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High pulse energy passive Q-switching of a diode-pumped Tm:YLF laser by Cr:ZnSe

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Abstract

A passively Q-switched diode-pumped Tm:YLF laser with polycrystalline Cr:ZnSe as the saturable absorber is demonstrated for the first time, to the best of our knowledge. By using saturable absorbers with different initial transmission, the maximum pulse energy reached 4.22 mJ with peak power of 162.3 kW for a pulse duration of 26 ns. The maximum output average power amounted to 2.2 W. These results constitute significant improvement from the highest average power, pulse energy and peak power results for the PQS Tm:YLF laser to date.

Keywords: diode pumped solid state lasers, passive Q switched lasers, rare earth doped and insulator lasers, mid infrared lasers

(Some figures may appear in colour only in the online journal)

1. Introduction

Lasers operating in the 2 μm region, especially pulsed lasers, have been proposed for applications in a wide variety of fields. The significant absorption in water and therefore in human tissue causes these lasers to be attractive for medical applications, such as surgery. Lasers at 2 μm work as a pump source for non-linear crystals or for Cr:ZnSe lasers and optical parametric oscillators. 2 μm laser sources are also attractive for military applications: this region is both eye-safe and shows low atmospheric absorption, making it an excellent wavelength for remote sensing, laser radar, infra-red countermeasures, and optical communications [1, 2].

The Tm ion, emitting on the ^{3}F4 $\rightarrow$ ^{3}H6 transition, is attractive because its absorption band around 800 nm matches the emission of AlGaAs laser diodes designed for Nd^{3+}-ion pumping. Passive Q-switching of such diode-pumped solid state lasers by a saturable absorber (SA) is a widespread technique to get short pulses, due to the simplicity, reliability and low cost of the system design. The Cr:ZnSe and Cr:ZnS SAs have relative high absorption cross sections [3], and thus do not necessarily require focusing the laser mode to a small area on the saturable absorber. This feature allows more flexibility in the resonator design. Another advantage of these crystals is a low saturable intensity which leads to a reduced risk of damage during Q-switched operation [4].

The Cr:ZnS crystal SA has been applied in several PQS lasers such as Ho:YAG [5, 6], Tm:KY(WO4) [7], Tm:KLu(WO4) [8]. From the different gain media that have been reported, the fluoride crystalline hosts have showed the best performances so far. Faoro *et al* [9] first demonstrated a PQS Tm:YLF laser with polycrystalline Cr:ZnS SA with 0.9 mJ pulse energy. Dai *et al* reported a similar system in which maximum average output power reached 478 mW [10]. In another work [11], 1.26 mJ was obtained with Tm:$LiLuF_4$ as the gain medium and Cr:ZnS as the SA. With Tm:BYF [12], 0.72 mJ of pulse energy was obtained with Cr:ZnS as the SA in a 40 ns pulse. These high extracted pulse energies are due to the long excited state lifetime in fluoride hosts that allows high energy storage. These reports demonstrate the importance of the fluoride matrices as hosts for Tm active ion based lasers.

A well-known condition for a SA to fulfill passive Q switch requirements is $\sigma_{sa}/A_{sa} > \sigma_g/A_g$, where σ_{sa} and σ_g are the absorption cross section of the SA and the emission cross

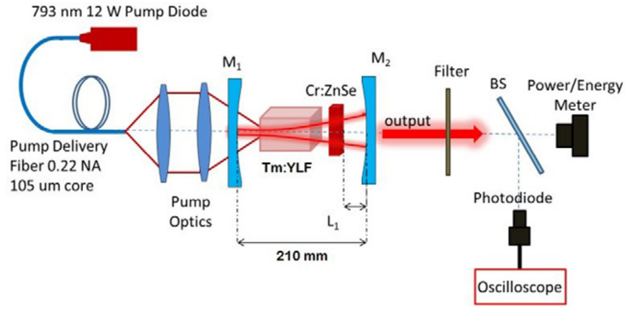

Figure 1. Schematic of the experimental setup.

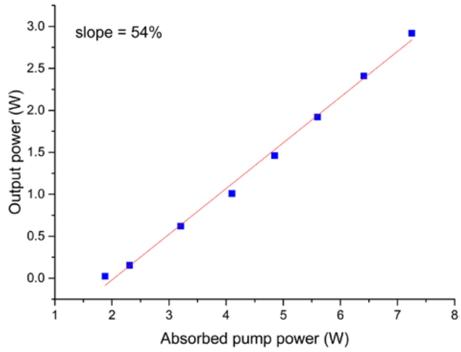

Figure 2. Output power in CW operation.

