Efficient continuous-wave laser operation of Tm:KLu(WO_4)$_2$ near 2 µm

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Abstract: Maximum output powers of 1.4 and 4 W and slope efficiencies of 60 and 69% were obtained with a Tm:KLu(WO_4)$_2$ laser near 2 µm under Ti:sapphire and diode laser pumping, respectively.

OCIS Codes: (140.5680) Rare earth and transition metal solid-state lasers; (140.3070) Infrared and far-infrared lasers; (140.3480) Lasers, diode-pumped; (160.5690) Rare earth doped materials

1. Introduction

Thulium (Tm) lasers are at present the only tunable solid state systems operating near 2 µm and their availability in all time formats is important for various applications. However, only few of the crystal hosts (YAG and the related LAG, YLF and $YAlO_3$) have provided multiwatt output powers in the continuous-wave (CW) regime. The monoclinic potassium double tungstates are interesting for the medium power range (up to ≈10 W) because they possess several unique features: The relatively large ion separation allowing highest doping levels with minimum quenching effect and the highest absorption and emission cross sections which is partly due to the strong anisotropy of the biaxial host [1]. Their maximum absorption cross section for the $^3H_6 \rightarrow ^3H_4$ Tm-transition is slightly above 800 nm with a relatively large linewidth which makes them ideal for pumping with AlGaAs diodes. Several recent laser studies were devoted to KY(WO_4)$_2$ (Tm:KYW) and KGd(WO_4)$_2$ (Tm:KGdW) ([1] and references therein) but the maximum power achieved so far with a diode pumped Tm:KYW laser was 1.8 W [2].

Here, we report on the crystal growth, spectroscopy, and laser operation of KLu(WO_4)$_2$ (hereafter KLuW) doped with Tm-ions at several concentrations and compare it to Tm:KGdW. The two laser polarizations, $\boldsymbol{E//N_m}$ and $\boldsymbol{E//N_p}$, are compared under identical conditions with polarized Ti:sapphire laser pumping in a Brewster geometry. In the case of unpolarized diode pumping and normal incidence the naturally selected polarization was $\boldsymbol{E//N_m}$.

2. Experimental results and discussion

KLuW crystallizes in the C2/c space group, a = 10.576(7)Å , b = 10.214(7)Å , c = 7.487(2)Å, β = 130.68(4)º, and Z = 4 [3]. The $\boldsymbol{N_p}$ principal optical axis is parallel to the ***b*** crystallographic axis. The other two optical axes, $\boldsymbol{N_m}$ and $\boldsymbol{N_g}$, lie in the ***a-c*** crystallographic plane and $\boldsymbol{N_g}$ is rotated by 18.5º in the clockwise direction with respect to ***c*** (with ***b*** pointing towards the observer) [3]. Four different compositions corresponding to $KLu_{1-x}Tm_xW$ with x = 0.005, 0.01, 0.03 and 0.05 were grown by the Top Seeded Solution Growth (TSSG) method. The growth began on a KLuW seed and the temperature was decreased by about 10-20 K at a rate of 0.1-0.2 K/h. It took 4-10 days depending on the cooling rate. The crystal rotation was at 40 rpm. The actual composition obtained from Electron Probe Microanalysis (EPMA) gave a distribution coefficient for Tm close to 1. The samples used here had compositions of $KLu_{0.963}Tm_{0.037}W$ and $KLu_{0.95}Tm_{0.05}W$. The 3% doped sample was $\boldsymbol{N_g}$-cut (thickness: 2.92 mm) so that it could be used for $\boldsymbol{E//N_m}$ and $\boldsymbol{E//N_p}$. The 5% doped sample and an analogous Tm:KGdW reference sample (composition: $KGd_{0.959}Tm_{0.041}W$) were $\boldsymbol{N_p}$-cut (thickness: 2 mm) and could be used only for $\boldsymbol{E//N_m}$ because of the extremely low $\boldsymbol{E//N_g}$ cross sections. All samples had an aperture of ≈3×3 mm^2. The measured polarized absorption spectra as well as the calculated by the reciprocity method emission spectra are similar to those known for Tm:KGdW and Tm:KYW. The maximum absorption cross section for $\boldsymbol{E//N_m}$ is 5.95×10^{-20} cm^2 at 802 nm (FWHM=4 nm). The maximum absorption cross section for $\boldsymbol{E//N_p}$ is 9.96×10^{-20} cm^2 at 793.5 nm but here the FWHM is only 1 nm.

