Passive $Q$-switching of the diode pumped Tm$^{3+}$:KLu(WO$_4$)$_2$
laser near 2-µm with Cr$^{2+}$:ZnS saturable absorbers

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Abstract: Pulse energies as high as 145 µJ, peak powers of 6 kW and pulse durations in the 25-30 ns range were generated with a passively $Q$-switched diode-pumped Tm$^{3+}$:KLu(WO$_4$)$_2$ laser using polycrystalline Cr$^{2+}$:ZnS as saturable absorber.

1. Introduction

Infrared 2 µm solid-state lasers based on Tm$^{3+}$:Ho$^{3+}$ and codoped (Tm$^{3+}$:Ho$^{3+}$) active media are important for medical applications due to the strong optical absorption by water, and remote sensing (LIDAR) of CO$_2$ and water in the atmosphere, as well as for pumping Optical Parametric Oscillators (OPO's) for conversion into the mid-IR. The Tm$^{3+}$ ion, emitting on the $^4_{F_4} \rightarrow ^3_{H_6}$ 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 (PQS) of such diode-pumped solid state lasers (DPSSL) by a saturable absorber (SA) is a common technique to generate short and high peak power pulses, mainly due to the simplicity and low cost of the cavity design. It has been applied to several Tm$^{3+}$-doped laser materials such as YAG [1], KY(WO$_4$)$_2$ [2,3], and YAP [4] using Cr:ZnSe and Cr:ZnS crystals, PbS quantum dots, and InGaAs/GaAs semiconductor based SAs.

PQS in monoclinic double tungstate crystals around 1.9 µm with Cr$^{2+}$:ZnS and Cr$^{2+}$:ZnSe SAs was first investigated using Tm$^{3+}$:KY(WO$_4$)$_2$ and codoped Yb$^{3+}$,Tm$^{3+}$:KY(WO$_4$)$_2$ [2]. The best result of 116 mW output power at a repetition rate of 20 kHz with Yb$^{3+}$,Tm$^{3+}$: KY(WO$_4$)$_2$ and Cr$^{2+}$:ZnS corresponds to a single pulse energy of 6.7 µJ and a pulse duration of 63 ns. Note that such high repetition rates do not allow one to fully utilize the long storage time of Tm which intrinsically limits the pulse energy. More recently, PQS of Tm$^{3+}$:KY(WO$_4$)$_2$ has been achieved also using PbS-doped glass as SA [3]. In this set-up, up to 44 µJ of single pulse energy was produced at a repetition rate of 2.5 kHz but for the pulse duration only an upper detection limit of 60 ns was given. In previous work, we demonstrated $Q$-switched laser pulses generation in Tm$^{3+}$:KLuW laser using Cr$^{2+}$:ZnSe as saturable absorber delivering pulse energies as high as 16 µJ at a repetition rate of 6.5 kHz at 1908 nm [4].

Other Tm$^{3+}$ laser crystals were passively $Q$-switched using semiconductor based SAs, e. g. Tm$^{3+}$:YAP [5] achieving a maximum pulse energy of 28.1 µJ at a repetition rate of 43.7 kHz, however, the pulse duration, 447 ns, was rather long. The highest pulse energy (~400 µJ) from a diode-pumped PQS laser, to the best of our knowledge, has been achieved with Tm$^{3+}$:YAG using Cr$^{2+}$:ZnSe as SA [1], however, the pulse duration in this laser was also untypically long for PQS (about 300 ns), resulting in a peak power of about 1 kW.

In this work, PQS of a DPSSL based on the monoclinic potassium lutetium tungstate KLu(WO$_4$)$_2$, doped with 3 at.% Tm$^{3+}$ is reported (hereafter Tm:KLuW). In these biaxial crystals, three principal optical axes exist associated with the three refractive indices, $n_p<n_m<n_g$. The $N_p$ principal optical axis is parallel to the $b$ crystallographic axis. The other two axes of the optical ellipsoid, $N_m$ and $N_g$, lie in the $a$-$c$ crystallographic plane and the location of $N_g$ with respect to the $c$ crystallographic axis is at 18.5º in the clockwise direction when $b$ is pointing towards the observer [6]. Among the attractive properties of KLuW as host are the high absorption and emission cross sections for the pump and laser radiation for the selected polarization along $N_m$ and the possibility of high doping level.

2. Experimental setup

For the laser experiments, we constructed an L-shape hemispherical resonator depicted in Fig. 1. The pump was delivered through the plane mirror (M1), antireflection (AR) coated for the pump wavelength (802 nm) and high reflection (HR) coated for the laser wavelength (1900-2400 nm). As output coupler (M3) we tested mirrors with transmission $T_{oc}=5\%$ and 10\% (1820-2050 nm) and radius of curvature $R_{oc}=-75$ mm. The bending mirror (M2) was
plane, AR_p-polar (45°, 790-820 nm) and HR_p-polar (45°, 1700-2280 nm) + HR_p-polar (45°, 1790-2120 nm). The pump source was a fiber-coupled (NA=0.22, 200 µm core diameter) AlGaAs diode laser delivering up to 10 W at 802 nm. The active elements were cut for propagation along the $N_p$ direction with dimensions $2 \times 3 \times 3 \text{ mm}^3$ along $N_p \times N_m \times N_g$. The AR-coated samples (both for pump and laser wavelengths) were mounted in a Cu holder with circulating water at 16°C for heat dissipation. The incident pump beam was focused to a 200 µm spot diameter on the crystal with a lens assembly of 20 mm focal length. The polycrystalline $\text{Cr}^{2+}$:ZnS SA samples (IPG Photonics), were specified with low signal transmission (corrected for Fresnel reflections) of $T_0=78$, 85 and 92% at 1910 nm. The AR-coating reduced the reflection to about 1% per surface. The SAs were 2.2 mm thick, with lateral dimensions of $4.5 \times 9.3 \text{ mm}^2$. The output pulses were detected with a fast InGaAs photodiode with <35 ps risetime and measured with a LeCroy oscilloscope with 1 GHz bandwidth.

