Bi Su(苏良碧)[3]

[1]*National Key Laboratory of Tunable Laser Technology, Harbin Institute of Technology, Harbin 150001*
[2]*School of Opto-electronic Information Science and Technology, Yantai University, Yantai 264005*
[3]*Synthetic Single Crystal Research Center, CAS Key Laboratory of Transparent and Opto-functional Inorganic Materials, Shanghai Institute of Ceramics, Chinese Academy of Sciences, Shanghai 201899*

(Received 6 March 2019)

We experimentally investigate the continuous-wave (cw) and acousto-optical (AO) Q-switched performance of a diode-pumped Ho:$(Sc_{0.5}Y_{0.5})_2SiO_5$ (Ho:SYSO) laser. A fiber-coupled laser diode at 1.91 μm is employed as the pump source. The cw Ho:SYSO laser produces 13.0 W output power at 2097.9 nm and 56.0% slope efficiency with respect to the absorbed pump power. In the AO Q-switched regime, at a pulse repetition frequency of 5 kHz, the Ho:SYSO laser yields 2.1 mJ pulse energy and 21 ns pulse width, resulting in a calculated peak power of 100 kW. In addition, at the maximum output level, the beam quality factor of the Q-switched Ho:SYSO laser is measured to be about 1.6.

PACS: 42.55.Xi, 42.60.Pk, 42.72.Ai DOI: 10.1088/0256-307X/36/6/064201

High-power 2-μm diode-pumped solid-state lasers (DPSSLs) have a series of applications in many important technical fields such as medical surgery, wind sensing and middle-infrared optical frequency conversions. The thulium (Tm)-doped laser was first used to obtain DPSSL 2-μm laser light owing to the advantages of pumping of the laser diode (LD) around 800 nm and the two-for-one cross-relaxation process. However, for some applications, for example, the pumping of the middle-infrared $ZnGeP_2$ (ZGP) optical parametric oscillator,[1] the Tm-doped laser is not preferred due to its output wavelength less than 2.05 μm. In contrast, the holmium (Ho)-doped laser with output wavelength of more than 2.05 μm is more suitable to apply in some technical applications. In the past two decades, the Ho laser has become an excellent choice to generate 2-μm laser radiation. The absorption peaks of $^5I_7$ level of Ho ions are located around 1.9 μm. Thus the Tm-bulk or Tm-fiber laser at 1.9 μm is the first choice for the pumping of Ho lasers due to its high power and high beam quality. With high quantum efficiency, the Tm laser-pumped Ho laser has the advantages of high conversion efficiency and low thermal loading. Unfortunately, the conversion efficiency of the overall laser system is not high due to its cascading structure (LD→Tm→Ho). In addition, the Tm laser-pumped Ho lasers have a complex structure because the thermal loading is difficult to control in high-power Tm-bulk or Tm-fiber lasers. To solve this problem, a 1.9-μm LD was selected as the pump source of the Ho laser owing to its compactness and simplicity. In 1995, the first use of a 1.9-μm LD-pumped Ho laser was demonstrated in Ho:YAG crystal.[2] In 2008, a cw output power of 40 W at 2122 nm was demonstrated in an LD stack-pumped Ho:YAG laser.[3] In 2013, an LD-pumped Ho:Lu_2O_3 laser was also demonstrated with a pulse energy of 5 mJ at 100 Hz pulse repetition frequency (PRF).[4] Recently, fiber-coupled LD-pumped Ho:$KLu(WO_4)_2$,[5] Ho:YVO_4,[6] Ho:Y_2O_3[7] and Ho:YLF[8] lasers were presented with Watts output power level. In addition, the traditional Ho:YAG[9] and Ho:YAP[10] lasers produced more than 10 W output power under pumping of fiber-coupled LDs at 1.9 μm.

