Diode-pumped laser performance of Tm:Sc_2SiO_5 crystal at 1971 nm*

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The 4-at.% Tm:Sc_2SiO_5 (Tm:SSO) crystal is successfully obtained by the Czochralski method. The optical properties and thermal conductivity of the crystal are investigated. The broad continuous wave (CW) laser output of (100)-cut Tm:SSO with the dimensions of 3 mm×3 mm×3 mm under laser diode (LD)-pumping is realized. The full width at half maximum (FWHM) of the laser emitting reaches up to 21 nm. The laser threshold of Tm:SSO is measured to be 0.43 W. Efficient diode-pumped CW laser performance of Tm:SSO is demonstrated with a slope efficiency of 25.9% and maximum output power of 934 mW.

Keywords: diode-pumped lasers, laser materials, crystal growth

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1. Introduction

The 2.0-μm lasers are promising lasers for both military and civil applications such as laser radar, remote sensing (1.8 μm–2.0 μm, $^3F_4 \rightarrow {}^3H_6$ transition), medicine (2.3 μm, $^3H_4 \rightarrow {}^3H_5$ transition), and telecommunication (1.5 μm, $^3H_4 \rightarrow {}^3F_4$ transition). The 2.0-μm laser based on Tm:$CaWO_4$ crystal was first reported at 77 K by Johnson *et al.* in 1962.[1] Later, lasing oscillation was operated successfully with a tungsten lamp-pumped Tm:YAG crystal at Bell Labs.[2] However, the Tm laser at 2.0 μm could only be achieved at low temperature (77 K) with a threshold up to 200 J–500 J at that time. With the advent of high-power AlGaAs laser diode (LD), Tm-doped crystals aroused particular interest, for their absorption bands are around 770 nm–800 nm (Tm^{3+}, $^3H_6 \rightarrow {}^3H_4$ transition) and the emission spectra intervals are around 1.8 μm–2.0 μm or 2.3 μm. In 1990, Stoneman and Esterowitz reported the continuous tunable laser from 1.87 μm to 2.16 μm (150 nm) of Tm:YAG crystal with a slope efficiency reaching up to 59%.[3] In 1998, 1.4-W-laser output at 1.9 μm was obtained from 6.9-at.% Tm:$GdVO_4$ crystal with a slope efficiency of 58%.[4] Then, diode-pumped 2.0-μm oscillation of Tm^{3+} has been demonstrated in numerous fluoride hosts such as $GdLiF_4$,[5] KY_3F_{10},[6] CaF_2,[7] $LiLuF_4$,[8] BaY_2F_8,[9] and KYF_4,[10] YLF[11] crystal. In 2008, 0.67-W-CW laser emitting at 2058.4 nm was obtained from Tm:Lu_2SiO_5 crystal with a slope efficiency of 21%.[12] Later, passive mode locking of a continuous wave diode-pumped Tm:KYW laser at 1.94 μm was demonstrated by using glass doped with PbS quantum dots as a saturable absorber in 2010.[13]

Sc_2SiO_5 (SSO) crystal with monoclinic structure obtained by the Czochralski method is of comprehensive interest due to its favorable thermal property (7.5 $W{\cdot}m^{-1}{\cdot}K^{-1}$) and the negative refractive index temperature coefficient (-6.3×10^{-6} K^{-1}). Sixfold coordinated Sc ions which were accommodated at two different crystallographic sites[14] can be substituted by rare earth ions easily. Er:SSO has been developed into a laser gain medium.[15] Passive mode-locking and CW laser performances of Yb:SSO[16–19] and Ho:SSO[20] crystal were also reported. The spectral behavior of Nd:SSO crystal

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showed that Nd:SSO would be a promising gain medium in solid-state lasers.[21,22] For Tm:SSO, the crystal structure and optical properties were investigated which display advantageous properties.[14,23,24] The laser potential of Tm:SSO crystal was assessed. In 2011, diode-pumped Tm:SSO laser emitting at 1.98 μm was reported, showing that the output power increased up to 520 mW and the slope efficiency reached 18.7%.[25] In this work, using the LD pumping source, the maximum output power of 934 mW is obtained and the corresponding slope efficiency reaches up to 25.9%. The encouraging results verify the good characteristic of Tm:SSO crystal for high average power. Besides, the LD laser performances are compared with those of Ti:sapphire pumping under different pump wavelengths.