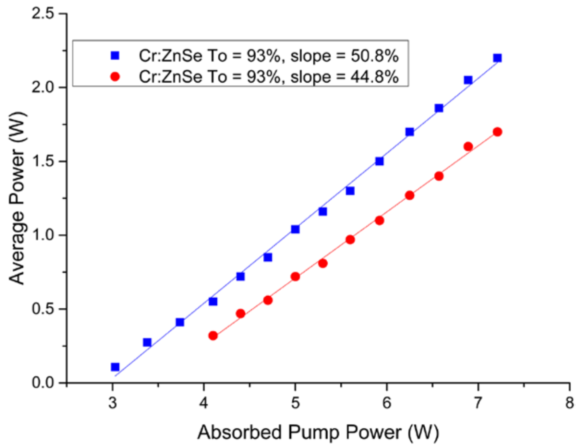

Figure 3. Laser average power in pulsed operation.

section of the gain medium at the lasing wavelength, respectively, and A_{sa} and A_g are the mode area at the SA and gain medium.

Due to the Cr:ZnSe higher absorption cross section than the Cr:ZnS crystal, ($8.7 \times 10^{19}\,cm^2$ for Cr: ZnSe and $5.2 \times 10^{19}\,cm^2$ for Cr:ZnS) [3], Cr:ZnSe should be better suited as passive Q switch since it meets the mentioned criterion at lower intracavity fluencies. However, to date, only the use of Cr:ZnS as the SA successfully led to high output pulse energy in Tm doped gain media. A few attempts to use Cr:ZnSe as a SA did not success [8] nor lead to significant results. In [13], Cr:ZnSe was used to passively Q switch a Tm doped silica fiber, but the obtained pulse energy was only 4.3 μJ. In [14], a Tm:YAG in combination with Cr:ZnSe outputted 0.4 mJ of pulse energy but the pulse width of 300 ns was rather long, resulting in low peak power. In contrast, in [4], Cr:ZnSe was used as the PQS for a Tm:YAG laser and a high pulse energy was reported but the system was flashlamp pumped, resulting in very low efficiency.

The motivation for this work was to investigate the potential of Cr:ZnSe as a PQS by using it in a combination with a Tm doped fluoride gain crystal.

In this letter, we report significant improvement in pulse energy, peak power and average power in a Tm:YLF laser using polycrystalline Cr:ZnSe as SA instead of Cr:ZnS.

To the best of our knowledge, this is the first time that Cr:ZnSe is used as PQS for a Tm:YLF laser. The maximum pulse energy reached 4.22 mJ with peak power of 162.3 kW for a pulse duration of 26 ns. The maximum output average power amounted to 2.2 W.

2. Experimental setup

For the laser experiments, we used a linear resonator design, see figure 1. The pump was delivered through a plano-concave input mirror (M1) with a radius of curvature of $R = -100$ mm, antireflection (AR) coated for the pump wavelength and high reflection (HR) coated for the 1850–2000 nm range. For the output couplers (M2), a plano-concave mirror with $R = -200$ mm coated with different reflection coefficients (70 and 90%) were applied. The total resonator length was 210 mm. The pump was delivered by a fiber coupled AlGaAs laser diode with a 105 μm core diameter and a NA of 0.22, emitting up to 12 W at 793 nm. The pump beam was collimated and focused into an initial pump spot radius of 200 μm on the Tm:YLF crystal through the input resonator mirror. The Tm:YLF laser crystal was 8 mm long and has a cross section of 3 × 3 mm. The Tm-doped concentration was 4 at.%. The laser crystal was wrapped in Indium foil and placed in a copper holder. The holder is inserted in a circulating water cooled aluminum housing and maintained at 18 °C for heat dissipation. Two Cr:ZnSe (IPG Photonics) were specified with low signal transmission (corrected for Fresnel reflections) of $T_0 = 93$ and 85%.

The SA optimal position that maximized the pulse energy without damaging the crystal surfaces was experimentally found to be $L_1 \sim 8$ cm from the output.

The SAs were ~2 mm thick with apertures of 4 × 4 mm. They were placed in copper holders without a cooling coupler.

After filtering the residual pump power, the output pulses were detected with an extended InGaAs photodiode with 12.5 GHz bandwidth. The repetition rate and FWHM were measured on a fast oscilloscope. The pulse energy and average power were measured with a pyroelectric energy sensor (PE-50-C, Ophir Optronics) and a thermopile sensor (3A-FS-SH, Ophir Optronics), respectively. The laser spectrum was acquired by an extended InGaAs 1D array spectrometer (BaySpec).

