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Compact passively Q-switched Tm:YLF laser with a polycrystalline Cr:ZnS saturable absorber

Yufen Dai, Yanyan Li, Xiao Zou, Benxue Jiang, Yin Hang, Yuxin Leng *

State Key Laboratory of High Field Laser Physics, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China

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ABSTRACT

A compact passively *Q*-switched diode-pumped Tm:YLF laser with polycrystalline Cr:ZnS as the saturable absorber is demonstrated. In the *Q*-switching regime, the maximum average output power reached 478 mW with the incident pump power of 16 W, which is the highest average output power for PQS Tm:YLF laser up to now. The maximum pulse energy of 529 μJ was obtained with 8.96 kW peak power and 59 ns pulse duration near 1.9 μm, respectively.

1. Introduction

Lasers based on Tm^{3+}-ion, emission around 2 μm, play an important role in medical applications, military technologies, remote sensing, and as well as can be used as the pumping sources for Cr:ZnSe laser and optical parametric oscillator to achieve efficient conversion into mid-infrared region [1–3]. Considering the simplicity, reliability and economy, passively *Q*-switched (PQS) with Cr:ZnSe/Cr:ZnS saturable absorbers (SAs) is a better choice to obtain laser pulses with short pulse duration and high peak power near 2 μm. The Cr:ZnSe/Cr:ZnS SAs have relative high absorption cross sections ($\sim 8.7\times10^{19}$ cm^2 for Cr:ZnSe and $\sim 5.2\times10^{19}$ cm^2 for Cr:ZnS) [4] which will result in the unnecessary requirement of intracavity focusing in PQS processes. And a lower saturable intensity (~11 kW/cm^2 for Cr:ZnSe and ~14 kW/cm^2 for Cr:ZnS) [4] of Cr:ZnSe/Cr:ZnS SAs will lead to a reduced vulnerability to damage during *Q*-switched operation [5]. The Cr:ZnSe/Cr:ZnS crystal SAs have been applied in several PQS lasers such as Tm:YAG, Ho:YAG [5], Tm:KY(WO_4) [6], Tm:$LiLuF_4$ [7], Tm:KLu(WO_4) [8], Tm-silica fiber [9], Er:glass [10], Er:YAG [11]. The better performance of PQS laser near 2 μm was achieved with a Tm:$LiLuF_4$ laser using polycrystalline Cr:ZnS SA(T_{SA}=78%) with the maximum pulse energy of 1.26 mJ and the shortest pulse duration of 7.6 ns, but the average output power was only 203 mW and the pulse repetition rate was 161 Hz [7].

Because of its natural birefringence, the weaker thermal lensing effect and better mechanical properties comparing with other Tm-doped materials, Tm:YLF laser crystal with absorption band at around 800 nm and emission band at 1850 nm–2000 nm is an attractive laser material to obtain efficient, simple and cost-effective diode-pumped solid-state lasers. At present, the Tm:YLF laser has been researched by several groups [12–14], such as stable output wavelength, narrow linewidth CW Tm:YLF laser has been demonstrated by Yao et al. with the maximum output power of 14 W based on double Fabry–Perot etalons and dual-end-pumping configuration [13]. But PQS Tm:YLF laser was reported less up to now, a PQS Tm:YLF laser with polycrystalline Cr:ZnS SA(T_{SA}=85%) has been demonstrated by Faoro et al., the maximum average output power is 98 mW and the repetition rate is 120 Hz with a pulse duration of ~14 ns [15].

In this letter, a compact PQS diode-pumped Tm:YLF laser based on a home-grown polycrystalline Cr:ZnS saturable absorber was demonstrated. With the polycrystalline Cr:ZnS SA inserted in the plano-concave resonant cavity, the maximum average output power reached 478 mW at 1885 nm under the incident pump power of 16 W, which is the highest average output power for PQS Tm:YLF laser up to now. The pulse repetition rate went from 60 Hz to 378 Hz and pulse duration varied from 75 ns to 59 ns with the increase of pump power. Up to 529 μJ pulse energy with 8.96 kW peak power and 59 ns pulse duration respectively was obtained at a pulse repetition rate of 378 Hz.

