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

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Abstract: We demonstrate passive mode locking based on the novel monoclinic double tungstate crystal Yb:KLu$(WO_4)_2$. We report the shortest pulses ever produced with an Yb-doped tungstate laser using a semiconductor saturable absorber. A pulse duration of 81 fs has been achieved for an average power of 70 mW at 1046 nm. We compare the performance of the polarization oriented parallel to the N_m- and N_p-crystallo-optic axes. Results in the femtosecond and picosecond regime are presented applying either Ti:sapphire or diode laser pumping. The great potential of Yb:KLu$(WO_4)_2$ as an active medium for ultrashort pulses is demonstrated for the first time, to our knowledge.

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

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1. Introduction

The increased attraction of Yb-doped lasers has been emphasized by establishing novel active materials with the Yb^{3+}-ion as a dopant in the 1-µm spectral range [1]. Ytterbium based compact high-power femtosecond laser sources have developed rapidly over the past few years in a great number of hosts [2-7]. This is due to the promising peculiarities of the Yb^{3+}–ion related to the very simple energy level scheme constituted of only two levels: the $^2F_{7/2}$ ground state and the $^2F_{5/2}$ excited state. Effects like excited state absorption, cross relaxation and up-conversion, are absent. The Yb^{3+} ion also has a small quantum defect as a result of the close pump and laser wavelengths, leading to low thermal load. The broad and intense Yb^{3+} absorption lines resulting from the Stark splitting, are covered by high-power InGaAs laser diodes.

The strongly anisotropic 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 [8]. The isostructural KLu(WO_4)$_2$ (KLuW) exhibits very similar spectroscopic properties when doped with Yb^{3+} [9], characterized by large absorption and emission cross sections. KLuW offers the additional option of high Yb-doping reaching the stoichiometric KYb(WO_4)$_2$ (KYbW) [10] with practically no concentration quenching. Such 100% doping could be achieved up to now only in KYW and YAG but the quenching effect was present in YAG. The crystal structure of the monoclinic low-temperature phase of KLuW was first studied in 1968 [11]. KLuW belongs to the C2/c space group and a summary of some of its physical characteristics (unit cell parameters, density, melting and crystallization temperature, hardness and SRS-active vibration modes) can be found in Ref. 12. Many laser relevant properties like refractive index, optical transparency, and thermal conductivity are very similar to KYW and KGdW [12]. We could already demonstrate continuous-wave (CW) laser operation of Yb:KLuW in the 1 µm spectral range. The highly efficient laser performance with this novel Yb-doped monoclinic double tungstate was achieved with 2.2-2.8 mm thick, 5 and 10 at% Yb-doped KLuW samples oriented for polarization parallel to the crystallo-optic axis N_m. Output powers of the order of 1 W with pump efficiencies as high as 50% were obtained at room temperature [13]. The CW laser results were comparable to those reported for Yb:KGdW and Yb:KYW [8].

With monoclinic Yb-doped tungstates, some of the most promising results with respect to diode-pumped femtosecond generation have been obtained. For Yb:KGdW, mode-locked by a semiconductor saturable absorber (SAM), the shortest pulse duration was 100 fs, [14]. From an Yb:KYW laser, pulse durations of 71 fs applying Kerr-lens mode locking [15] and 101 fs using a SAM [16] were demonstrated. For the latter, the highest average power from an Yb-

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doped tungstate-based oscillator of 22 W in the sub-300 fs range was achieved applying the thin disk laser concept [7].

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

The top-seeded solution growth slow-cooling method was used to synthesize single crystals of KLuW and Yb:KLuW with various dopant concentrations. Inclusion-free crystals with dimensions of 13×7.5×11.5 mm^3 were obtained. The N_p crystallo-optic axis coincides with the *b* crystallographic axis, and N_g is located at 18.5º from the *c* axis in the *a*-*c* plane ($n_p<n_m<n_g$ holds for the corresponding refractive indices). The maximum absorption cross-section amounts to $\sigma_a = 1.18\times10^{-19}$ cm^2 at 981 nm for light polarization parallel to the N_m-crystallo-optic axis and the FWHM of this line amounts to 3.6 nm. The emission cross section has a maximum of $\sigma_e = 1.47\times10^{-19}$ cm^2 for $E//N_m$ at 981 nm [9]. In order to estimate the potential gain bandwidth for the mode-locked operation in the N_m- and N_p-orientation, the gain cross section $\sigma_{gain} = \beta\sigma_e - (1 - \beta)\sigma_a$ for different population inversion β is calculated and presented in Fig. 1. β is the ratio of the excited ion density to the total Yb-ion density. The fluorescence decay time measured at room temperature for 0.5% doped Yb:KLuW, 375 µs, is slightly longer than the 300 µs measured for Yb:KYW and Yb:KGdW by the same method.

