

Epitaxially grown Yb:KLu(WO₄)₂ composites for continuous-wave and mode-locked lasers in the 1 μm spectral range

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Abstract

Epitaxial layers of up to 50% Yb-doped monoclinic KLu(WO₄)₂ could be successfully grown on passive KLu(WO₄)₂ substrates. These composite samples were characterized and continuous-wave and mode-locked laser operation was achieved with Ti:sapphire and diode-laser pumping. A 10% Yb-doped epitaxy provided an output power exceeding 500 mW at 1030 nm and a maximum slope efficiency of 66% with Ti:sapphire laser pumping. A 50% Yb-doped epitaxy exhibited serious thermal problems without special cooling and rather limited cw performance. Quasi-cw operation provided in this case an average output power of 43 mW at 1032 nm for a 10% duty cycle. More than 100 mW cw could be generated at 1030 nm also with diode-pumping of the 10% Yb-doped KLu(WO₄)₂ epitaxy. Pulses as short as 114 fs were generated at 1030 nm with this same sample under Ti:sapphire laser pumping in a laser mode-locked by a saturable absorber mirror.

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1. Introduction

Yb³⁺ is a very promising activating ion possessing a number of advantages over Nd³⁺ for laser operation in the 1 μm spectral range [1]. These include (1) the relatively simple two-level energy scheme for which disturbing up-conversion and excited-state absorption processes are absent, (2) the lower quantum defect which means also lower thermal load and more possibilities for power scaling, (3) the longer energy storage time, and (4) the broader spectral linewidths which means on the one hand reduced requirements to the pump source and in particular the laser diodes and on the other hand higher potential to achieve tunable generation and short (femtosecond) pulses.

Concerning crystalline hosts, the monoclinic potassium double tungstates, to which the title compound KLu(WO₄)₂ (KLuW) belongs, have several additional advantages [2]: (1) for any rare earth dopant they allow very high doping levels to be achieved without concentration quenching because the relevant ion separation is relatively large, (2) for any rare earth ion the absorption and emission cross sections are one of the largest, partly due to the strong anisotropy, and (3) for Yb-doping the main absorption peak near 980 nm is very suitable for InGaAs pumping diodes.

In the case of KLuW specific advantages come from the smallest difference in the ionic radii of the ‘passive’ Lu-ion and the ‘active’ Yb-ion, which additionally facilitates high doping levels reaching 100% for the stoichiometric KYb(WO₄)₂ (KYbW) [3]. The extremely high absorption cross section peak for polarization parallel to the *N_m* opti-

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cal axis ($1.18 \times 10^{-19} \text{ cm}^2$ at 981.1 nm with a FWHM = 3.6 nm [4]) results in absorption lengths as low as 13.3 μm for the stoichiometric KYbW. Such thin layers are very interesting for implementation in high power thin-disk lasers [5] because they can ensure more efficient heat removal and greatly simplified single-pass pump geometries but since their practical realization is impossible, growing them on passive isostructural substrates seems a very promising solution. This was our main motivation for the development and laser studies of Yb-doped monoclinic epitaxies. The very initial results based on KY(WO₄)₂ or KYW (20% doped Yb:KYW on a KYW substrate) were published in [6]. Here we report on our most recent and superior results achieved with Yb:KLuW epitaxies both in the continuous-wave (cw) and the mode-locked regime.

2. Experimental

Yb-doped KLuW layers were grown on KLuW substrates by liquid phase epitaxy (LPE) with 10, 20 and 50 at.% doping in the melt. We used a vertical furnace in which the axial gradient is negligible so that the layer grows homogeneously as described in [6,7]. The 10% and 50% samples used in the present work had an Yb-ion density of 7.89×10^{20} and 3.45×10^{21} ions/cm³, respectively, determined by electron probe microanalysis. The thickness of the activated layer was 100 and 38 μm , and the thickness of the whole sample including the substrate was 1.2 and 2.4 mm, respectively. The crystals were grown along the *b* crystallographic direction (parallel to the N_p optical axis) because of the better crystalline quality. In such monoclinic crystals the other two principal optical axes N_m and N_g lie in the *a-c* plane. The samples were cut and used for propagation along the *b* (N_p) axis and polarization of the electric field parallel to the N_m axis which results in maximum absorption and emission cross sections [4]. The high crystalline quality of the samples was confirmed by a ZYGOTM interferometer. No cracks at the interface layer-substrate were found. The epitaxial surfaces had radius of curvature RC = 0.71 and 0.42 m for the 10% and 50% Yb-doped layers, respectively. The corresponding surface roughness had a rms value of <0.8 and 0.9 nm. Fig. 1 shows the surface profile of the 50% Yb-doped KLuW epitaxy.