2. Experimental setup

The experimental setup of PQS Tm:YLF laser is shown in Fig. 1. The resonator consisted of a plane dichroic input mirror (high transmission at 793 nm, high reflectivity at 1850–2050 nm) and a

* Corresponding author. Tel.: +86 216 991 8423.
E-mail address: lengyuxin@mail.siom.ac.cn (Y. Leng).

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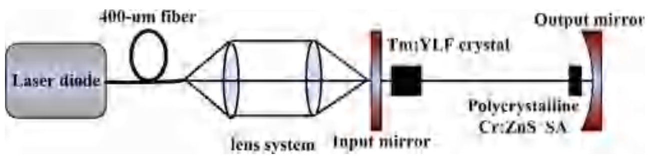

Fig. 1. Experimental setup of PQS Tm:YLF laser.

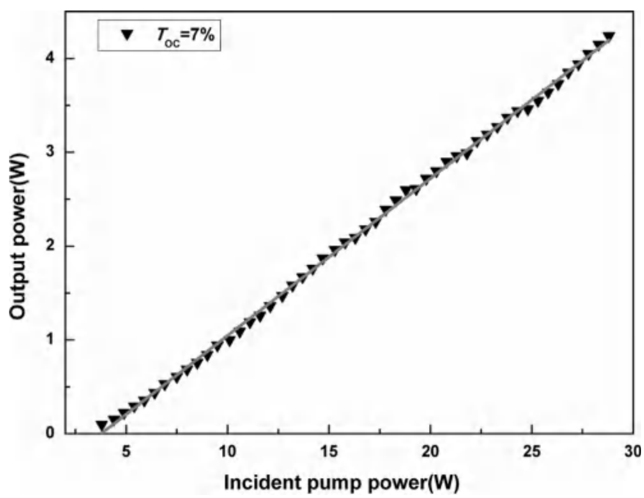

Fig. 2. CW laser performance of Tm:YLF laser.

spherical dichroic output coupler with a radius of curvature of 200 mm (high reflectivity at 793 nm, $T=7\%$ at 1918 nm). The length of the cavity was 195 mm. The pump light was a fiber-coupled laser diode with a 400 μm core diameter and an NA of 0.22, delivering up to 35 W at 793 nm. The incident pump beam was shaped and focused by the 1:1 lens system into the Tm:YLF crystal. The 4 at% Tm-doped YLF crystal (polished with parallel end faces, uncoated) was used as gain medium with dimensions of 5×5 (mm) in the cross section and 10 mm in length, and was wrapped with the indium foil and mounted in a water-cooler cooper block at the temperature of 15 °C. A polycrystalline Cr:ZnS with the transmittance of 78% at 1902 nm as the SA, provided by the Shanghai Institute of Optics and Fine Mechanics (SIOM). It was uncoated with dimensions of 5×3 (mm) in the cross section and 3 mm in length.

3. Results and discussion

In CW regime, without Cr:ZnS SA, the output power of Tm:YLF laser as a function of incident pump power with the 7% transmittance of output coupler is shown in Fig. 2. The threshold of pump power was 3.8 W, and the maximum output power of 4.5 W was achieved at 1902 nm with the slope efficiency of 17%. The laser radiation was σ polarized (perpendicular to the crystal c axis).

In the case of PQS regime, the Cr:ZnS SA was inserted next to the output coupler to decrease the energy density, in case that the SA was damaged. The average output power of PQS Tm:YLF laser is shown in Fig. 3. The threshold of pump power increased to 6 W. The maximum average output power of 478 mW was obtained under the incident pump power of 16 W, which is the highest output power for PQS Tm:YLF laser. The Q-switched conversion efficiency (the ratio of Q-switched average output power to the respective free-running output power) [10] of $\sim$17% was achieved at the maximum average output power.