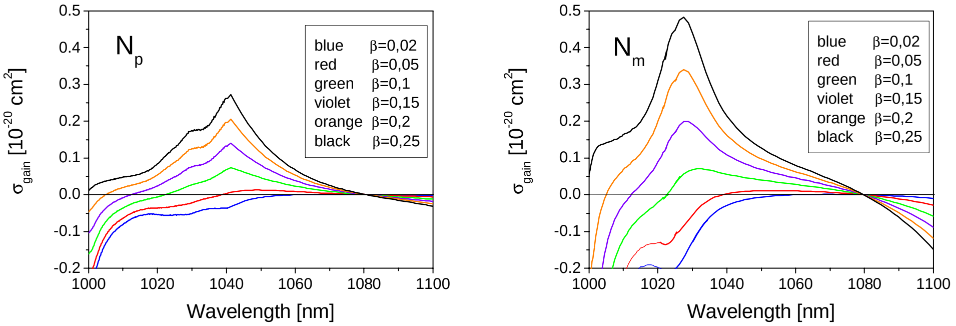

Fig. 1. Gain cross section σ_{gain} for polarization along the N_p- and N_m-crystallo-optic axes of Yb:KLuW and different population inversion β. Note that the N_g-polarization is unfavourable because of the small cross sections.

3. Mode-locked laser operation of Yb:KLuW

The cavity setup is illustrated in Fig. 2. Initial experiments were performed with a Ti:sapphire laser as a pump source, which emitted up to 3 W of output power near 980 nm. For the diode-pumped operation a tapered diode laser (TDL) [16] was used at the same wavelength, delivering up to 2 W at an M^2<4 for the slow axis emission.

We studied longitudinal pumping in a *Z*-shaped astigmatically compensated resonator with two folding mirrors (radius-of-curvature: ROC=-10 cm) in the middle to form a 30-µm cavity waist at the position of the Yb:KLuW crystal. 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 4.3×10^{20} Yb^{3+}-ions/cm^3. The crystals were mounted under Brewster angle between the two folding mirrors. No special provision was made for cooling the samples. One arm of the resonator contained an additional focusing mirror (ROC=-10 or -15 cm) 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 inserted. The SAM's were grown by the MOCVD-method and consisted of a bottom Bragg mirror comprising 25-pairs AlAs/GaAs quarterwave 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 [17] with a saturable absorption of ≈1%. Its relaxation time was measured by the pump-probe technique to be less than 5 ps.

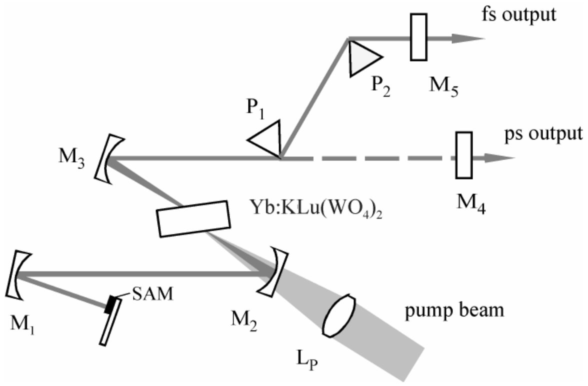

Fig. 2. Setup of the mode-locked $Yb:KLu(WO_4)_2$ laser: SAM - saturable absorber mirror; M_1 - focusing mirror; M_2, M_3 - folding mirrors, P_1, P_2 - SF10 Brewster prisms; M_4, M_5 - output couplers (OC = 1 to 5%), L_P - *f*=6.28 cm focusing lens.

In a preliminary experiment the 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 [13], 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% [13]. The measured CW lasing threshold amounted to about 280 mW of absorbed power. Although the Yb:KLuW crystals were not actively cooled, thermal problems did not occur.

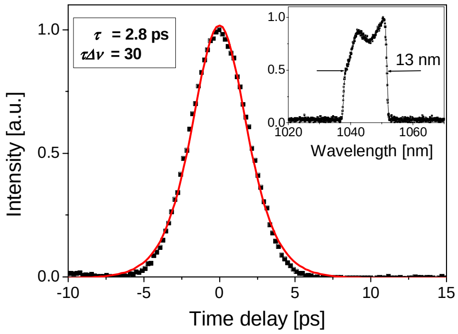

Fig. 3. Autocorrelation trace and spectrum (inset) of the $Yb:KLu(WO_4)_2$ laser in the picosecond regime (Ti:sapphire laser pumping).

