

Continuous-wave and mode-locked laser operation of epitaxially grown Yb:KLu(WO₄)₂ composites

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Abstract: Epitaxial layers of Yb:KLu(WO₄)₂ were grown on KLu(WO₄)₂ substrates and highly efficient cw (66% slope efficiency and 415 mW output power) and passively mode-locked (114 fs pulse duration) operation at 1030 nm is demonstrated.

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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 region which are related to its simple two-level energy scheme. Yb-doped monoclinic KRE³⁺(WO₄)₂ single crystals are host-dopant combinations interesting for highly efficient laser operation by pumping with InGaAs laser diodes near 980 nm [1]. The doping level can reach the stoichiometric structure KYb(WO₄)₂, or KYbW [2], but thermo-mechanical limitations do not allow the fabrication and use of active elements with a thickness less than 100 μm corresponding to the absorption length. The latter, when operating in the absorption maximum at 981 nm, reaches 13.3 μm for KYbW. In fact, layers of KYbW on KGd(WO₄)₂ (KGdW) or KY(WO₄)₂ (KYW) substrates seem feasible for thin-disk lasers [3]. Very recently, we demonstrated for the first time 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 [4]. 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 even in the case of KYW and KYbW. The closer ionic radii of Lu and Yb make the low-temperature monoclinic phase of potassium lutetium tungstate KLu(WO₄)₂ (KLuW) potentially interesting as a passive host due to the possibility not only for doping with very high concentrations of Yb³⁺ but also for the growth of KYbW/KLuW epitaxies. The maximum absorption cross-section of the 981 nm line of Yb:KLuW amounts to 1.18×10⁻¹⁹ cm² (linewidth of 3.6 nm) and the emission cross section has a maximum of 1.47×10⁻¹⁹ cm², also at 981 nm, for light polarization parallel to the N_m-crystallo-optic axis [5]. Both values and many other relevant laser properties are very close to those reported for Yb-doped KGdW and KYW [1]. The closer unit cell parameters of KYbW and KLuW, listed in Table 1, 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 which was the main motivation for our recent investigation of the laser performance of Yb:KLuW bulk crystals [5] permitted now the epitaxial growth of Yb:KLuW layers on KLuW substrates, which is demonstrated for the first time in the present work.

Table 1: Unit cell parameters (C2/c space group, room temperature) of KLuW and KYW in comparison to the stoichiometric KYbW as an ideal epitaxial layer. For comparison the values for YAG and the other known stoichiometric Yb-crystal YbAG are also included.

lattice parameters	<i>a</i> [Å]	<i>b</i> [Å]	<i>c</i> [Å]	β	average
KLuW (ref. [5])	10.576(7)	10.214(7)	7.487(2)	130.68(4)°	
KYbW (ref. [2])	10.590(4)	10.290(6)	7.478(2)	130.70(2)°	
difference	0.13%	0.74%	0.12%	0.02%	0.33%
YAG (ref. [6])	12.0116(3)				
YbAG (ref. [6])	11.9380(5)				
difference	0.61%				0.61%
KYW (ref. [2])	10.6313(4)	10.3452(6)	7.5547(3)	130.752(2)°	
KYbW (ref. [2])	10.590(4)	10.290(6)	7.478(2)	130.70(2)°	
difference	0.39%	0.53%	1.01%	0.04%	0.64%

2. Epitaxial crystal growth

Yb-doped KLuW layers 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. 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 with an Yb-doping concentration of 10%, grown on the (010) face, amounted to 130 μm . For the laser experiments the (010) faces of the epitaxial crystal were additionally polished resulting in a layer thickness of 100 μm . The substrate thickness amounted to 1.1 mm.

