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Tunable cw Lasing of $Tm:KGd(WO_4)_2$ near 2 μm

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Abstract: We describe highly efficient room temperature laser operation of $Tm:KGd(WO_4)_2$ on the $^3F_4 \rightarrow {}^3H_6$ transition, tunability from 1790 to 2042 nm and pump efficiency of 40%, and consider the effect of doping level, pump wavelength and polarization.

OCIS codes: (140.5680) Rare earth and transition metal solid-state lasers; (140.3380 Laser materials

1. Introduction

All-solid-state Tm-doped lasers have potential applications in medicine, laser radar and atmosphere monitoring. They are promising for the 2 μm spectral region due to their broad tunability and the possibility for diode pumping near 800 nm. In monoclinic double tungstates the $^3H_6 \rightarrow {}^3H_4$ absorption line of the Tm^{3+}-ion is broader and shifted to longer wavelengths (more suitable for AlGaAs laser diodes) than in YAG or YLF. The cross sections in these strongly anisotropic biaxial crystals are in general larger and concentration quenching effects are weaker. The combination of broad fluorescence line, large emission cross section and relatively short (compared to YAG and YLF) upper level lifetime is an unique advantage for future experiments on passive mode-locking.

The first cw room-temperature operation of a Tm-doped monoclinic double tungstate, $KY(WO_4)_2$, with longitudinal Ti:sapphire laser pumping was achieved in 2000 [1]. The successful growth of the isostructural $Tm:KGd(WO_4)_2$ (Tm:KGdW) with high quality was demonstrated only recently [2]. The spectroscopic properties of Tm:KGdW relevant to laser operation were studied in the orthogonal frame of the optical indicatrix and a maximum emission cross section of $\sigma_e = 3.27 \times 10^{-20}$ cm^2 at 1834 nm was calculated for polarization $E//N_m$ by the reciprocity method from the absorption spectra [2]. The measured decay time of the upper laser level ($^3F_4$) population varies between 1690 and 1530 μs for Tm doping of 5 to 10% [2]. We present here cw laser results with Tm:KGdW obtained at room temperature using a tunable pump source. This allowed us to compare both polarizations $E//N_m$ and $E//N_p$ with special emphasis on the tuning behaviour for future passive mode-locking experiments.

2. Experimental set-up

An astigmatically compensated X-type cavity with a total length of 85 cm (Fig.1) was used in the present work in contrast to previous studies with $Tm:KY(WO_4)_2$ which relied on simple two-mirror resonators [1,3]. It allows easy insertion of tuning elements and also extension with mode-locking devices. Mirrors M1-M3 were highly reflecting (HR>99.9%) from 1800 to 2075 nm and AR-coated on the rear side for high transmission from 780 to 1020 nm. The output coupler transmission was varied between T_{OC}=1.5 and 10%. As a pump source we employed a tunable Ti:sapphire laser delivering an output power of more than 3 W. Its linewidth was 0.3 nm but, without additional stabilization, slow wavelength fluctuations as large as 1 nm occurred.

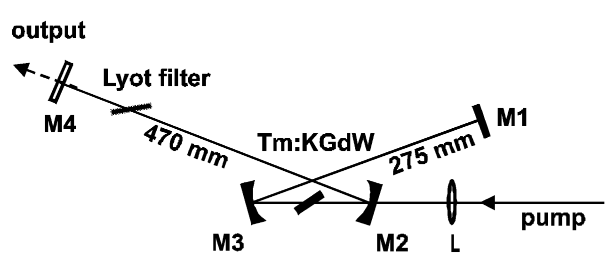

Fig.1: Laser set-up. L: f=70 mm AR-coated lens, M1: plane total reflector, M2-M3: RC=-100 mm mirrors, M4: plane output coupler.