3. Experimental results and discussion

In CW operation, without SA, the output power of the Tm:YLF laser as a function of incident pump power with a 90% reflectance output coupler is shown in figure 2. The

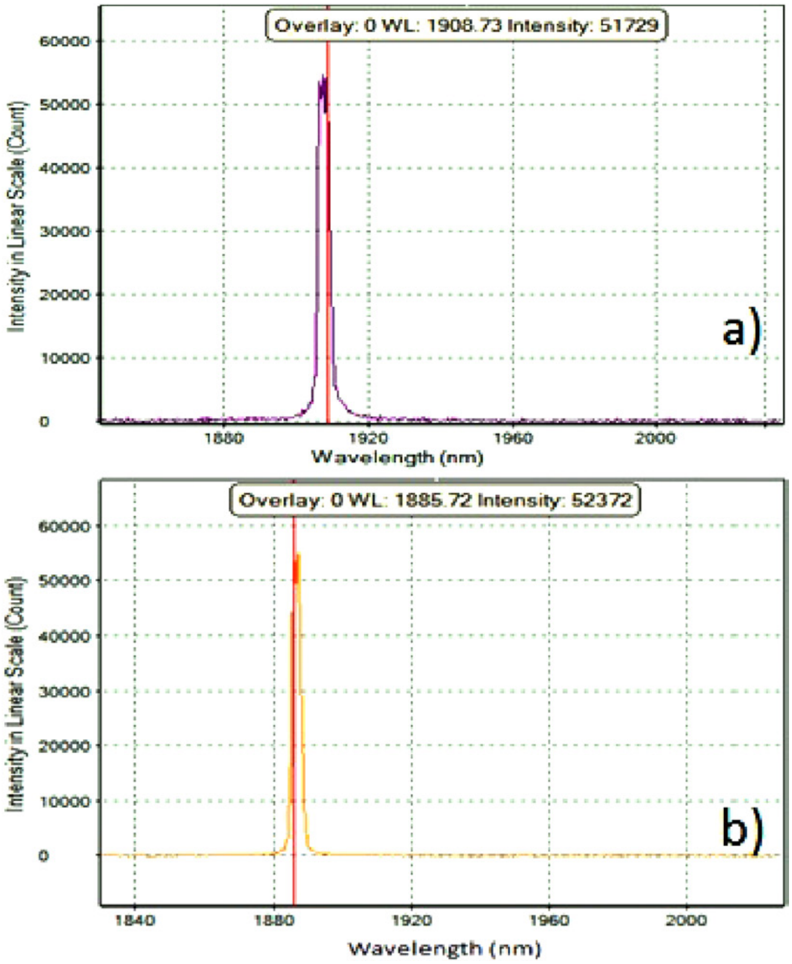

Figure 4. Laser emission spectrum. (*a*) The spectrum's peak at 1908 nm for CW operation. (*b*) The spectrum's peak at 1885 nm for pulsed operation.

pump power threshold was 2.97 W, and the maximum output power of 2.92 W was achieved at ~7 W absorbed pump power. The slope efficiency was 30.1% and the measured emission wavelength was at 1908 nm (see figure 4(*a*)). The laser radiation was σ polarized (perpendicular to the crystal *c* axis).

For PQS operation, the obtained average output power is shown in figure 5. The corresponding pulse width, pulse energy, peak power and repetition rate are shown in figure 5. With Cr:ZnSe SA of a T_0 = 93% and 70% reflectance output coupler, the highest average output power of 2.2 W was achieved with optical conversion and slope efficiencies of 30.5 and 50.8%, respectively. The repetition rate increased almost linearly with the pump power reaching 860 Hz at a single pulse energy of 2.6 mJ. The measured minimum FWHM pulse duration was 40 ns, resulting in a peak power of 65 kW.

With Cr:ZnSe SA of T_0 = 85% and 70% reflectance output coupler, the maximum average output power was 1.7 W. The optical conversion and slope efficiencies were 23.6 and 44.8%, respectively. At maximum absorbed pump power, the repetition rate was 400 Hz, and the single pulse energy of 4.22 mJ, together with a FWHM pulse width of 26 ns, correspond to a peak power of ~160 kW. It should be noted that during the measurements, no secondary pulses nor parasitic emission between pulses were observed. These average power, pulse energies and peak powers are the highest reported, so far, for a Tm:YLF passively Q-switched laser.