Among the many host materials, silicate crystals are promising for the doping of rare earth (RE) ions. Recently, the novel disordered silicate crystal $(Sc_{0.5}Y_{0.5})_2SiO_5$ (SYSO) was grown with Sc:Y=1:1 in the YSO crystal. Its structure was similar to YSO crystal (class $2/m$, space group $C2/c$). Compared with other conventional silicate crystals such as YSO, LSO and SSO, a stronger inhomogeneous lattice field was offered in the SYSO crystal due to the multiple types of crystallographic sites, which is beneficial to enlarge and broaden the emission spectrum of RE ions.[11] Based on these advantages, the RE-doped SYSO crystal became a good candidate to achieve an efficient laser output. In 2012, the lasing performance of RE-doped SYSO was first demonstrated in a Nd:SYSO laser with tri-wavelength output.[12] In 2017, the first 2-μm laser action in RE-doped SYSO crystal was reported in a Tm:SYSO laser with an output power of about 0.6 W at 2022 nm.[13] Moreover, the spectral properties and cw lasing performance of Ho:SYSO crystal were studied at room

*Supported by the National Natural Science Foundation of China under Grant Nos 51572053, 61805209 and U1530152.
**Corresponding author. Email: xmduan@hit.edu.cn
© 2019 Chinese Physical Society and IOP Publishing Ltd

temperature.[14]

In this Letter, we present the cw and acousto-optical Q-switched performance of the diode-pumped Ho:SYSO laser. With pumping of a fiber-coupled LD at 1.91 μm, the diode-pumped cw Ho:SYSO laser produces up to 13.0 W output power at 2097.9 nm, corresponding to an optical efficiency of 44.7% and a slope efficiency of 56.0% with respect to the absorbed pump power. In the Q-switching regime, the Ho:SYSO laser with a PRF of 5 kHz produces 2.1 mJ pulse energy and 21 ns pulse width, resulting in a calculated peak power of 100 kW.

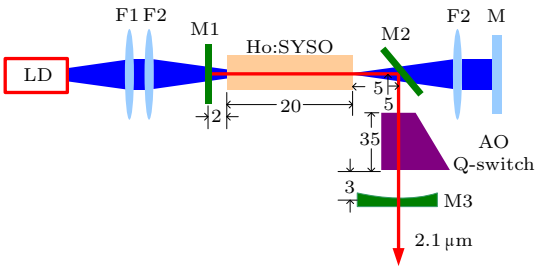

Fig. 1. The experimental setup of LD-pumped Ho:SYSO laser.

Figure 1 schematically depicts the experimental setup of the LD-pumped Ho:SYSO laser. In our experiment, a 40 W 1.91-μm fiber-coupled LD (Ultra-500, QPC Corp.) with core diameter of 600 μm and numerical aperture of 0.22 was employed to pump the Ho:SYSO crystal. The M^2 factor of the LD was approximately 110. Its output spectrum was measured by an optical spectrum analyzer (AQ6375, Yokogawa), which indicates that its central wavelength at maximum output power was located around 1911 nm with a full width at half maximum (FWHM) of approximately 2 nm. The red shift of about 7 nm was observed from the LD threshold (1904 nm) to 40 W power (1911 nm). The lens F1 with a focal length of 30 mm was used to collimate the LD pump light. The pump beam was focused into the Ho:SYSO crystal with lens F2 (30 mm focal length), and the residual pump light was re-focused into the crystal by the flat mirror M coated with high reflective film for pump wavelength and the other lens F2. The LD pump diameter was calculated to be approximately 600 μm. The pump Rayleigh length z_r ($z_r = \pi\omega_p^2 n/\lambda_p M_p^2$) was calculated to be about 2.5 mm inside the Ho:SYSO crystal with refraction index $n = 1.84$. The pump waist was located at about 4 mm from the end face of the crystal. The a-cut Ho:SYSO crystal, with a dopant concentration of 0.5 at.% and dimensions of 4×4(cross-section)×20(length) mm^3, was used as the gain medium. Its end face was polished and coated with an anti-reflection film for pumping and lasing wavelength. According to the spectral data of Ho:SYSO crystal,[14] the absorption coefficient is about 0.36 cm^{-1} in the spectral range from 1900 to 1920 nm, which is very beneficial to stabilize the pump absorption efficiency. The single-pass pump absorption of the Ho:SYSO crystal was measured to be almost constant at approximately 50% under LD powers of 5 W, 15 W and 30 W, leading to a 75% pump absorption of the Ho:SYSO crystal under pump recycling conditions. Some 0.1-mm-thick indium foils and a copper heatsink were used to mount the Ho:SYSO crystal. A thermoelectric cooler was used to maintain the heatsink temperature of 15℃. The cavity with a physical length of 70 mm had an L-shaped architecture, which consisted of a 0° dichroic mirror M1 with high transmission at pump wavelength and high reflectivity at lasing wavelength, a flat 45° dichroic mirror M2 with high transmission at pump wavelength and high reflectivity at lasing wavelength, and an output coupler M3 with a curvature of 500 mm. A quartz acousto-optical (AO) Q-switch with a length of 35 mm and aperture of 1.8 mm was employed for the Q-switching operation. It has more than 45% diffraction efficiency. The rated radio frequency power was 20 W at a frequency of 41 MHz. The Ho laser beam diameter in the middle of the Ho:SYSO crystal was calculated to be about 620 μm according to the ABCD matrix method, leading to a 51.6% mode overlapping coefficient.[15]