The present study was limited to doping levels of 5 and 7.5% and absorbed powers of up to P_{abs}≈1 W using the following three uncoated samples: (1) a d=1.71 mm thick plate with 5% Tm-doping [N=2.57 10^{20} ions/cm^3 Tm concentration corresponding to a stoichiometric composition of $KGd_{0.959}Tm_{0.041}(WO_4)_2$], cut and oriented for laser polarization parallel to N_m and propagation along the N_p axis, (2) a d=1.58 mm thick plate of the same composition, cut and oriented for laser polarization parallel to N_p and propagation along the N_m axis, and (3) a d=1.92 mm thick plate with 7.5% Tm doping [N=3.78 10^{20} ions/cm^3 Tm concentration corresponding to a stoichiometric composition of $KGd_{0.939}Tm_{0.061}(WO_4)_2$], cut and oriented for laser polarization parallel to N_m and propagation along the N_p axis.

3. Experimental results

Fig. 2 shows the dependence of the laser output power on the absorbed pump power at 801.5 nm for the 5% Tm-doped KGdW samples cut for E//N_m and E//N_p. For E//N_m the threshold absorbed pump power was 70 mW (T_{OC}=1.5%) and 130 mW (T_{OC}=10%). The maximum output power (400 mW) for E//N_m and P_{abs}=1 W was obtained with T_{OC}=3%. The corresponding pump efficiency with respect to the absorbed power (40%) is very close to the quantum efficiency limit (42%) for a lasing wavelength of 1924 nm if cross relaxation processes are neglected. Both, thresholds and efficiencies achieved for E//N_m are comparable to the results demonstrated previously with Tm:$KY(WO_4)_2$ [1,3]. The output powers obtained for E//N_p were in general lower (by ⅓ to ½ depending on T_{OC}) and the threshold absorbed pump power was 120 mW (T_{OC}=1.5%) and 180 mW (T_{OC}=5%). It is the first time Tm-generation is obtained for E//N_p in a monoclinic double tungstate – in all previous works, e.g. [1,3], the active elements were cut along the N_p-axis. The increased thresholds and the lower output powers indicate smaller gain cross section in the case E//N_p as compared to E//N_m as could be expected from spectroscopic studies [2]. The calculated inversion dependent gain cross sections for both polarizations confirm this conclusion. However, for E//N_p lower pump powers can be used at 794 nm as compared to 801.5 nm to achieve the same pump efficiencies. Thus in terms of maximum output powers, thresholds and slope efficiencies the results at this pump wavelength were essentially the same with respect to their dependence on P_{abs}. The same is valid also for the 7.5% Tm-doped KGdW sample used for E//N_m and pumped at 801.5 nm. Specifically, with the T_{OC}=5% output coupler this sample provided a similar maximum output of 400 mW and a pump efficiency of 40% at P_{abs}=1 W. No essential differences in the output characteristics of the laser could be observed for pumping at slightly longer wavelengths (e.g. at 806 nm), better suited for laser diodes, the basic dependence being again on P_{abs}.

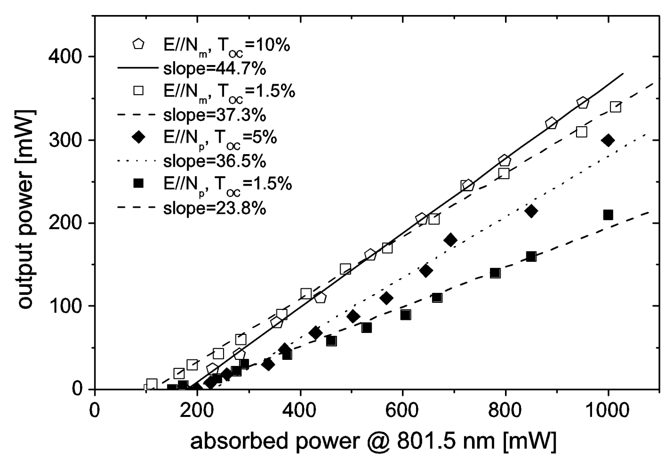

Fig.2: Input-output characteristics of the 5% Tm:KGdW laser for polarization parallel to the N_m and N_p principal optical axes.

