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.

OCIS codes: (140.3540) *Q*-Switched lasers; (140.3070) Infrared and far-infrared lasers; (140.3480) Lasers, diode-pumped

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 $^3F_4 \rightarrow {}^3H_6$ 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, $AR_{s\text{-pol},p\text{-pol}}$(45°, 790-820 nm) and $HR_{s\text{-pol}}$(45°, 1700-2280 nm) + $HR_{p\text{-pol}}$(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_g direction with dimensions 2 × 3 × 3 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 16ºC 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 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 × 9.3 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.

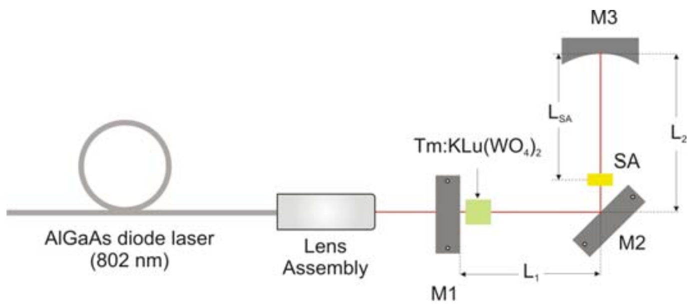

Fig. 1. Setup of the PQS Tm^{3+}:KLuW laser. SA: Cr^{2+}:ZnS saturable absorber, M1: dichroic pump mirror, M2: HR-laser, HT-pump mirror, M3: output coupler.

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 Tm^{3+}:KLuW crystal and SA position (L_{SA}=40 mm), respectively.

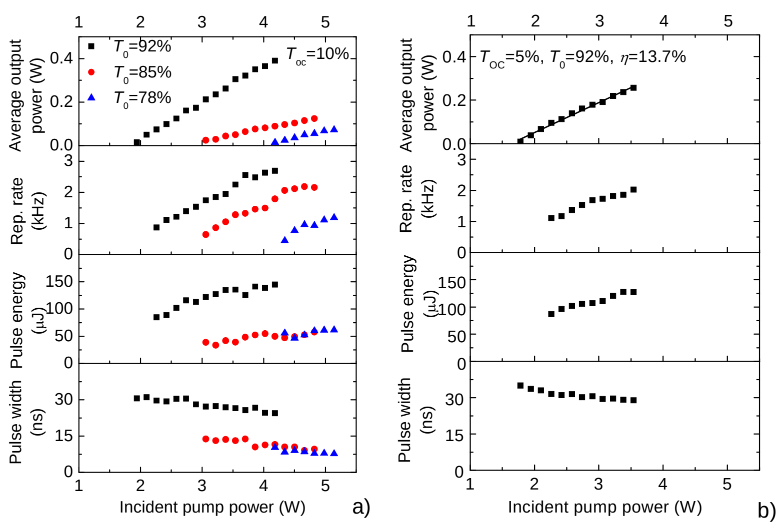

Fig. 2. PQS characteristics of the 3 at.% Tm^{3+}:KLuW laser with a) T_{oc}=10% for T_0=92%, 85% and 78% Cr^{2+}:ZnS SAs, and b) T_{oc}=10% for T_0=92%.

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.

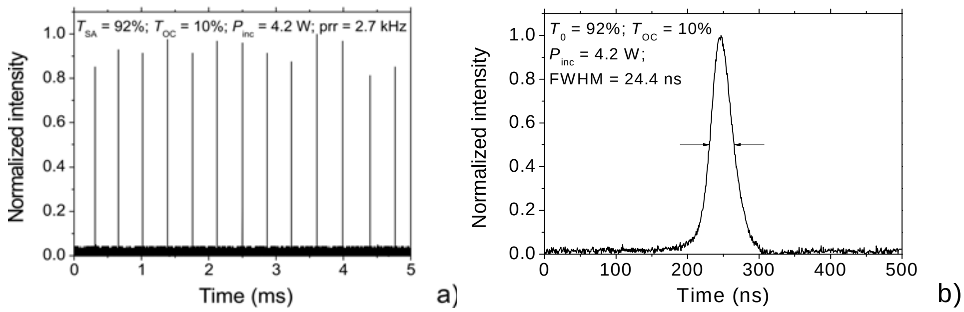

Fig. 3. a) Pulse train stability (prr: pulse repetition rate), and b) single pulse shape using T_{oc}=10% and Cr^{2+}:ZnS SA with T_0=92%.

The laser wavelength in PQS operation for T_{oc}=5% was λ_L=1918 nm with 2 nm bandwidth, while the laser emission for T_{oc}=10% was in the λ_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 µJ (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 µJ and maximum peak power of 4.4 kW. The maximum energy achieved with T_{oc}=10% was 145 µJ 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 $M_x^2 = M_y^2 = 1.2$.

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 µJ, 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.

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