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Active Q-switching operation of slab Ho:SYSO laser wing-pumped by fiber coupled laser diodes

XIAOMING DUAN,[1,8] YINGJIE SHEN,[2] JING GAO,[3] HONGBO ZHU,[4,5] CHUANPENG QIAN,[1] LIANGBI SU,[6] LIHE ZHENG,[6,9] LINJUN LI,[7,10] BAOQUAN YAO,[1] AND TONGYU DAI[1]

[1]*National Key Laboratory of Tunable Laser Technology, Harbin Institute of Technology, Harbin, 150001, China*
[2]*School of Opto-Electronic Information Science and Technology, Yantai University, Yantai, 264005, China*
[3]*Suzhou Guoke Medical Science & Technology Development Co. Ltd., Suzhou, 215163, China*
[4]*State Key Laboratory of Luminescence and Application, Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, 3888 Southeast Lake Road, Changchun, 130033, China*
[5]*CREOL, University of Central Florida, Orlando, FL 32816, USA*
[6]*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, China*
[7]*The Higher Educational Key Laboratory for Measuring & Control Technology and Instrumentations of Heilongjiang Province, Harbin University of Science and Technology, Harbin, 150080, China*
[8]*xmduan@hit.edu.cn*
[9]*zhenglihe@gmail.com*
[10]*lilj2019@126.com*

Abstract: In this paper, we demonstrate the continuous-wave and acousto-optical Q-switched performance of diode-pumped slab Ho:$(Sc_{0.5}Y_{0.5})_2SiO_5$ (Ho:SYSO) laser at 2.1 µm for the first time. Two 1.91-µm laser diodes were used to pump the Ho:SYSO crystal. With a wing-pumping structure, at absorbed pump power of 44.7 W, the continuous wave slab Ho:SYSO laser produced 20.7 W maximum output power at 2097.9 nm, resulting in a slope efficiency of 53.1% with respect to the absorbed pump power. In the Q-switched regime, the slab Ho:SYSO laser produced up to 3.4 mJ pulse energy with 20 ns minimum pulse width at pulse repetition frequency of 5 kHz, corresponding to a peak power of 170 kW.

1. Introduction

High power diode-pumped solid-state laser (DPSSL) operating in the 2-µm spectral range are attractive for many technical applications such as medical surgery, environment monitoring, remote sensing, range finding and nonlinear optical frequency conversions [1–3]. Based on the $^3F_4 \rightarrow ^3H_6$ transition, the thulium (Tm)-doped lasers pumped by laser diode (LD) around 800 nm are widely applied to realize DPSSL 2-µm laser owing to efficient two-for-one cross relaxation process. However, Tm-doped lasers can hardly produce wavelength beyond 2.05 µm, which is not preferred in some technical applications, such as the pumping of middle infrared $ZnGeP_2$ (ZGP)-OPO [4]. The $^5I_7 \rightarrow ^5I_8$ transition of holmium (Ho) ions is another technical approach to generate the 2-µm laser radiation. The strong absorption peaks of $^5I_7$ level of Ho ions were located around 1.9 µm. Thus 1.9-µm Tm-bulk or Tm-fiber lasers become good choices for pumping of Ho lasers due to their high power and high beam quality. However, this cascading architecture (LD→Tm→Ho) leads to low conversion efficiency of overall laser system. Moreover, the thermal management is difficult in high

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power Tm-lasers, resulting in a complex structure and big size. In order to overcome this problem, 1.9-μm LD could be used as the pump source of Ho laser due to its compactness and simplicity. The first DPSSL Ho-laser was demonstrated in a Ho:YAG laser with output power of about 0.7 W and slope efficiency of 35% early in 1995 [5]. In 2008, the high power 1.9-μm LD stacks were used to improve the output power of DPSSL continuous wave (CW) Ho:YAG laser and realized the 40 W maximum output power at 2122 nm [6]. In addition to Ho:YAG, the DPSSL Ho:Lu_2O_3 laser was also demonstrated with 1.9-μm LD stacks pumping, which produced pulse energy of 5 mJ at 100 Hz pulse repetition frequency (PRF) [7]. Recently, commercial fiber-coupled 1.9-μm LD is available for pumping of Ho-laser. The fiber-coupled DPSSL Ho:$KLu(WO_4)_2$ [8], Ho:YVO_4 [9], Ho:Y_2O_3 [10] and Ho:YLF [11] lasers were demonstrated with Watts-level output power. Furthermore, the DPSSL Ho:YAG [12] and Ho:YAP [13] laser with more than 10 W output power were investigated by using fiber coupled 1.9-μm LD.