The spectra of Tm:YLF laser in the PQS regime is shown in figure 4(*b*). The emission wavelength of the PQS regime was 1885 nm, blue shifted to a shorter wavelength as compared to the CW regime. The polarization of laser radiation in the PQS regime was π. The polarization switching is a result of higher gain for π polarization at shorter oscillation wavelength, due to the quasi three level nature of the gain medium and is in accordance with the individual peaks observed in the polarized emission spectra of Tm:YLF [9, 15]. A typical pulse shape for the T_0 = 93% Cr:ZnSe SA is shown in figure 6. It can be noticed that the pulse duration does not significantly change with the pump power.

4. Conclusion

To summarize, passively Q switching of a Tm:YLF laser with a Cr:ZnSe saturable absorber was demonstrated, for the first time, to the best of our knowledge. The maximum average output power was 2.2 W achieved by Cr:ZnSe SA of

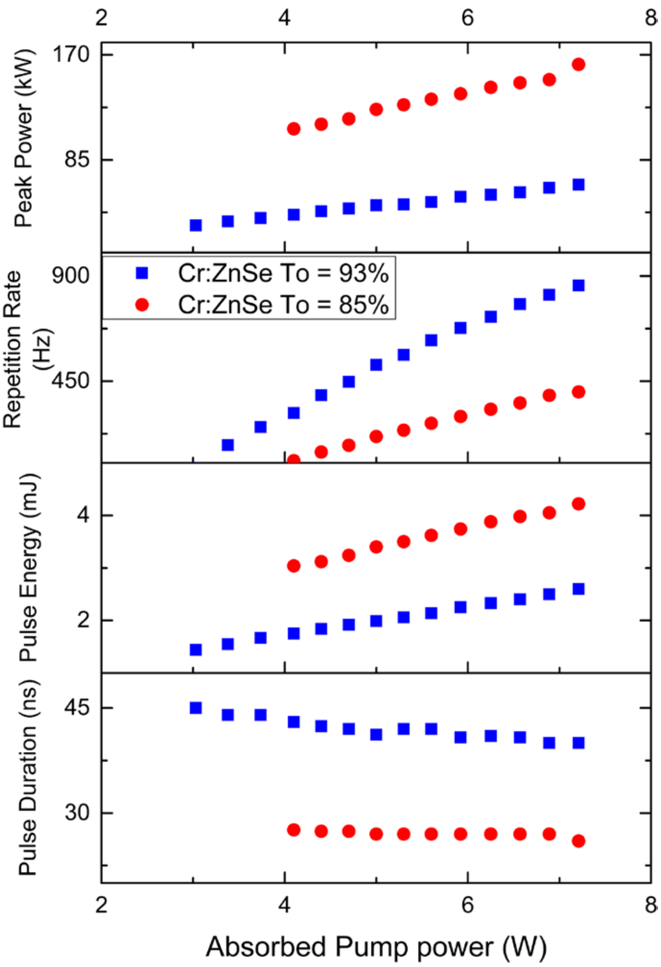

Figure 5. Pulse parameters for the passive Q switched Tm:YLF laser.

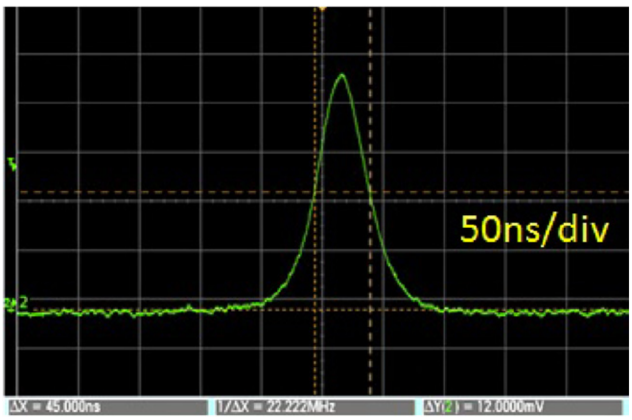

Figure 6. Typical pulse shape with a measured FWHM of 45 ns for Cr:ZnSe with $T_0 = 93\%$.

T_0 = 93%. With a T_0 = 85% Cr:ZnSe, the maximum pulse energy was 4.22 mJ, with minimum pulse width of 26 ns, corresponding to a peak power of ~160 kW. These results are the highest achieved so far for a Tm:YLF laser, and make this source attractive for high peak power applications.

Acknowledgments

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