The spectra of Tm:YLF laser in CW and PQS regime are shown in Fig. 4. The emission wavelength of PQS regime was 1885 nm shifted to shorter wavelength as compared to CW regime. The

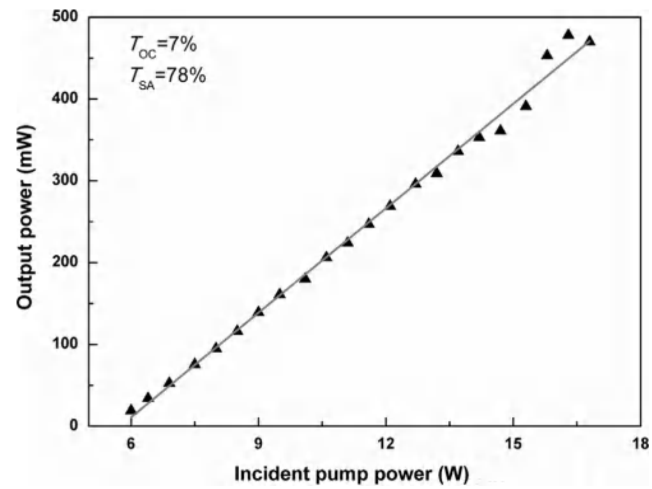

Fig. 3. Average output power of the PQS Tm:YLF.

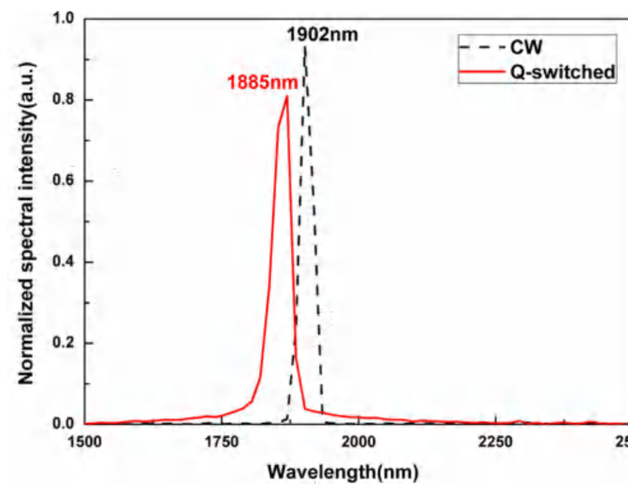

Fig. 4. Tm:YLF laser spectra in CW and PQS regimes.

polarization of laser radiation in PQS regime was π. The polarization switching is a result of higher gain for π polarization at shorter oscillation wavelength and is in accordance with the individual peaks observed in the polarized emission spectra of Tm:YLF [15,16]. The linewidth of PQS Tm:YLF laser as a function of incident pump power was also observed, as shown in Fig. 5. The linewidth was 45 nm near the threshold pump power, and the linewidth slightly narrowed with the increase of incident pump power.

Pulse duration and pulse repetition rate were detected by using an InGaAs PIN photodiode with 1 MHz cut-off frequency and recorded by using a Tektronix oscilloscope with 500 MHz bandwidth. The pulse duration and pulse repetition rate are shown in Fig. 6 as a function of incident pump power. The pulse duration was insensitive to the pump power, varying from 75 ns to 59 ns as the pump power increased, which was mainly caused by the cavity losses and the gain before pulses were independent from the pump power in PQS lasers. And the single pulse shape with pulse duration of 75 ns is shown in Fig. 7. The repetition rate was 60 Hz near threshold, increasing to 378 Hz at the pump power of 10.6 W. The coatings of mirrors were damaged as we measured the average output power at the pump power of 16 W, therefore, the pump power didn't been increased any more when we measured the pulse duration and the pulse repetition rate (the maximum incident pump power was 10.6 W), in case that the coatings of mirrors were damaged again by the high pulse energy. There is no

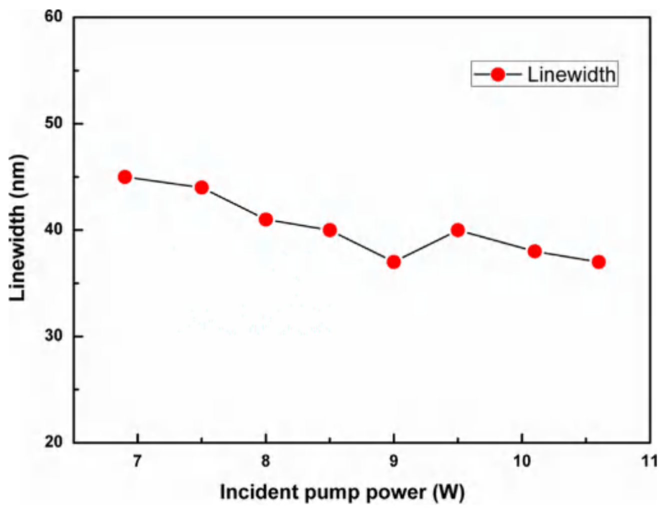

Fig. 5. Linewidth of PQS Tm:YLF laser versus incident pump power.