In addition to the host materials mentioned above, the silicate crystals are also attractive for doping of rare earth (RE) ions. The first 2-μm laser action of RE-doped silicate was reported in a Ti:Al_2O_3-pumped Tm:YSO laser [14]. During the past few years, the DPSSL Tm:LSO [15] and Tm:SSO [16] lasers have been demonstrated. Moreover, the 2-μm Ho:LSO [17] and Ho:SSO [18] lasers were presented with Tm-bulk or Tm-fiber lasers pumping. Recently, a part of Y ions were used to replace the Sc ions in YSO crystal, the novel disordered silicate crystal $(Sc_{0.5}Y_{0.5})_2SiO_5$ (SYSO) was grown with structure like YSO (class 2/m, space group C2/c). Compared with YSO, LSO and SSO etc. silicate crystals, the stronger inhomogeneous lattice field was offered owing to the multiple types of crystallographic sites, which is beneficial to enlarge and broaden the emission spectrum of RE ions [19]. Therefore, the RE-doped SYSO crystal is a promising gain medium for high efficient and high power laser output. In 2012, the first RE-doped SYSO laser has been demonstrated in a DPSSL CW Nd:SYSO laser with tri-wavelengths output [20]. In 2018, A DPSSL CW Tm:SYSO laser with output power of about 0.6 W at 2022 nm presented the first 2-μm laser action in RE-doped SYSO crystal [21]. Moreover, the spectral properties and CW lasing performance of Ho:SYSO crystal was studied at room temperature [22]. Its maximum absorption cross section of $^5I_7$ level is 0.79×10^{-20} cm^2 at 1943 nm, which is suitable for high power 1.94-μm pumping. However, to the best of our knowledge, there is no report on the Q-switched performance of Ho:SYSO laser up to now.

In this paper, we present the first 1.91-μm LD-wing-pumped slab Ho:SYSO laser under CW and acousto-optical Q-switching regimes. In the CW regime, the DPSSL slab Ho:SYSO laser delivered the 20.7 W output power at 2097.9 nm and 53.1% slope efficiency with respect to the absorbed pump power. In the acousto-optical Q-switching regime, at PRF of 5 kHz, the maximum pulse energy of 3.4 mJ and minimum pulse width of 20 ns were obtained, corresponding to a peak power of 170 kW. In addition, the beam quality factors (M^2) of DPSSL Q-switched Ho:SYSO laser at maximum output power were measured to be 1.6 in the vertical direction and 1.9 in the horizontal direction, respectively.

2. Experimental setup

The experimental setup of dual end-pumped slab Ho:SYSO laser was shown schematically in Fig. 1. An *a*-cut slab Ho:SYSO crystal with dopant concentration of 0.5 at.% was used as the gain medium, which has dimensions of 1.5×3 mm^2 in cross section and 40 mm in length. Both end faces of the crystal were polished and antireflection coated for pump and lasing wavelength. Two 1.91-μm fiber-coupled LDs (Ultra-500, QPC Corp.) with output power of 30 W were used as the pump source of the slab Ho:SYSO laser. The core diameter and numerical aperture of the pigtail fiber was 600 μm and 0.22, respectively. The M^2 factor of the LD was about 110. The emission spectrum of LD was recorded by an optical spectrum analyzer (AQ6375, Yokogawa) with resolution of 0.1 nm. The LD wavelength was centered at about 1911 nm at output power of 30 W with a full width at half maximum (FWHM)