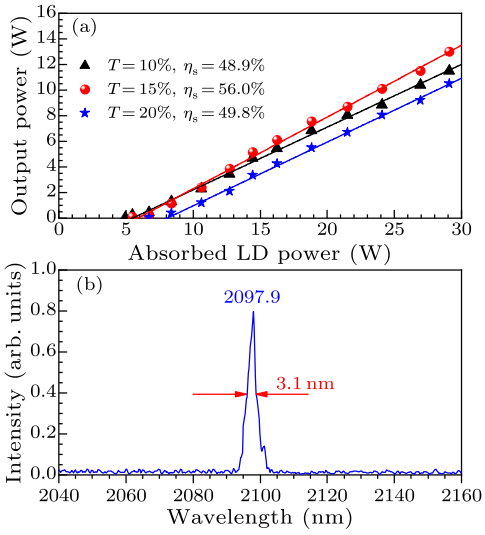

Fig. 2. The output power (a) and spectrum (b) of our cw Ho:SYSO laser with different output transmittances.

In this experiment, a power meter (S425C, Thorlabs) was used to measure the output power. The cw output characteristics of the diode-pumped Ho:SYSO laser with three output transmittances of 10%, 15% and 20% were investigated as shown in Fig. 2(a). The threshold pump powers were 4.9 W, 5.5 W and 6.7 W for output transmittances of 10%, 15% and 20%, respectively. In the case of an output transmittance of 15%, the maximum output power of 13.0 W was achieved at the absorbed pump power of 29.1 W, corresponding to an optical efficiency of 44.7% and a slope efficiency of 56.0% with respect to the ab-

sorbed pump power. With output transmittances of 10% and 20%, the slope efficiencies decrease to 48.9% and 49.8%, respectively. It can be seen that the maximum output power is achieved with the output transmittance of 15%, caused by the low threshold pump power and highest slope efficiency in this work. Compared with the well-known Ho:YAG crystal, although the Ho:SYSO crystal has a larger emission cross-section at 2097 nm,[14,16] the slope efficiency of the Ho:SYSO laser is lower and unstable under the above three output transmittances. Maybe this phenomenon is caused by the larger passive loss of the Ho:SYSO crystal. We can estimate this by the formula $P_{\rm th} = k(\delta_0 - (\ln R_1 R_2)/2L)$,[17] where $P_{\rm th}$ is the threshold power, δ_0 is the passive loss of the laser crystal, R_1 and R_2 are the reflectivities of the input and output mirrors, and L is the crystal length. In our experiment, R_1 is equal to 100%, thus the passive loss of Ho:SYSO crystal is calculated to be about 0.05 $\rm cm^{-1}$. The output spectra of the Ho:SYSO laser with different output transmittances were recorded by an optical spectrum analyzer (AQ6375, Yokogawa), as shown in Fig. 2(b). The central wavelength of 2097.9 nm is observed with a FWHM of about 3.1 nm for the above three output transmittances. In addition, with varying LD pump power, no obvious changes can be observed in the output spectrum.