The Yb-fluorescence lifetime was measured for both doping levels with the pinhole method (Fig. 2) and compared to bulk Yb(10%):KLuW. This method helps to avoid reabsorption effects. The lifetime was only slightly lower for the 50% Yb-doped epitaxy ($224.3 \pm 2.3 \mu\text{s}$) than for the 10% Yb-doped epitaxy ($241.1 \pm 25 \mu\text{s}$) and both values were in reasonable agreement with the $254 \pm 9 \mu\text{s}$ measured for the bulk sample.

For pumping we used a tunable Ti:sapphire laser (960–1025 nm, linewidth < 1 nm, max. 3 W) and a diode laser. The Gaussian beam of the Ti:sapphire laser could be used also for pumping in a second pass, after reflection at one of the cavity mirrors. The tapered diode laser delivered up to

2 W at $M^2 < 3$ for the slow axis emission. It was tunable by the temperature from 975 to 982 nm and its spectral linewidth was about 1 nm. A standard astigmatically compensated V-shaped cavity was used for the cw laser experiments and a similar Z-shaped cavity was employed for the mode-locked experiments (see Fig. 3). The pump beam was focused by means of an anti-reflection coated lens L with a focal length of 62.8 mm. The folding mirror (M_2 , RC = -100 mm) was highly transmitting at the pump wavelength (near 980 nm). The end mirror for the cw experiments (M_1 , RC = -50 mm), see Fig. 3(a), was highly transmitting (for single pass pumping) or highly reflecting (for double pass pumping) at the pump wavelength. The transmission of the output coupler, M_3 , could be varied between 0.1% and 10%.

For mode-locking experiments (Fig. 3(b)), the end mirror M_1 was substituted by an analogous folding mirror with RC = -100 mm in the Z-shaped cavity. The intensity on the saturable absorber mirror (SAM) which terminated the resonator was increased by the additional focusing mirror M_3 (RC = -100 mm). The output couplers, M_4 (for the picosecond regime) or M_5 (for the femtosecond regime), terminated the second cavity arm. The dispersion compensated cavity configuration contained two Brewster angle SF10 prisms, P_1 and P_2 , separated by 31 cm (Fig. 3(b)). The SAM was grown by metal organic vapor-phase epitaxy (Ferdinand-Braun-Institute, Berlin, Germany) and con-

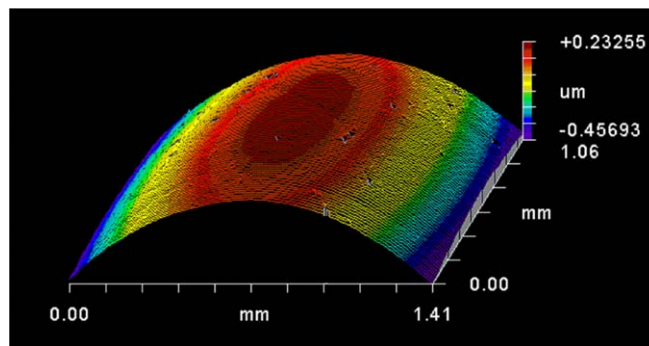


Fig. 1. Surface profile of the 50% Yb-doped KLuW composite measured with a ZYGO interferometer.

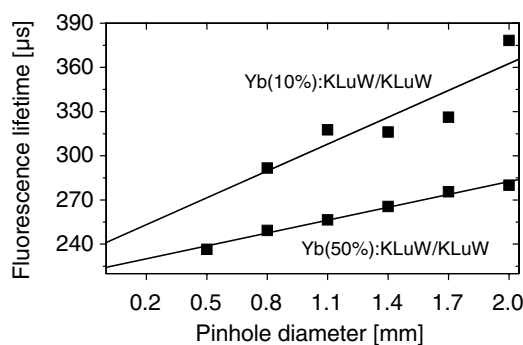


Fig. 2. Fluorescence lifetime measurement of the epitaxial Yb:KLuW/KLuW samples with different doping by the pinhole method.