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linewidth of about 2 nm. The wavelength shift of about 7 nm was recorded from LD threshold (1904 nm) to 30 W output power (1911 nm). Due to varying central wavelength of 1.9-μm LDs depended on their operating temperature, the pump absorption efficiency is not stable in the Ho:SYSO crystal because of its narrow absorption peaks around 1.94 μm. Therefore, the 1.94-μm LD is not preferred to pump the Ho:SYSO crystal. But the absorption curves of Ho:SYSO crystal is near flat in the spectral range from 1902 nm to 1929 nm [22], which was far away from the absorption peak. This is beneficial to stabilize the pump absorption efficiency of Ho:SYSO crystal under 1.91-μm LD pumping, which was called wing-pumping architecture. The unpolarized LD pump beam was collimated by a lens F1 with a 30 mm focal length. Then the collimated beam was re-focused into the slab Ho:SYSO crystal with another lens F2 (30 mm focal length), resulting in a pump diameter of approximately 600 μm. The pump Rayleigh length zr ($zr = \pi\omega_p^2 n/\lambda_p M_p^2$) 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 4.5 mm from the end face of the crystal. In our previous work [22] a Tm-fiber was used as the pump source which has 66.2 mm pump Rayleigh length. In contrast, the pump Rayleigh length was too short under LD pumping conditions, leading to bad overlap between the pump and laser beam. In order to overcome this problem, the four side faces of Ho:SYSO crystal were polished to achieve total internal reflection for pump beam. The single-pass non-lasing pump absorption of slab Ho:SYSO crystal was measured to be approximately 75% for both low and high pump level, which was caused by almost constant absorption coefficient (0.36 cm^{-1}) in the spectral range from 1904 nm to 1911 nm [22].

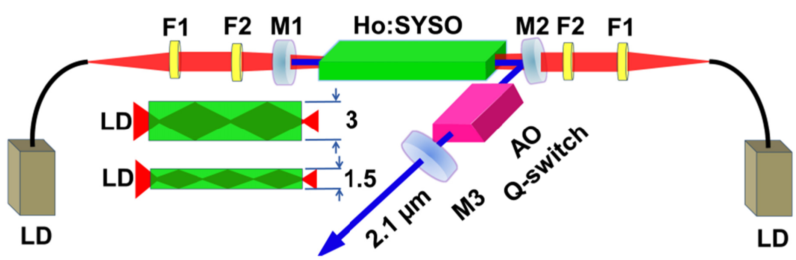

Fig. 1. Experimental setup of Ho:SYSO laser wing-pumped by two 1.91-μm LDs. Insertion indicates pump beam propagation inside Ho:SYSO crystal in vertical and horizontal directions.

The slab Ho:SYSO crystal was wrapped with 0.1mm-thickness indium foils and placed in a copper heatsink. The heatsink temperature was controlled at 20 °C by the thermoelectric coolers. We used an L-shaped cavity with physical length of 90 mm to realize the dual-end pumping architecture. The flat 0° dichroic mirror M1 had high transmission (T = 99.5%) at 1.91 μm and high reflectivity (R = 99.7%) at 2 μm. The flat 45° dichroic mirror M2 had high transmission (T = 95%) at the LD wavelength and high reflectivity (R = 99.7%) at 2 μm. The plano-concave mirror M3 with a radius of curvature of 500 mm was used as the output coupler. A quartz acousto-optical (AO) Q-switch with a length of 35 mm and an aperture of 1.8 mm was employed for Q-switching operation. It had more than 45% diffraction efficiency. The rated radio frequency power was 20 W at a frequency of 41 MHz. With ABCD matrix method, we estimated that the Ho laser beam diameter on the slab Ho:SYSO crystal was about 610 μm. Meanwhile, the calculated results indicated that this cavity was stable with more than 40 mm thermal focal length from Ho:SYSO crystal.

3. Experimental results

A power meter (S425C, Thorlabs) was employed to measure the output power in this work. Three output transmittances of 10%, 15% and 20% were used to investigate the CW output characteristics of DPSSL slab Ho:SYSO laser, as shown in Fig. 2(a). For transmittances of

10%, 15% and 20%, the threshold pump powers were 4.9 W, 5.5 W and 6.7 W, respectively. The passive loss of Ho:SYSO crystal can be estimated by a formula $P_{th} = k(\delta_0\text{-}(\ln R_1R_2)/2L)$ [23]. Where P_{th} is the threshold power, δ_0 is the passive loss of the laser crystal, R_1 and R_2 are the reflectivity of the input and output mirror, and L is the length of the laser crystal. In this work the value of R_1 is the product of the reflectivity of the M1 and M2. With the experimental parameters, the passive loss of Ho:SYSO crystal was calculated to be about 0.03 cm^{-1}. With output transmittance of 15% and absorbed pump power of 44.7 W, the slab Ho:SYSO laser yielded as high as 20.7 W maximum output power, corresponding to a 53.1% slope efficiency and a 46.3% optical-to-optical efficiency with respect to the absorbed pump power The power stability of the slab Ho:SYSO laser was estimated over a period of one hour. When the absorbed pump power was 44.7 W, the output power slowly fluctuated between 20.5 W and 20.9 W, which indicated that the power stability was approximately 2%. For transmittances of 10% and 20%, the slope efficiencies decreased to 45.1% and 49.7%, respectively. There is no roll-over phenomenon observed due to the good thermal stability rising from low thermal load and good thermal management in slab Ho:SYSO crystal. The output spectra of slab Ho:SYSO laser under different output transmittances were measured by the optical spectrum analyzer (AQ6375, Yokogawa). Only one oscillating line of 2097.9 nm was observed with a FWHM linewidth of about 3.1 nm for three output transmittances, as shown in Fig. 2(b). Besides, no obvious fluctuations of central wavelength and linewidth were observed with varying of LD pump power.