3. Results

In order to avoid direct heating of the SA by the non-absorbed residual pump, we designed the L-shaped cavity with a length of $L_1+L_2=L_c$ and $L_1=30$ mm, in which the folding mirror transmits the non-absorbed pump. The estimated laser beam diameters were 140 and 350 µm at the $\text{Tm}^{3+}$:KLuW crystal and SA position ($L_{SA}=40$ mm), respectively.

Figure 2a shows the average output power, repetition rate, pulse energy and pulse duration (FWHM) obtained in stable PQS regime using $T_{oc}=10\%$ and Fig. 2b the same parameters with $T_{oc}=5\%$ for which only the $T_0=92\%$ SA ensured stable operation. For $T_{oc}=10\%$, the SA with $T_0=92\%$ Q-switched the laser in almost any position in the second arm but the highest output power was obtained at the maximum possible separation from the output coupler, $L_{SA}=40$ mm (350 µm spot size). For $T_{oc}=5\%$, with the same SA most stable operation was achieved at $L_{SA}=20$ mm (400 µm spot size). The maximum average output power amounted to 0.39 W with $T_{oc}=10\%$ and 0.26 W with $T_{oc}=5\%$ at incident pump powers of 4.2 and 3.5 W, respectively, the limits set by SA bleaching. At the same pump...
levels, the output power in the CW regime (SA removed), was 0.66 and 0.75 W for $T_{oc}=10\%$ and 5\%, respectively, which translates into CW to PQS conversion of 59\% and 35\%, respectively. The estimated small-signal absorption of the Tm$^{3+}$:KLuW crystal was 70\%, so that the net pump efficiency in the PQS regime was 13\% and 11\% for $T_{oc}=10\%$ and 5\%, respectively.

![Figure 3. a) Pulse train stability (prr: pulse repetition rate), and b) single pulse shape using $T_{oc}=10\%$ and Cr$^{2+}$:ZnS SA with $T_0=92\%$.](image)

The laser wavelength in PQS operation for $T_{oc}=5\%$ was $\lambda_L=1918$ nm with 2 nm bandwidth, while the laser emission for $T_{oc}=10\%$ was in the $\lambda_L=1917-1925$ nm range. The instabilities of the pulse train reduce with increasing power, e.g. from ±20\% at $P_{inc}=3.5$ W to ±10\% at $P_{inc}=4.2$ W (Fig. 3a) for $T_{oc}=10\%$. The pulse shape corresponding to this case is shown in Fig. 3b. With the $T_0=92\%$ SA, the pulse duration was slightly shorter for $T_{oc}=10\%$ in comparison to $T_{oc}=5\%$, decreasing typically from ~30 ns to ~24 ns. The shortest pulses (~10 ns) for $T_{oc}=10\%$ were obtained with the $T_0=78\%$ SA for a pulse energy of 50 $\mu$J (Fig. 2a), the peak power is 5 kW. The repetition rate at maximum power with $T_{oc}=5\%$ was 2 kHz corresponding to a maximum single pulse energy of 127 $\mu$J and maximum peak power of 4.4 kW. The maximum energy achieved with $T_{oc}=10\%$ was 145 $\mu$J at a repetition rate of 2.7 kHz, with peak power of 6 kW. In fact this energy corresponded to saturation at incident pump powers ~4 W, with further increase of the average output power only due to the increasing repetition rate (Fig. 2). The quality of the beam, determined by the knife-edge method, was $M^2_x = M^2_y = 1.2$.

4. Conclusion

We have achieved passive Q-switched operation of a diode-pumped Tm$^{3+}$:KLuW laser emitting near 1920 nm using polycrystalline Cr$^{2+}$:ZnS samples as saturable absorbers. The best results without optical damage were obtained with $T_{oc}=10\%$ and $T_0=92\%$ for 3 at.% Tm doping in terms of maximum energy of 145 $\mu$J, pulse durations in the 24-30 ns range, repetition rate around 2.7 kHz and 0.39 W of average output power. In comparison with [2], based on similar laser crystal and SA, the improvement achieved is by a factor $>3$ in the average power, $>20$ in the pulse energy and $>50$ in the peak power. We conclude that polycrystalline Cr$^{2+}$:ZnS is superior as SA at wavelengths around 2 µm in comparison with PbS quantum dots-doped glass [3] or semiconductor SAs [5] for PQS of diode-pumped Tm$^{3+}$-lasers.

References