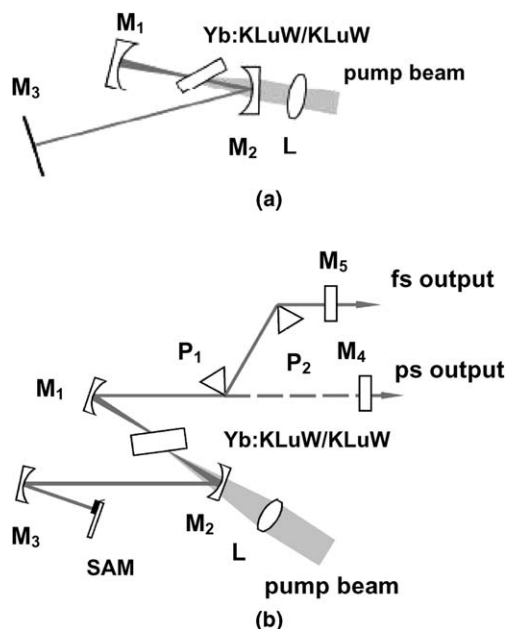


Fig. 3. Experimental set-up of the V-shaped (a) and Z-shaped (b) cavities used for cw and mode-locked operation with the intracavity prisms and SAM.

sisted of a bottom Bragg mirror comprising 25 pairs of AlAs/GaAs quarterwave layers. The reflection band extended from 980 to 1070 nm. The absorber was a 10-nm-thick InGaAs surface quantum well structure with a saturable absorption of $\approx 1\%$. Its relaxation time, measured by the pump-probe technique, amounted to less than 5 ps.

The uncoated epitaxial samples were positioned at Brewster angle and mounted on a copper base without special measures for heat removal. The estimated pump waist in the position of the samples was roughly $30\ \mu\text{m}$ in the case of Ti:sapphire laser pumping and slightly larger for the diode laser.

3. Results and discussion

3.1. Continuous-wave operation

Limiting the pump power of the Ti:sapphire laser to 1.85 W (incident on the epitaxy) a maximum output power of 415 mW was achieved with single pass pumping of the $100\ \mu\text{m}$ thick 10% Yb-doped epitaxy using an output coupler of 3% transmission. The resulting pump efficiency was 55% calculated with respect to the absorbed power. The maximum slope efficiency of 66% was achieved with higher output coupling (10%). Both the pump and slope efficiencies were higher in comparison to our previous results with 10% Yb-doped bulk KLuW crystals [8]. Moreover, the decreased thresholds (of the order of 70 mW absorbed power) and the shorter oscillation wavelength (decreasing from 1040 nm for 1% output coupler to 1026 nm for 10% output coupler) indicate strongly reduced reabsorption of the epitaxy in comparison to the bulk crystals. Even without cooling no damage of this epitaxial crystal occurred

regardless of the high power levels (intracavity intensity exceeding $1\ \text{MW}/\text{cm}^2$) applied.

Since strong bleaching of the single pass absorption was observed we implemented also double pass pumping, exchanging mirror M_1 in Fig. 3(a). This really improved the overall absorption and we achieved a maximum output power of 515 mW at 1030 nm with a 3% output coupler.

Pumping with the diode laser in a single pass produced a maximum output power of 105 mW at 1030 nm for a maximum incident pump power of 1.25 W and 3% output coupler. This gives a pump efficiency of 20% with respect to the absorbed power. The highest slope efficiency with respect to the absorbed power was 37.1% using an output coupler of 5% transmission. Thresholds as low as 120 mW (absorbed power) were measured with the 1% output coupler.

We obtained lasing with the $38\ \mu\text{m}$ thick 50% Yb-doped epitaxy at 1032 nm using at first double pass pumping with the Ti:sapphire laser in the cavity shown in Fig. 3(a) with 1% output coupler. This was possible, however, only applying a chopper with a duty cycle of 10%. The average laser power reached 43 mW for an average incident pump power of 125 mW. There were strong indications of thermal effects when we tried to increase the duty cycle. We also observed strong feedback to the Ti:sapphire pump laser which makes it difficult to accurately estimate the actual efficiencies with respect to the absorbed powers and also the thresholds.

Therefore we had to employ the single-pass pumping configuration, again exchanging mirror M_1 in Fig. 3(a). An output power of 20 mW was reached for 1% output coupler at an incident pump power of 97 mW (both average values with the 10% duty cycle chopper). The corresponding slope efficiency was 42% (Fig. 4). The laser threshold was 18 mW of incident power (9 mW of absorbed power). The laser wavelength was 1032 nm independent of the output coupler (1%, 2%, or 3%).