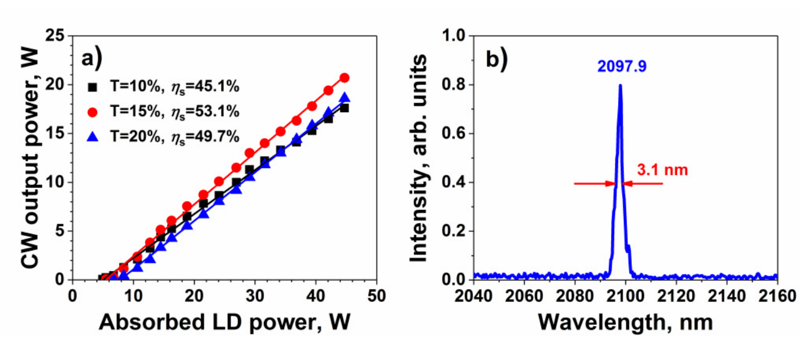

Fig. 2. The CW a) output power and b) spectrum of Ho:SYSO laser with different output transmittances.

With best output transmittance of 15%, we investigate the AO Q-switched performance of Ho:SYSO laser. Figure 3(a) gives the output powers under CW and Q-switched mode with different PRFs. At PRF of 20 kHz, the slab Ho:SYSO laser produced 19.6 W maximum average output power and 51.1% slope efficiency. For PRF of 10 kHz and 5 kHz, the slope efficiencies decreased to 47.4% and 44.0% and the maximum average output power decreased to 18.2 W and 17.1 W, respectively. With maximum output level at PRF of 20 kHz, the M^2 factors of Q-switched slab Ho:SYSO laser was measured by a slit scanning beam profiler (BP109-IR2, Thorlabs), as shown in Fig. 3(b). It can be seen that the M^2 factors were 1.6 and 1.9 in vertical and horizontal directions, respectively. Moreover, the output wavelengths of Q-switched Ho:SYSO laser were also measured by the optical spectrum analyzer. Compared with CW mode, no obvious changes were observed in the Q-switched mode.

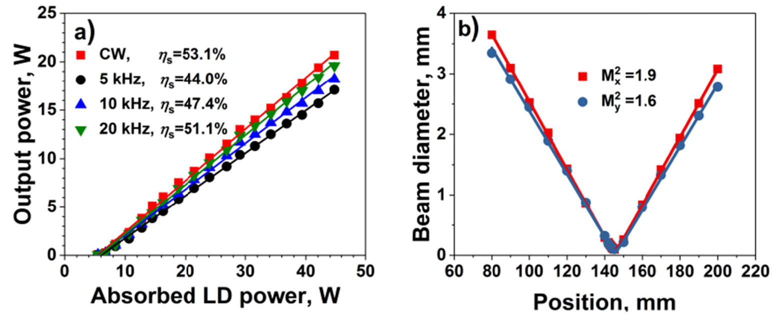

Fig. 3. The a) output power and b) M^2 factors measurement of AO Q-switched Ho:SYSO laser.

The temporal pulse profiles were detected by a fast InGaAs photodetector (ET-5000, EOT) and recorded by a digital oscilloscope (DPO4000, Tektronix). Figures 4(a), 4(b), and 4(c) depicted the pulse widths, pulse energies, and peak powers of AO Q-switched slab Ho:SYSO laser with PRFs of 5 kHz, 10 kHz and 20 kHz, respectively. Figure 4(d) depicts the profiles of the minimum pulse widths for above three PRFs. The minimum pulses widths of 20, 23 and 36 ns were obtained for three PRFs, respectively. The maximum pulse energies of 3.4, 1.8, and 1.0 mJ were achieved, corresponding to the calculating maximum peak powers of approximately 170 kW, 78.3 kW and 27.8 kW for PRFs of 5 kHz, 10 kHz and 20 kHz, respectively. In addition, the pulse-to-pulse stability was measured to be approximately 7% at PRF of 10 kHz. Table 1 summarizes the representative works of DPSSL silicate lasers at 2 µm. It is observed that our work increased the output power to 20W-level in DPSSL 2-µm silicate lasers and realized the highest slope efficiency.