2. Experiment

Sc_2SiO_5 crystal with a nominal 4-at.% Tm^{3+} concentration was obtained by the Czochralski method with the (010)-cut pure Sc_2SiO_5 crystal as a seed in nitrogen atmosphere (0.04 MPa). The seed was rotated at a rate of 20 rpm and the pulling rate was 1.0 mm/h. The transparent Tm:SSO crystal with a diameter of 30 mm was obtained. The density of 4.0-at.% Tm:SSO crystal was measured to be 3.49 g·cm^{-3} by the buoyancy method at room temperature.

Low temperature absorption spectra were recorded with Viarian Model 5E UV-VIS-NIR Absorption Spectrophotometer. Samples were placed into an Oxford Model CF 1204 continuous flow liquid helium cryostate equipped with a temperature controller. Spectrum bandwidth employed was 1.0 nm in near infrared (NIR) region. The NIR spectral region mentioned above was determined by PbS detector installed in the spectrophotometer. In order to acquire the data of low temperature emission spectra the same cryostate was used. The stimulated emission cross section can be conveniently evaluated by the reciprocity method which takes advantage of the relation between absorption cross section and emission transition between the ground and the first excited multiplet. The spectroscopic properties and the crystal structure of 4-at.% Tm:SSO has been reported in Ref. [14]. Figure 1 shows the absorption bands of $^3H_6 \rightarrow {}^3H_4$, $^3H_6 \rightarrow {}^3F_4$ transitions and the emission band of $^3F_4 \rightarrow {}^3H_6$ transition near 1.9-μm region. The absorption cross-section of Tm:SSO at 791 nm was about 5.55 $\times 10^{-21}$ cm^2.[14]

The refractive index along the ⟨100⟩-direction was about 1.8418 nm at 790 nm at room temperature. The values of thermal conductivity coefficient (κ) of the grown Tm:SSO crystal were measured to be 2.17 W·m^{-1}·K^{-1} for a crystallographic axis, 1.95 W·m^{-1}·K^{-1} for b crystallographic axis and 2.03 W·m^{-1}·K^{-1} for c crystallographic axis by the laser thermal conductivity meter (NETZSCH LFA427 MicroFlash, German), respectively. They were much smaller than that of pure SSO crystal (7.5 W·m^{-1}·K^{-1}). It is because of the decline of the crystal quality and the lattice distortion resulting from the difference in ionic radius between the Tm and Sc ions.

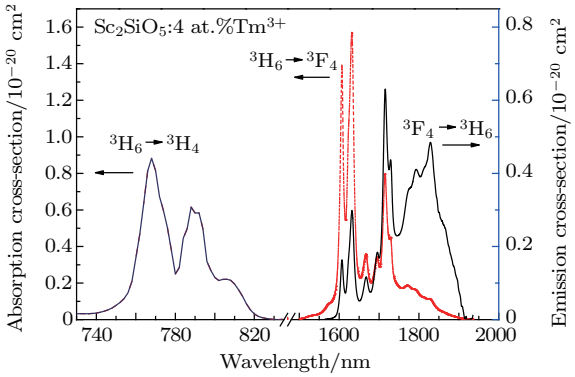


Fig. 1. (color online) Absorption bands of $^3H_6 \rightarrow {}^3H_4$, and $^3H_6 \rightarrow {}^3F_4$ transitions and the emission band of $^3F_4 \rightarrow {}^3H_6$ transition near 1.9-μm region.