The FWHM of 162 nm obtained for the tunability curve for T_{OC}=1.5% and E//N_m (Fig.3) is in principle capable of supporting sub-50-fs pulses near 1950 nm if this laser could be mode-locked. Tuning with T_{OC}=10% extends this range down to 1790 nm. Thus the output coupler had an essential influence on the tuning range achieved. Without the Lyot filter the laser wavelength continuously decreased with increasing the output coupling. Similar effects were observed also with the 5% Tm-doped sample cut for E//N_p polarization and the 7.5% Tm-doped sample used at E//N_m. In both cases the wavelength exhibited jumps when exchanging the output couplers. The reasons for these jumps can be traced back to the multiple minima in the wavelength dependence of the gain. Such a behaviour could be predicted also by calculation of the average inversion necessary to achieve threshold by taking into account the actual sample parameters. In the case of E//N_p the tunability range is shifted to shorter wavelengths independent of the pump wavelength.

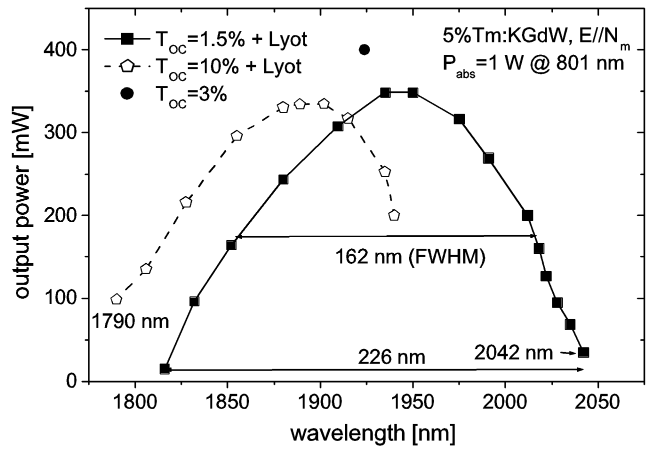

Fig.3: Achieved tunability for T_{OC}=1.5% (squares) and T_{OC}=10% (pentagons) with the 5% Tm:KGdW sample and E//N_m using a 3 mm thick quartz plate. For comparison the generation wavelength and output power obtained without tuning element and T_{OC}=3% are given for the same absorbed pump power P_{abs}=1 W (circle).

4. Conclusion

In conclusion, we studied the potential of Tm:KGdW as a tunable 2 µm cw laser at room temperature. Besides the advantages in comparison to Tm:YAG or Tm:YLF outlined in the introduction, it can be added that the tuning range is not only broader but also complementary to Tm:YAG and Tm:YLF at shorter wavelengths. The bandwidths supported by Tm:KGdW are pretty large so that mode-locking with passive methods (e.g. semiconductor saturable absorber) seems very promising. The further extension of the present results to yet higher output powers to the efficient heat removal from the active volume by a proper crystal holding construction. While the sample thickness used in the present work could be advantageous for utilizing the Kerr-effect self-mode-locking mechanism, thinner samples of higher doping level could further decrease the requirements to the spatial quality of diode based pump sources. It could be verified in the present work that doping levels of 7.5% have no degradation effect on the laser performance and on the basis of the spectroscopic results in [2] it can be expected that levels as high as 20% would be still feasible. The experiments with the tunable pump source permitted on one hand to compare pumping through different Stark levels, whose absorption lines depended on the polarization, on the other hand it could be confirmed that the use of conventional AlGaAs laser diodes should be uncritical both with respect to their (exact) wavelength and their linewidth.

We established that Tm:KGdW can operate also in the E//N_p polarization although with lower efficiency. At present it is unclear whether this could lead to some advantages in terms of bandwidth in the mode-locking regime but this polarization seems to provide higher gain at shorter wavelengths than E//N_m. The present results represent an improvement of $\approx$100 nm in the tuning range and an 8-fold increase in the output power in comparison to previous results with the isostructural Tm:KY$(WO_4)_2$ [3] but there are no reasons to conclude that Tm:KGdW possesses some intrinsic advantages. Instead we conclude that all passive hosts belonging to the family of the monoclinic double tungstates are very promising materials for Tm-lasers.

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