The estimated small signal absorption of this sample was 78% at 981 nm. The actual absorption in the single-pass pump configuration was about 64% in lasing conditions at higher pump power levels. This indicates that the

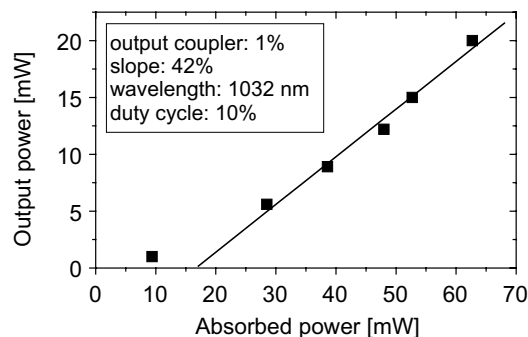


Fig. 4. Quasi-cw laser performance of the Yb(50%):KLuW/KLuW epitaxial composite with a 10% pump duty cycle. The average powers are presented: experimental points (squares) and linear fit for the slope (line).

absorption bleaching effect (reduction of the absorption down to 42% was observed in non-lasing conditions) was partially compensated at higher pump levels by the recycling effect.

It was also possible to achieve pure cw oscillation with single pass pumping in the absorption maximum and 0.1% output coupler, however, the efficiency was very low. The output power was 17 mW at 1046.1 nm for an incident power of 400 mW (absorbed power of 250 mW). The laser threshold was 76 mW of incident power (absorbed power of 46 mW). The output power quickly dropped to zero at incident pump levels above 400 mW. Pump powers exceeding 500 mW obviously damaged this epitaxial sample because strong scattering of the transmitted pump beam was observed behind the sample. This damage was confirmed later by simple observation with a microscope. It was located at the upper surface of the epitaxial layer.

Finally, we tested an analogous 50% Yb-doped KLuW epitaxy with a larger thickness (67% μm) but the results could not be improved. We achieved lasing only under quasi-cw pumping and the strong thermal problems persisted.

3.2. Mode-locked operation

Mode-locked operation was achieved with the 10% Yb-doped KLuW epitaxy using the Ti:sapphire laser as a pump source. The cavity configuration without the intracavity prisms (Fig. 3(b)) produced pulses of 1.8 ps duration (FWHM assuming sech^2 pulse shape) at a pulse repetition frequency of 100 MHz. The emission spectrum was centered at 1030 nm. The maximum output power obtained was 119 mW for an output coupler of 3% corresponding to a pump efficiency of 17% and a slope efficiency of 27% with respect to the absorbed power. The time-bandwidth product in this case was 1.78 (far exceeding the Fourier limit of 0.315).

The insertion of the two prisms into the cavity (see Fig. 3(b)) allowed to produce pulses as short as 114 fs at the same wavelength and a repetition rate of 101 MHz. The average output power was 31 mW for an absorbed power of 632 mW and output coupler of 1%. The time-bandwidth product of 0.43 in this case is only slightly above the Fourier limit. The output power could be increased using the 3% output coupler and 94 mW were obtained, again at 1030 nm, for an absorbed pump power of 671 mW. The FWHM increased to 200 fs but the pulses were almost bandwidth-limited (time-bandwidth product: 0.32).

We believe that the lower limit for the obtained pulse duration was partially due to the reflection characteristics of the folding mirrors which are restricted by the close separation of the laser and pump wavelengths and this was evidenced by the shape of the recorded pulse spectra on the low-wavelength side. In a very similar laser configuration we previously achieved shorter (81 fs) pulse durations

at 1046 nm under the same experimental conditions using a 2.8 mm thick bulk Yb(5%):KLuW crystal [9]. Although the present results with the epitaxial sample are not superior in terms of pulse duration, the strongly reduced reabsorption of the 10% Yb-doped KLuW epitaxy in comparison with the analogous bulk crystals, which is manifested in the shorter oscillation wavelengths, is expected to provide potentially broader gain bandwidths and consequently shorter (below 80 fs) output pulses if specially designed dichroic coatings for the folding mirror M_2 are used.

4. Conclusion

The results obtained so far with Yb-doped monoclinic KLuW epitaxies make us confident that better management of the heat dissipation as well as better adjustment of the layer thickness to the Yb concentration will further increase the output powers in the cw regime allowing operation of 100% doped epitaxies, and shorten the pulse duration in the mode-locked regime.

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