The setup used for Ti:sapphire laser pumping was an astigmatically compensated X-type cavity with a total length of 90 cm and folding mirrors with RC=-10 cm. The output couplers had a transmission T_{OC}=1.5 to 10%. The linewidth of the 3.5 W Ti:sapphire laser was 0.2 nm and the pump spot was 37 µm (waist). The active elements were placed under Brewster angle which defines the laser polarization and the pump polarization was always the same.

The two polarizations, ***E//N$_m$*** and ***E//N$_p$***, were compared with the 3% Tm-doped KLuW sample supplied with active cooling (at 10°C). Some of the results for T_{OC}=5% and optimum pump wavelengths λ_P are shown in Fig. 1a. A maximum output power of 1.4 W for P_{abs}=2.47 W was achieved for ***E//N$_m$*** and the threshold was 125 mW. This corresponds to an optical efficiency of 56.7% with respect to P_{abs}. The laser wavelength varied from λ_L=1917 nm (T_{OC}=10%) to 1951 nm (T_{OC}=1.5%). The higher thresholds and lower slope efficiencies η for ***E//N$_p$*** are attributed to the lower gain cross section. The laser wavelengths for ***E//N$_p$*** were always somewhat shorter. The efficiency and the threshold (in terms of P_{abs}) remained unchanged for ***E//N$_p$*** at λ_P=802 nm while the absorption obviously dropped. Comparing the two identical samples of KLuW and KGdW with 5% Tm-doping we established that the laser performance of KLuW is improved by roughly 50% in terms of threshold, efficiencies and output powers.

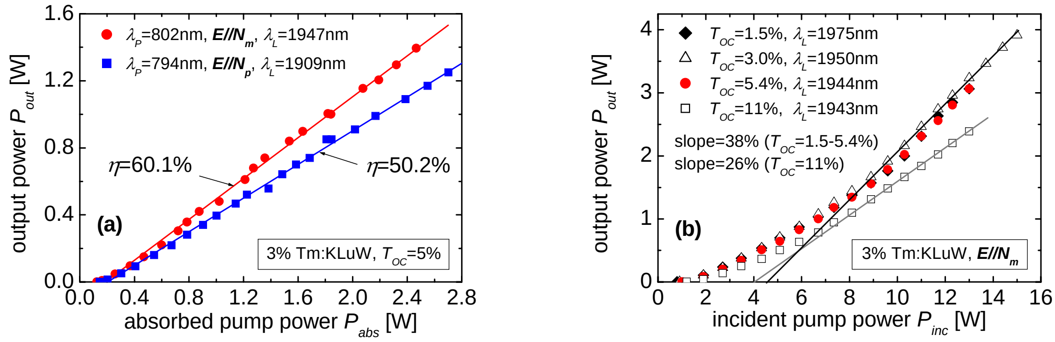

Fig. 1. Input-output characteristics of the Ti:sapphire laser pumped Tm:KLuW laser for two polarizations in terms of absorbed pump power (a) and input-output characteristics of the diode laser pumped Tm:KLuW laser for ***E//N$_m$*** in terms of incident pump power (b).

The unpolarized diode laser module used for pumping contained a single 50 W commercial bar clamped without using any soldering process and simple adapted beam shaping optics. The emission wavelength depended on the operating current and the maximum output power available near 802 nm at an operating temperature of 25°C was 14 W (linewidth: 2 nm). The 3% Tm-doped KLuW sample was placed in a nearly hemispherical, 50 mm long cavity close to the plane mirror through which the laser was pumped so that the polarization could be only naturally selected (by the higher gain cross section). Room temperature was maintained by water cooling. The curved output couplers had T_{OC}=1.5 to 11%. The oscillating polarization was always ***E//N$_m$***. The maximum output power achieved with T_{OC}=3% for P_{inc}=15 W was P_{out}=4 W at λ_L=1950 nm (Fig. 1b). The slope efficiency calculated with respect to P_{abs} amounted to η=69% and the maximum optical efficiency reached 47%. In terms of slope efficiency the present results are better than the highest values previously reported with double tungstates (η=52-53% with Tm:KYW [2, 4]) or any other Tm-host. Assuming a quantum efficiency of 2 for the cross-relaxation process, the limit is η=82%. Obviously cross-relaxation is very efficient in Tm:KLuW even at a doping level of 3%. In our case the slope efficiencies with diode pumping were higher in comparison with Ti:sapphire laser pumping but the two cavities were very different. Nevertheless, Ti:sapphire laser pumping provided higher optical efficiency and lower threshold. The linear dependence of the output power in the case of diode pumping (practically the same for T_{OC}=1.5…5.4%) is reached at higher pump levels which is typical for three-level laser systems in the presence of reabsorption. Measurements of the output beam quality performed at high power levels gave values of the M^2 parameter of 2.3 and 2.1 in the two planes or an average value of 2.2.

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