

# Laser Operation of Bulk Crystals and Epitaxially Grown Composites of Yb:KLu(WO<sub>4</sub>)<sub>2</sub>

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**Abstract:** Bulk and epitaxial composites of Yb:KLu(WO<sub>4</sub>)<sub>2</sub> were grown and characterized. CW-lasing @1μm was demonstrated achieving conversion efficiencies of 50% and output powers of 1W for the bulk and 25.5% and 0.5W for the composite Y b:KLu(WO<sub>4</sub>)<sub>2</sub>.

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## 1. Introduction

The increasing attraction of Yb-doped lasers has been emphasized by establishing novel active materials with the Yb<sup>3+</sup>-ion as a dopant [1]. Yb<sup>3+</sup> is a very promising activating ion due to the very simple energy level scheme constituted of only two levels: the <sup>2</sup>F<sub>7/2</sub> ground state and the <sup>2</sup>F<sub>5/2</sub> excited state. Effects like excited state absorption, cross relaxation and up-conversion, are absent. The Yb<sup>3+</sup> 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 absorption lines resulting from the Stark splitting, are covered by high-power InGaAs laser diodes.

The strongly anisotropic monoclinic double tungstates KY(WO<sub>4</sub>)<sub>2</sub> (KYW) and KGd(WO<sub>4</sub>)<sub>2</sub> (KGdW) doped with Yb<sup>3+</sup> ions have been recognized as attractive host-dopant combinations for diode-pumped solid-state lasers in the spectral range around 1 μm [2]. In contrast to KGdW, KYW can be doped with very high concentrations of Yb reaching the stoichiometric structure KYb(WO<sub>4</sub>)<sub>2</sub> (KYbW) [3] with practically no concentration quenching. Such highly Yb-doped materials are potentially interesting for thin film laser designs which profit from the relaxed requirements to the pump laser beam quality and the possibility for efficient transversal cooling, especially in the high power regime. Limitations related to the thermo-mechanical properties, however, set a technological challenge for a free standing active element with a thickness matching the absorption length. The latter, depending on the doping level, can be substantially below 100 μm, reaching 13.3 μm for KYbW. Epitaxially grown Yb-doped/undoped composites present a promising alternative solution as gain media for thin disk lasers [4] because this technology allows the fabrication of homogeneous epitaxial crystalline layers having a thickness down to the 10 μm-range. In fact, layers of KYbW on KGdW or KYW substrates seem feasible for thin-disk lasers. Very recently, we demonstrated for the first time to our knowledge laser operation based on epitaxial double tungstate structures by using a 25-μm thin, 20 at% Yb-doped KYW layer on a KYW substrate crystal [5]. Continuous-wave (CW) lasing at 1030 nm with 40 mW of output power could be achieved. However, the crystal lattice mismatch seems to be the basic limitation on the achievable interface quality and this limitation will be even more stringent in the case of KYW and KYbW [5]. The closer ionic radii of Lu and Yb makes the low-temperature monoclinic phase of potassium lutetium tungstate KLu(WO<sub>4</sub>)<sub>2</sub> (KLuW) potentially interesting as a passive host due to the possibility not only for doping with very high concentrations of Yb<sup>3+</sup> but also for the growth of KYbW/KLuW epitaxies. The closer unit cell parameters of KYbW and KLuW with differences of 0.12...0.74% against 0.39...1.01% between KYbW and KYW can be seen as a prerequisite for the growth of high quality epitaxial structures. This fact was our main motivation for investigating Yb:KLuW bulk crystals. The crystal structure of the monoclinic low-temperature phase of KLuW was studied as early as 1968 [6]. KLuW belongs to the C2/c space group and is isostructural to KYW and KGdW and many relevant properties like refractive index, optical transparency, and thermal conductivity are very similar [7].

## 2. Crystal growth and spectroscopic characterization

Yb-doped and undoped single crystals of KLuW were grown by the Top-Seeded Solution Growth (TSSG) slow-cooling method. Epitaxial Yb:KLuW layers on KLuW substrates have been grown with high crystalline quality by the Liquid Phase Epitaxy (LPE) method. The LPE experiments were performed in a vertical furnace with practically no axial gradient to obtain homogeneous epitaxial layers on every crystal face. It is important to note that the epitaxial growth takes place on all natural faces of the crystals used as substrates. The thickness of the Yb:KLuW layer, grown on the (010) face amounted to 130 μm with an Yb-doping concentration of 10 at%. For

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the laser experiments the (010) faces of the epitaxial crystal were additionally polished resulting in a layer thickness of 100  $\mu\text{m}$ .