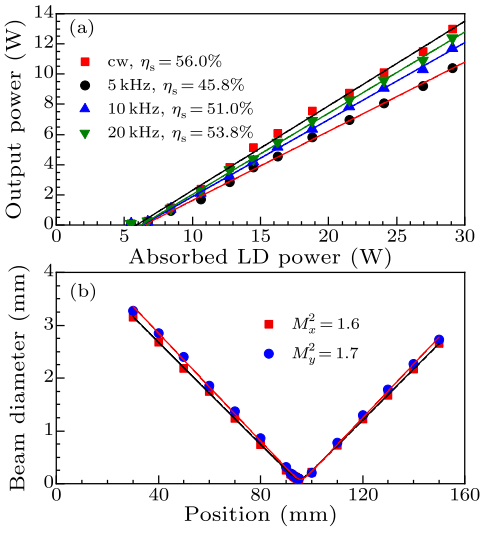

Fig. 3. The output characteristics (a) and M^2 measurement (b) of AO Q-switched Ho:SYSO laser.

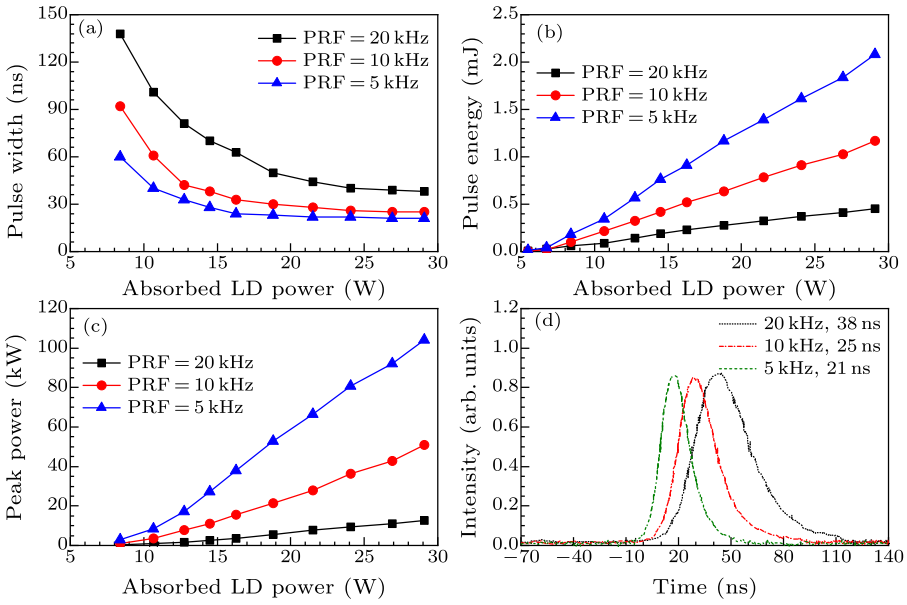

Fig. 4. The pulse widths (a), pulse energies (b), peak powers (c) and minimum pulse profiles (d) of AO Q-switched Ho:SYSO laser with PRFs of 5 kHz, 10 kHz and 20 kHz.

Using an output coupler with a transmittance of 15%, the AO Q-switched performance of the Ho:SYSO laser is investigated as shown in Fig. 3(a). In the case of a PRF of 20 kHz, a 12.4 W average output power and 53.8% slope efficiency are achieved when the absorbed pump power is 29.1 W. With PRFs of 10 kHz and 5 kHz, the average output powers decrease to 11.7 W and 10.4 W, corresponding to slope efficiencies of 51.0% and 45.8%, respectively. In addition, the M^2 factor of the Q-switched Ho:SYSO laser is also investigated. At the maximum average output power, using a slit scanning beam profiler (BP109-IR2, Thorlabs), the M^2 factor is measured to be approximately 1.6 in both horizontal and vertical directions, as shown in Fig. 3(b). Moreover, the full divergence angle of the output laser beam is also estimated to be approximately 3.8 mrad by the same beam profiler.