When the SAM was inserted into the cavity used for mode locking, even without intracavity prisms, the laser operated in the picosecond regime with a pulse repetition rate of 98 MHz. Pulses as short as 2.8 ps near 1043 nm were obtained at a maximum average output power of 540 mW with a 5% output coupler. The maximum pump efficiency in the mode-locked regime reached 32%. The measured autocorrelation traces were fitted assuming a $sech^2$-pulse shape as commonly done. Figure 3 shows a typical autocorrelation function together with the emission spectrum. Both, experimental data (squares) and the fit (line) are plotted. The 13 nm broad spectrum (FWHM) could support pulses of sub-100 fs duration, which means that the experimentally obtained pulse duration in the picosecond mode exceeds the Fourier limit by a factor of 30 (Fig. 3). Significant differences between the two crystal orientations could not be observed in the picosecond regime.

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 (Fig. 2). The resulting pulse repetition rate was 95 MHz. The deconvolved FWHM of the shortest pulse was 81 fs 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 transform-limited sech^2-pulses. The obtained pulse duration for a SAM mode-locked Yb-doped tungstate laser is substantially shorter than the ≈100 fs limits reported for diode-pumped Yb:KGdW and Yb:KYW [14,16]. The intensity autocorrelation trace together with the corresponding fit and the spectrum of the shortest pulses are shown in Fig. 4(a).

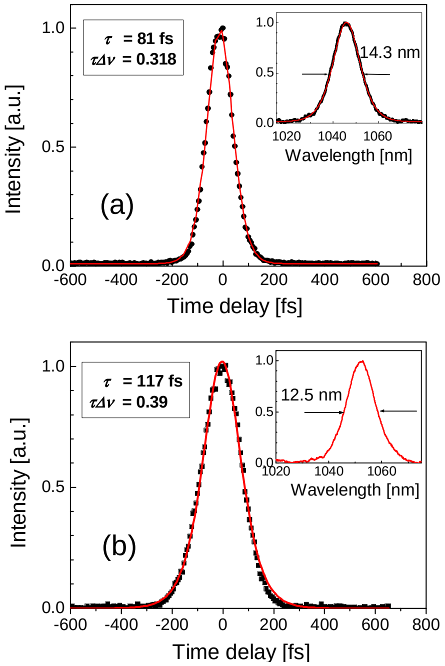

Fig. 4. Autocorrelation traces and spectra (insets) of the femtosecond Yb:KLu(WO$_4$)$_2$ laser: (a) N_m-oriention, Ti:sapphire laser pumping; (b) N_p-orientation, diode pumping.

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. 5. Only minor differences could be detected, contrary to the prediction of Ref. [15] for potentially shorter generated pulses for crystal orientations along the N_p-direction due to the broader spectrum of the emission cross section. As indicated by the calculated gain cross sections in Fig. 1, the achievable bandwidth at the same population inversion 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. 5).

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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. 4b. The corresponding spectrum, centered at 1053 nm, had a spectral bandwidth of 12.5 nm which yields a time-bandwidth product of 0.39, hence the pulses are almost Fourier-limited.

The observed transversal mode structure of the Yb:KLuW laser remained basically TEM_{00} both in the Ti:sapphire- and the diode-pumped configurations. For all arrangements investigated, the mode-locked operation showed no passive Q-switching [18], but tendencies towards double or multiple pulse operation were observed occasionally. This was reported also for the Kerr-lens mode-locked Yb:KYW laser [15]. With careful alignment these tendencies could be suppressed and the Yb:KLuW laser operation was stable for hours.

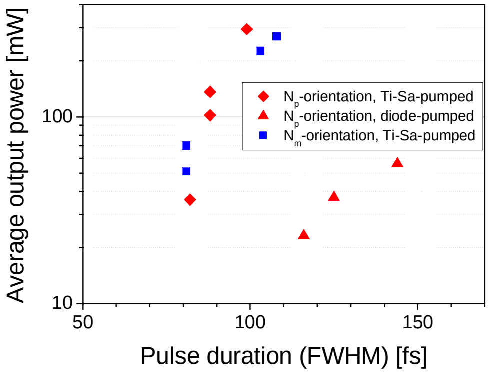

Fig. 5. Comparison of the femtosecond $Yb:KLu(WO_4)_2$ laser performance (average power vs. pulse duration) for polarization oriented parallel to the N_p- and N_m-crystallo-optic axes.

4. Summary

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.

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