The absorption cross section of Yb:KLuW was measured by optical density measurements at room temperature. The three polarizations correspond to the three orthogonal principal optical axes  $N_g$ ,  $N_m$  and  $N_p//b$  defined from the relation  $n_g > n_m > n_p$  for the refractive indices.  $N_g$  is located at  $\approx 18.5^\circ$  from the crystallographic axis  $c$  in the clockwise direction when the  $b$ -axis is pointing towards the observer.

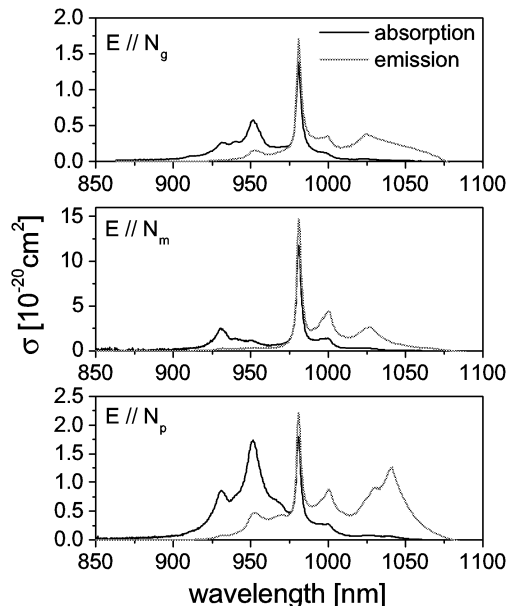


Fig. 1: Absorption (black) and calculated emission cross-sections (gray) of  $\text{Yb}^{3+}$  in KLuW.

The Stark components of the  ${}^2F_{7/2} \rightarrow {}^2F_{5/2}$  transition in Yb:KLuW can be seen as an absorption band in the polarized absorption spectra in Fig. 1 in the wavelength range between 850 and 1100 nm. They exhibit a high degree of optical anisotropy. The absorption is characterized by three main peaks centered at 981.1 nm, 951.4 nm and 930.9 nm. The maximum absorption cross-section calculated with an  $\text{Yb}^{3+}$  concentration of  $4.52 \times 10^{19} \text{ cm}^{-3}$  (0.5 at.% Yb-doped) amounts to  $1.18 \times 10^{-19} \text{ cm}^2$  for light polarization parallel to the  $N_m$ -crystallo-optic axis and the FWHM of this line amounts to 3.6 nm. These values are very close to those reported for 5 at.% Yb-doped KGdW and KYW [8], and the stoichiometric KYbW [3]. Fig. 1 also shows the emission cross sections for the three polarizations calculated by the reciprocity method. The emission cross section has a maximum of  $1.47 \times 10^{-19} \text{ cm}^2$  for  $E//N_m$  at 981.1 nm.

The measurement of the fluorescence lifetime was also performed with a 0.5% Yb-doped KLuW crystal to minimize effects like radiation trapping. The measured decay curve could be fitted by a single exponential corresponding to a lifetime of 375  $\mu\text{s}$  which is larger than the value measured by us and also by others of 300  $\mu\text{s}$  for 0.5% Yb-doped KYW [9].

### 3. Laser experiments

Laser generation was achieved using 5 and 10% Yb-doped KLuW bulk crystals and the 10% Yb-doped KLuW epitaxial composite. The thickness of the 5 and 10% doped Yb:KLuW crystals were 2.8 and 2.2 mm, and 1.1 mm (1 mm substrate and 100  $\mu\text{m}$  layer) for the composite structure, respectively. All samples were polished with their parallel faces normal to the  $N_p$ -principal optical axis ((010)-face) and oriented for polarization parallel to the  $N_m$ -optical axis. The active crystals were positioned between two folding mirrors under Brewster angle to minimize the Fresnel losses in an astigmatically compensated cavity. A four-mirror cavity was applied for the bulk crystals and a three-mirror cavity for the epitaxial Yb:KLuW. The lasers were end-pumped by two pump sources: a tunable cw Ti:sapphire laser, delivering more than 3 W near 980 nm focused to a beam waist of the order of 30  $\mu\text{m}$  at the position of the active medium and a tapered InGaAs diode laser delivering up to 2 W of output power around 978 nm with an  $M^2 < 4$  for the slow axis emission. For all Yb:KLuW crystals investigated, the optimum pump wavelength was around 980 nm corresponding to the absorption peak.