A fast InGaAs photodetector (ET-5000, EOT) and a digital oscilloscope (DPO 4000, Tektronix) were used to detect and record the temporal pulse profiles of the AO Q-switched Ho:SYSO laser. At PRFs of 5 kHz, 10 kHz and 20 kHz, the pulse widths, pulse energies and peak powers are shown in Figs. 4(a)–4(c), respectively. Minimum pulses widths of 21 ns, 25 ns

and 38 ns (see Fig. 4(d)) are obtained with PRFs of 5 kHz, 10 kHz and 20 kHz, respectively. The maximum pulse energies are calculated to be about 2.1 mJ, 1.2 mJ and 0.6 mJ, resulting in calculated peak powers of approximately 100 kW, 48 kW and 15.8 kW, respectively.

In conclusion, we have presented the cw and AO Q-switched performance of a diode-pumped Ho:SYSO laser under a pump recycling scheme. With pumping of a fiber-coupled LD at 1.91 μm, the Ho:SYSO laser yields up to 13.0 W cw output power at 2097.9 nm and 2.1 mJ pulse energy at a PRF of 5 kHz. In addition, the M^2 factor of the Q-switched Ho:SYSO laser is estimated to be about 1.6 at the maximum average output power. The experimental results indicate that the Q-switched Ho:SYSO laser could be a good pump source of middle-infrared ZGP-OPO.

References

[1] Zawilski K T, Schunemann P G, Setzler S D and Pollak T M 2008 *J. Cryst. Growth* **310** 1891
[2] Nabors C D, Ochoa J, Fan T Y, Sanchez A, Choi H K and Turner G W 1995 *IEEE J. Quantum Electron.* **31** 1603
[3] Scholle K and Fuhrberg P 2008 *Proc. of CLEO* p CTuAA1
[4] Lamrini S, Koopmann P, Scholle K and Fuhrberg P 2013 *Opt. Lett.* **38** 1948
[5] Jambunathan V, Mateos X, Cinta P M, Carvajal J J, Aguiló M, Díaz F, Griebner U and Petrov V 2011 *Appl. Phys. Express* **4** 072601
[6] Newburgh G A, Dubinskii M, Post S G and Dubinskii M 2011 *Proc. SPIE* **8039** 803905
[7] Newburgh G A, Word-Daniels A, Michael A, Merkle L D, Ikesue A and Dubinskii M 2011 *Opt. Express* **19** 3604
[8] Cui Z, Yao B, Duan X, Li J, Bai S, Li X, Zhang Y, Yuan J, Dai T, Ju Y, Li C and Pan Y 2015 *Chin. Phys. Lett.* **32** 084205
[9] Berrou A, Ibach T and Eichhorn M 2015 *Appl. Phys. B* **120** 105
[10] Duan X, Li L, Shen Y and Yao B 2018 *Appl. Phys. B* **124** 179
[11] Shi J, Liu B, Zheng L, Wang Q, Tang H, Liu J, Su L, Wu F, Zhao H, He N, Li N, Li Q, Guo C, Xu J, Yang K, Xu X, Ryba-Romanowski W, Lisiecki R and Solarz P 2018 *J. Cryst. Growth* **487** 83
[12] Liu S D, Zheng L H, He J L, Xu J, Xu X D, Su L B, Yang K J, Zhang B T, Wang R H and Liu X M 2012 *Opt. Express* **20** 22448
[13] Yang K, Feng T, Zhao S, Liu C, Li T, Ma W, Zou Z, Wang Q, Su L, Solarz P, Lisiecki R, Komar J, Xu J, Zheng L and Ryba-Romanowski W 2017 *J. Alloys Compd.* **712** 412
[14] Duan X, Qian C, Shen Y, Su L, Zheng L, Li L, Yao B and Dai T 2019 *Opt. Express* **27** 4522
[15] Fan T Y and Byer R L 1988 *IEEE J. Quantum Electron.* **24** 895
[16] Budni P A, Lemons M L, Mosto J R and Chicklis E P 2000 *IEEE J. Sel. Top. Quantum Electron.* **6** 629
[17] Findlay D and Clay R A 1966 *Phys. Lett.* **20** 277