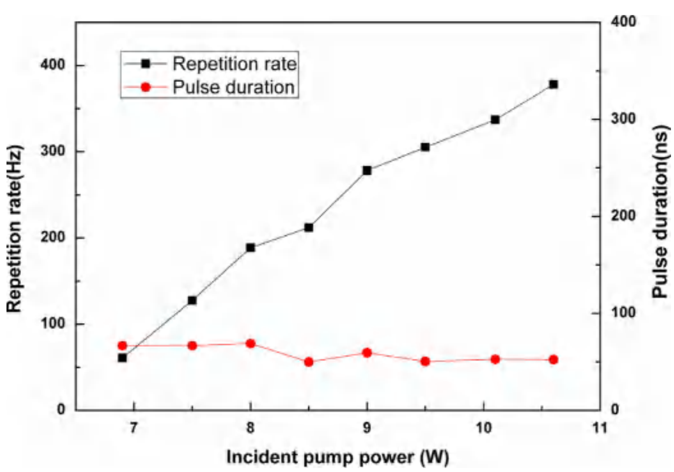

Fig. 6. Repetition rate and pulse duration of PQS Tm:YLF laser.

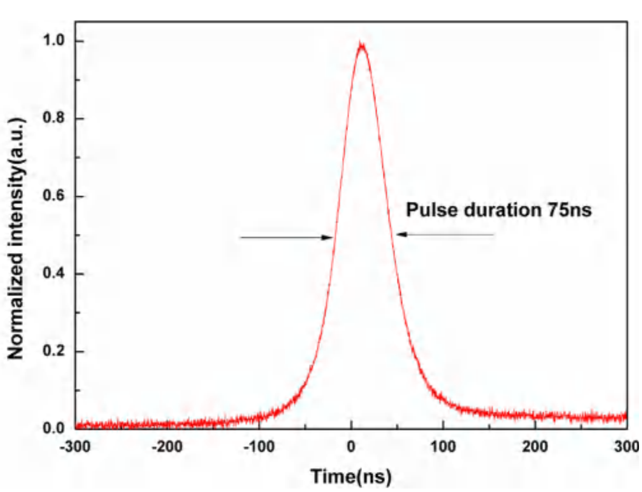

Fig. 7. Single pulse shape with pulse duration of 75 ns.

saturation for pulse repetition rate as is shown in Fig. 6, which means higher pump power if available will lead to higher repetition rate.

Up to 529 μJ pulse energy with 8.96 kW peak power and 59 ns pulse duration was obtained respectively at a pulse repetition rate of 378 Hz. Small jitters were observed in PQS regime. The instabilities of the system were mainly caused by the intrinsic nonlinear dynamics of the system such as the deterministic chaos and the thermal effect of SA and the structure of gain media [17–19]. On the other hand, the lifetime of upper laser level in Tm-doped laser hosts is several milliseconds, which far greater than the photon lifetime in resonant cavity. Thus, it will result in relaxation oscillation in intensity of laser, which may lead to the instability of repetition rate as well as the damage of coatings on cavity mirrors. In PQS regime, according to the theoretical analysis [20] and experimental data from letters [7,15] have published, the transmittance of SA is critical to obtain high pulse energy and short pulse duration, therefore, different transmittance of polycrystalline Cr:ZnS SA will be employed in further research.

4. Conclusion

In conclusion, a compact PQS diode-pumped Tm:YLF laser with polycrystalline Cr:ZnS as the SA was demonstrated. In the case of PQS regime, under the incident pump power 16 W, the maximum average output power reached 484 mW at 1885 nm. The pulse repetition rate increased from 60 Hz to 378 Hz and pulse duration varied from 75 ns to 59 ns with the increase of pump power. Up to 529 μJ pulse energy with 8.96 kW peak power and 59 ns pulse duration was obtained, respectively at a pulse repetition rate of 378 Hz. Further research will focus on higher pulse energy and shorter pulse duration of 2 μm diode-pump solid-state lasers.

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