Passively mode-locked Yb:KLu(WO_4)$_2$ laser

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Abstract: We report the shortest pulses (81 fs) ever produced with an Yb-doped tungstate laser using a semiconductor saturable absorber by passive mode-locking of monoclinic Yb:KLu(WO_4)$_2$ achieving an average power of 70 mW at 1046 nm.

OCIS Codes: (140.3580) Lasers, solid-state; (140.4050) Mode-locked lasers; (140.5680) Rare earth and transition metal solid-state lasers; (160.5690) Rare earth doped materials

1. Introduction

The increased attraction of Yb-doped lasers in the 1-μm spectral range has been emphasized by establishing novel active materials with the Yb^{3+} - ion as a dopant. Ytterbium based compact high-power femtosecond laser sources have developed rapidly over the past few years in a great number of hosts [1].

The monoclinic double tungstates KY(WO_4)$_2$ (KYW) and KGd(WO_4)$_2$ (KGdW) doped with Yb^{3+} ions have been recognized as attractive host-dopant combinations. The strongly anisotropic double tungstate KLu(WO_4)$_2$ (KLuW) exhibits very similar spectroscopic properties when doped with Yb [2], and is also characterized by large absorption and emission cross sections but with the additional option of highly doping up to the stoichiometric KYb(WO_4)$_2$. KLuW is isostructural to KYW and KGdW and many relevant properties like refractive index, optical transparency, and thermal conductivity are very similar. Some of the most promising results with respect to diode-pumped femtosecond generation have been obtained with the Yb-doped tungstates. For Yb:KGdW, mode-locked by a semiconductor saturable absorber mirror (SAM), the shortest pulse duration was 100 fs [3]. With Yb:KYW lasers, pulse durations of 71 fs applying Kerr-lens mode-locking [4] and 101 fs using a SAM [5] were obtained. Here we demonstrate for the first time, to our knowledge, mode-locked operation of the Yb:KLuW laser achieving sub-100 fs pulses for polarization parallel to the N_m- and N_p-crystallo-optic axes.

2. Spectroscopic characterization of Yb:KLuW

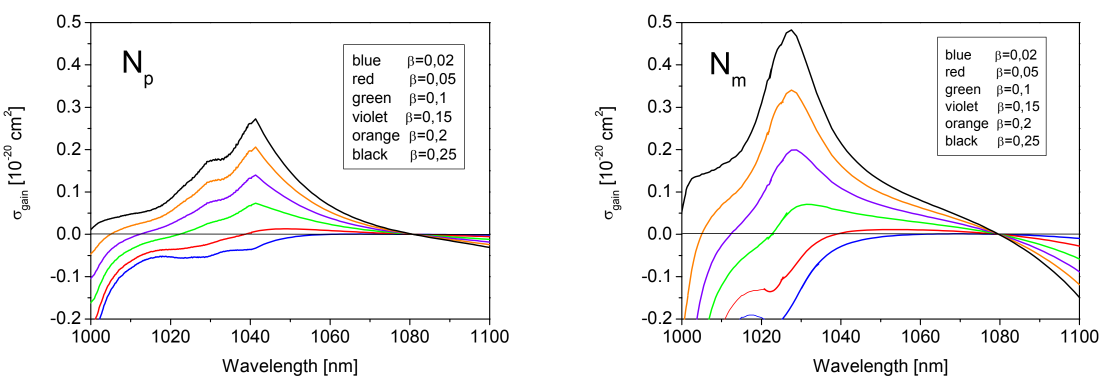

Fig. 1. Gain cross section σ_{gain} for polarization along the N_p- and N_m-crystallo-optic axes of Yb:KLuW and different population inversion rates β.

In order to estimate the potential gain bandwidth for the mode-locked operation in the N_m- and N_p-orientations, the gain cross section for different population inversion rates is calculated and presented in Fig. 1.

3. Experimental

Initial experiments were performed with a Ti:sapphire laser as a pump source, which emitted up to 3 W of output power at 980 nm. For the diode-pumped operation a tapered diode laser (TDL) [5] was used at the same wavelength, delivering up to 2 W at an $M^2<4$ for the slow axis emission. We studied a longitudinally pumped Z-shaped astigmatically compensated resonator with two folding mirrors in the middle to form a 30-µm cavity waist at the position of the Yb:KLuW crystal. One arm contained an additional focusing mirror to increase the intensity on the SAM, which terminated the resonator. The other arm contained a plane output coupler and two dispersion compensating prisms could be included. The SAM's were grown by the MOCVD-method and consisted of a bottom Bragg mirror comprising 25-pairs AlAs/GaAs quaterwave layers designed for a central wavelength of 1030 nm. The reflection bands extended from 980 to 1070 nm. The absorber was a 10-nm-thick InGaAs surface quantum well structure [6] with a saturable absorption of ≈1%. Its relaxation time was measured to be less than 5 ps.

For the experiments a 2.8-mm thick crystal oriented for N_m-polarization and a 3-mm thick crystal oriented for N_p-polarization were prepared, both doped with 5 mol% Yb in the solution during the growth. The crystals were put under Brewster angle between the two folding mirrors. No special provision was made for cooling the samples.