We investigate the laser property in CW laser operation. An experimental setup is presented schematically in Fig. 2. A fiber-coupled diode laser, which was much cheaper than Ti:Sapphire laser and often served as a pumping source for 2.0-μm laser, was used as a pump source in this work. The LD pumping source had a core-diameter of 100 μm and numerical aperture (NA) of 0.22, emitting a laser beam with a wavelength of 790 nm at room temperature. A series of lenses, with an image ratio of 1:1, was used to focus the pump beam onto the crystal. The input mirror (IM) was composed of two flat mirrors, anti-reflection (AR) coated at 780 nm–810 nm at S1 face, high-reflection (HR) coated at 1900 nm–2000 nm at S2 face. The output coupler (OC) was a concave one with a curvature radius of 100 mm, AR coated at 1900 cm–2000 nm on S3 face, S4 face has transmission at 1900 nm–2000 nm of 5%. The length of the cavity (L) was 100 mm. The laser crystal is (100)-cut Tm:SSO with the dimensions of 3 mm×3 mm×3 mm. Both of the surfaces of the Tm:SSO crystal were coated with high transmission (HT) at 1900 nm–2000 nm and AR at 750 nm–850 nm. The temperature of cooling water was controlled to be 10 °C.

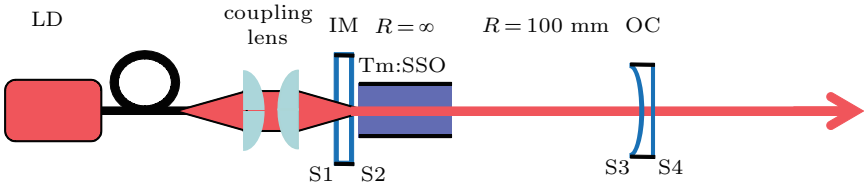


Fig. 2. (color online) Schematic setup of CW Tm:SSO laser.

3. Results and discussion

Figure 3 shows the spectrum of Tm:SSO laser, centered at 1971 nm. The FWHM reaches to 21.175 nm which is suitable for passive mode-locking and tunable laser output. Figure 4 shows the curve of the output power versus the absorbed pump power. The laser threshold of Tm:SSO laser is about 0.43 W. A slope efficiency of 25.9% is yielded by linear fitting to the experimental data with respect to incident diode power. The maximum output power reached to 934 mW with the beam quality M^2 of 1.4 when the pumping current is 17 A corresponding to a pumping power of 8.21 W. The absorbed power of pumping laser is about 4.02 W with an absorption efficiency of 49%. The maximum output power and the slope efficiency are much higher than that reported in Ref. [25]. As we know, doping concentration can affect laser output significantly, and it is more possible to obtain higher power with high concentration. From Ref. [25], the Tm^{3+} ion concentration of 3.6 at.% is lower than that in this work (4 at.%). Furthermore, higher slope efficiency of 25.9%, which is closely dependent on the crystal quality, indicates that the Tm:SSO crystal quality in this work is better. This is the best CW laser output result of Tm:SSO crystal. If we increase the current to 18 A, corresponding to the absorbed power of 4.4 W, the crystal cracks. The CW laser outputs of Tm:SSO with different output coupler T's and water temperatures are studied already and the maximum laser output power and slope efficiency, corresponding to $T = 5\%$ at a temperature of 10 °C, are 1.02 W and 16.1% respectively.[26] The passively Q-switched laser of Tm:SSO under LD-pumping is also reported and the mode-locked pulse width is sub-100 ps with a repetition rate of 92.6 MHz.[27]

Table 1 shows the comparison of the laser property between our work and the Tm laser in other hosts reported. The η value of Tm:SSO crystal is 25.9% which is lower than those of YAP, CaF_2, and KY_3F_{10} but higher than those of YAG and KYF_4. The data indicate that laser energy conversion efficiency of Tm:SSO is lower than those of YAP, CaF_2, and KY_3F_{10} but higher than those of YAG and KYF_4. The P_{thr} value of Tm:SSO, which is higher than those of $LuVO_4$, KYF_4, and BaY_2F_8 but lower than those of YAG, YAP, and $GdVO_4$, shows that the laser output under low input power is harder to generate than those of $LuVO_4$, KYF_4, and BaY_2F_8 but easier than those of YAG, YAP, and $GdVO_4$. The laser output power is almost 1 W which is remarkable. If the crystal quality is improved, the higher CW laser output power can be obtained.