With an output coupler transmission  $T_{\text{OC}}=2.8\%$  the bulk Yb:KLuW laser threshold could be reached for pump wavelengths between 965 and 1005 nm. For both doping levels of the bulk crystals we achieved with  $T_{\text{OC}}=10\%$  pump efficiencies as high as 50% and maximum output powers of  $P_{\text{out}}=1$  W in the CW regime using

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Ti:sapphire laser pumping. The slope efficiency for  $T_{oc}=5\%$  was  $\eta=56-57\%$ , as depicted in Fig. 2a. The results with laser diode pumping and the same output coupler, a maximum output power of 180 mW and  $\eta=42\%$  were affected by the lack of absorption saturation and the imperfect overlap of the pump and laser waists in the crystal. The most important conclusion from the comparison of the 5% and 10% Yb -doped bulk KLuW samples is that the crystal quality and presumably the upper level lifetime remain unaffected by the increased dopant density. This is clear from the fact that the results are almost identical in terms of conversion efficiency and threshold.

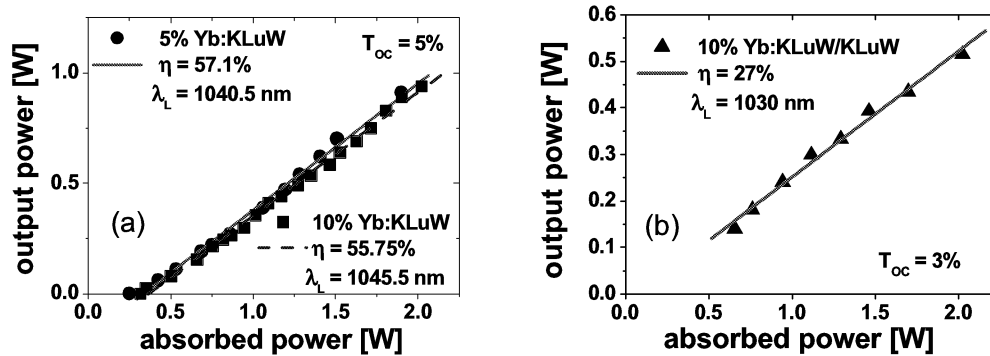


Fig.2: Laser characteristics of the Yb:KLuW bulk laser (a) and the Yb:KLuW/KLuW epitaxial composite (b) for polarization parallel to the  $N_m$  principal optical axis.

The maximum cw output power obtained from the epitaxial Yb:KLuW/KLuW laser reached 515 mW using a  $T_{oc}=3\%$ , see Fig. 2b. This corresponds to a maximum pump efficiency of 25.5% in a double pass. The maximum  $P_{out}$  slightly dropped with  $T_{oc}=5\%$  to 480 mW and amounted to 400 mW with the 1.1% output coupler. Using a chopper with 1:10 duty cycle the average output power of the epitaxial laser was 100 mW and the wavelength remained unchanged at 1030 nm. The estimated double pass absorption leads in this case to a pump efficiency of 40% which means a substantial increase in comparison with Fig. 2b. From the maximum output power obtained with the chopper, it can be concluded that CW output powers in excess of 1 W can be expected from this 100  $\mu\text{m}$  thick Yb:KLuW epitaxial laser once a proper cooling is provided.

## 4. Conclusion

In conclusion, we could demonstrate excellent laser performance of novel Yb:KLuW bulk crystals in the 1  $\mu\text{m}$  spectral range which was comparable to a 10% Yb-doped KYW reference sample. Based on these results, composite crystals consisting of thin Yb:KLuW layers on KLuW substrates were epitaxially grown with high crystalline quality and laser operation of such structures was studied for the first time to our knowledge.

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