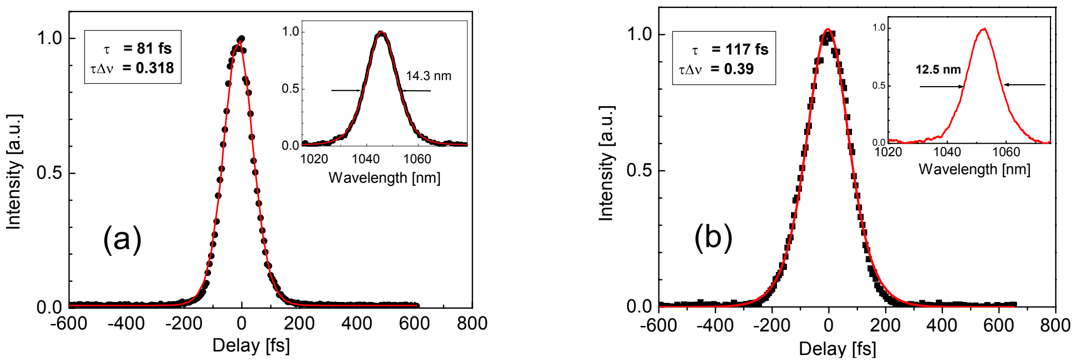

Fig. 2. Autocorrelation traces and spectra (insets) in the Ti-Sa-pumped (a) and in the diode-pumped regime (b).

In a preliminary experiment the continuous-wave (cw) laser performance of the N_p-oriented Yb:KLuW crystal was investigated applying the Ti:sapphire laser as a pump source. Using a 5% output coupler (OC) in a four mirror cavity identical with the one previously used to study N_m-oriented Yb:KLuW [2], the laser generated a maximum cw output power of 750 mW with a slope efficiency of 54.2% at a wavelength of 1046 nm. For the same absorbed pump power of 1.7 W the N_m-oriented crystal delivered 800 mW with a slope efficiency of 57% [2].

When the SAM was inserted into the cavity used for mode-locking, the laser operated in the picosecond regime with a pulse repetition rate of 98 MHz. Pulses as short as 3 ps around 1043 nm were obtained at a maximum output power of 540 mW without prisms in the cavity. The maximum pump efficiency in the mode-locked regime reached 32%. Significant differences between the two crystal orientations could not be observed in the picosecond mode.

For femtosecond operation, we optimized first the cavity design in order to obtain the shortest pulse duration using the N_m-oriented Yb:KLuW crystal. To this aim, two SF10 Brewster prisms with a tip-to-tip separation of 38 cm were inserted in the arm containing the output coupler. The resulting pulse repetition rate was 95 MHz. We achieved a pulse duration of 81 fs (FWHM) with an average power of 70 mW for 3% OC transmission. The corresponding output spectrum was centered at 1046 nm and had a bandwidth of 14.3 nm. This results in a time-bandwidth product of 0.318 corresponding to nearly transform-limited $sech^2$-pulses. The intensity autocorrelation trace together with the corresponding fit and the spectrum of the shortest pulses are shown in Fig. 2a.

Femtosecond operation was then investigated with the N_p-oriented Yb:KLuW crystal. The results achieved for polarization parallel to the N_m- and N_p-axes with the same resonator configuration, but with slightly different dispersion compensation, are compared in Fig. 3. Only minor differences could be detected. As indicated by the calculated gain cross section in Fig. 1, the achievable bandwidth at the same population inversion rate is nearly identical for both orientations and from our experimental results in the different operation regimes we can deduce similar population inversions. For both crystal orientations mode-locking was achieved with OC transmissions between 1% and 5%. The shortest pulse duration for the N_p-oriented crystal was 83 fs (FWHM) with an output power of 36 mW at 1049 nm using an 1% OC. A much higher average power of 295 mW could be generated for a pulse duration of 100 fs (Fig. 3).

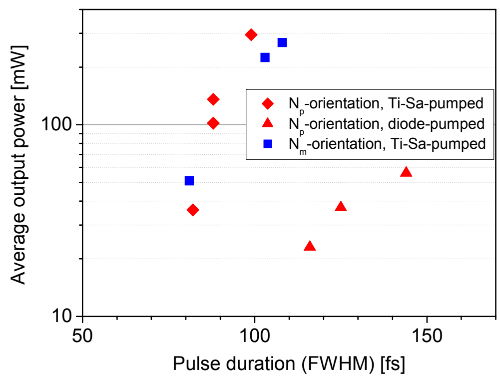

Fig. 3. Comparison of the Yb:KLuW femtosecond laser performance (average power vs. pulse duration) for polarization oriented parallel to the N_p- and N_m-crystallo-optic axes.

Using the TDL as a pump source, only the N_p-oriented crystal was investigated. By inserting the prisms into the cavity, stable mode-locking was achieved for OC transmissions between 1% and 3%. A 1-W pump power incident on the crystal resulted in a maximum mode-locked output power of 56 mW with a 3% OC. The lower efficiency compared to the experiments with Ti:sapphire laser pumping is caused by the imperfect match of the pump and resonator modes and the lower beam quality of the diode emission. At a pulse repetition frequency of 95 MHz a pulse duration of 117 fs (FWHM) was achieved, as shown in Fig. 2b. The corresponding spectrum, centered at 1053 nm, had a spectral bandwidth of 12.5 nm which yields a time-bandwidth product of 0.39.

4. Conclusion

In conclusion, we have demonstrated what we believe to be the first Yb:KLuW mode-locked oscillator. With dispersion compensation the laser generates transform-limited pulses with durations as short as 81 fs (Ti:sapphire-pumped) and 117 fs (diode-pumped) at a repetition rate of 95 MHz and average output powers of 70 mW and 23 mW, respectively. The comparison of the femtosecond laser performance for the two Yb:KLuW crystal orientations, polarization parallel to the N_m- and to the N_p-crystallo-optic axes, gave no evidence for significant differences with respect to the pulse duration, pulse quality and average power. The obtained pulse durations are slightly longer than the 71 fs obtained with a Kerr-lens mode-locked Yb:KYW laser [4], but much shorter than the 100 fs reported for SAM mode-locked Yb:KYW and Yb:KGdW lasers [5] which can be particularly attributed to the excellent crystal quality.

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