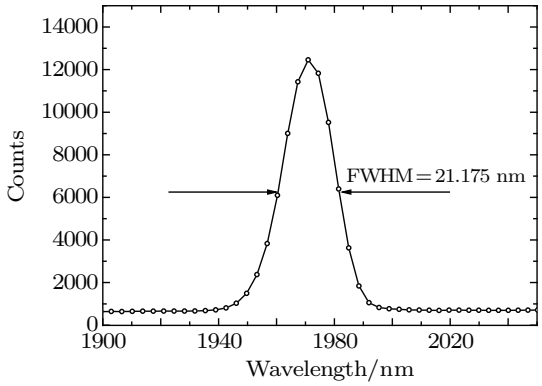


Fig. 3. Spectrum of Tm:SSO laser centered at 1971 nm.

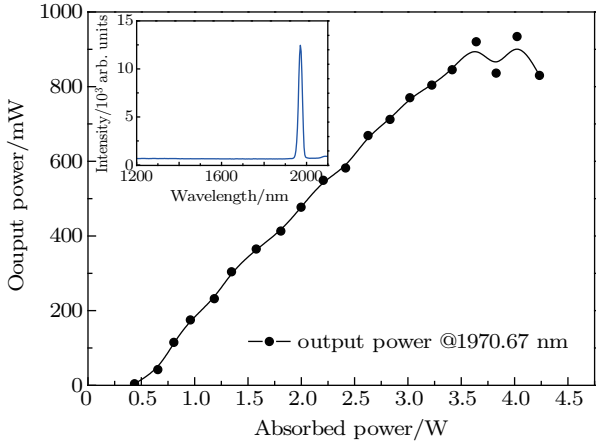


Fig. 4. (color online) CW laser output power of the Tm:SSO versus absorbed pump power, with inset showing the corresponding optical spectrum at the maximum output power.

Table 1. Laser properties (doping concentration, pumping source, maximum output power P_{out}, slope efficiency η, laser threshold P_{thr}) of Tm-doped hosts.

Hosts	Concentration	Pumping source	P_{out}/W	η/%	P_{thr} /W	Ref.
Tm:YAG	3.5	LD	200	22.8	600	[28]
Tm:KY_3F_{10}	4.7	777.8 nm	–	42.5	0.12	[6]
Tm:CaF_2	1.34	767 nm	–	41	0.068	[7]
Tm:BaY_2F_8	12	LD	0.65	32	0.185	[9]
Tm:KYF_4	10	LD	0.17	21	0.045	[10]
Tm:$LiLuF_4$	2	LD	10.4	40.4	–	[8]
Tm:$GdLiF_4$	8	LD	1.47	57	–	[5]
Tm:KLuW	5–15	LD	6	47	–	[29]
Tm:$GdVO_4$	7	808 nm	0.42	28	0.75	[30]
Tm:YAP	4	LD	8.5	44.5	5.6	[31]
Tm:$LuVO_4$	3	795.2	1.04	42.9	0.28–0.33	[32]
Tm:SSO	4	LD	0.934	25.9	0.43	this work

4. Conclusions

In this work, a 4-at.% Tm:SSO single crystal with high quality is grown by the Czochralski method. The CW laser performance at 1971 nm of the crystal under 790-nm LD pumping is investigated. The FWHM of wavelength is about 21 nm. The maximum output power is obtained at 934 mW with a slope efficiency of 25.9%. The mode-locking laser performances with the samples with higher quality are greatly anticipated.

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