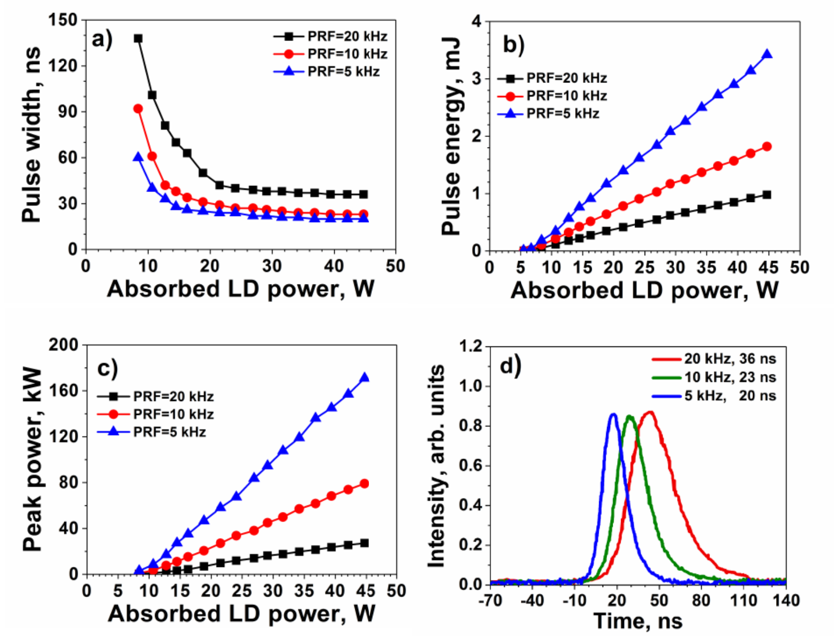

Fig. 4. The dependences of a) pulse widths, b) pulse energies, c) peak powers and d) minimum pulse profiles on PRFs of 5 kHz, 10 kHz and 20 kHz.

Table 1. Comparison of Output Characteristics of DPSSL 2-µm Silicate Lasers[a]

Gain mediums	dopant	l (mm)	λ_p (nm)	λ_l (nm)	P_{out} (W)	η_s	Ref.
Tm:LSO	4 at.%	5	790	2058.4	0.67	21%[b]	[15]
Tm:LSO	4 at.%	5	790	2054.9	0.65	21%[b]	[24]
Tm:LSO	3 at.%	7	790	2054.2	1.64	23.6%[b]	[25]
Tm,Ho:LSO	6at.%(Tm), 0.4at.%(Ho)	10	786	2070	3 (77K)	35%	[17]
Tm:SSO	4 at.%	3	792	~1980	0.52 (pulsed)	18.7%[b]	[16]
Tm:SSO	4 at.%	3	790	1976	1.02	16.1%	[26]
Tm:SYSO	4 at.%	3	790	2022	0.58	17.4%[b]	[21]
Ho:SYSO	0.5 at.%	20	~1910	2097.9	20.7 (CW) 3.4mJ(5kHz)	53.1%[b] 44.0%[b]	this work

[a]Where dopant is the doping concentration of RE ions, l is the doping length, λ_p is the pump wavelength, λ_l is the lasing wavelength, P_{out} is the maximum output power, and η_s is the slope efficiency, [b]with respect to absorbed pump power.

4. Conclusion

In summary, the first CW and AO Q-switched DPSSL slab Ho:SYSO laser was demonstrated. With 1.91-µm LD pumping, the slab Ho:SYSO laser delivered as high as 20.7 W output power at 2097.9 nm and 3.4 mJ pulse energy at PRF of 5 kHz under CW and Q-switching regime, corresponding to the slope efficiency of 53.1% and 44.0%, respectively. At the maximum output level, the M^2 factors of AO Q-switched slab Ho:SYSO laser were measured to be 1.6 and 1.9 for vertical and horizontal directions, respectively. This DPSSL AO Q-switched slab Ho:SYSO laser is a potential choice of pump source for high power compact middle infrared ZGP-OPO.

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