3. Laser experiments

3.1 Continuous-wave operation

The polished (010)-faces of the epitaxial crystal were normal to the N_p -principal optical axis and the sample was oriented for polarization parallel to the N_m -optical axis and propagation approximately along the N_p -optical axis. The composite crystal was positioned between two focusing mirrors (an $RC=-5$ cm end mirror and an $R=-10$ cm folding mirror) under Brewster angle to minimize the Fresnel losses in an astigmatically compensated three-mirror cavity. The laser was longitudinally pumped through the folding mirror using an $f=6.28$ cm lens by two pump sources: a tunable cw Ti:sapphire laser, delivering more than 3 W near 980 nm focused to a beam waist of about 30 μm in the position of the crystal and a tapered InGaAs diode laser (TDL) delivering up to 2 W of output power near 978 nm which could be tuned by temperature. The optimum pump wavelength, at the relatively low doping level, corresponds to the absorption peak at 981 nm. The measured single pass low-signal absorption of the 10% Yb/Lu-site KLuW layer at 981.5 nm amounted to 64% in good agreement with the calculated value of 64.7% for a 100 μm thickness under Brewster angle.

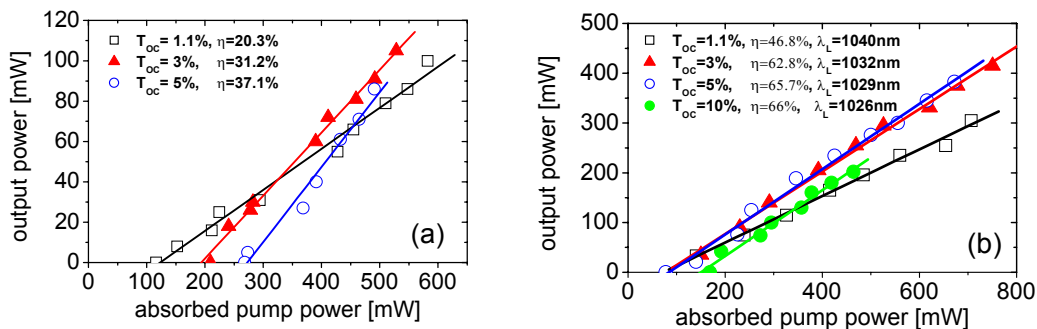


Fig. 1: Continuous-wave laser performance of the Yb:KLuW/KLuW epitaxial composite for the diode-pumped (a) and the Ti:sapphire laser pumped (b) configurations. The lasing wavelength in (a) was $\lambda_L=1030$ nm in all cases.

In the experiments with TDL pumping, cw laser operation could be obtained for transmissions (T_{OC}) of the plane output coupler between 1.1% and 10%. The output power versus the absorbed pump power (P_{abs}), measured in the lasing state, for three different T_{OC} is shown in Fig. 1a. The laser threshold achieved with the 100- μm -thin Yb:KLuW layer was as low as $P_{abs} \approx 120$ mW for $T_{OC}=1.1\%$. The thresholds we measured were 3 to 5 times lower than with the bulk Yb:KLuW samples [5] where reabsorption forced the laser to oscillate at longer wavelengths λ_L . At the maximum applied pump power the output power amounted to 105 mW and the pump efficiency with respect to P_{abs} reached 20%. The highest slope efficiency with respect to P_{abs} , $\eta=37.1\%$, was achieved for $T_{OC}=5\%$. The actual absorption depends on the depletion effect and can be substantially lower than the small signal value. It depends, however, also on the output coupler transmission since the different intracavity power produces a different recycling effect which counteracts the depletion [7].

With the Ti:sapphire laser used as a pump source in the same cavity configuration, a much better performance was achieved due to the improved matching between pump and laser modes as compared to the TDL pumping. The cw output characteristics are presented in Fig. 1b. The maximum measured output power of 415 mW corresponds to a maximum pump efficiency of 55% with respect to P_{abs} . The slope efficiency increases with T_{OC} reaching a maximum value of $\eta=66\%$ for $T_{OC}=10\%$. Both the pump and the slope efficiencies exceed those we recently reported for a 2.2-mm thick 10 at% Yb-doped bulk KLuW in a similar pump and laser configuration [5]. This is attributed to the strongly reduced reabsorption which leads to about 4 times lower thresholds in the case of the epitaxial sample and to shorter laser wavelengths λ_L . Note that the dependence of λ_L on T_{OC} in Fig. 1b can be explained by stronger absorption depletion and more homogeneous pumping along the beam path. It is interesting to note that even without cooling no damage of the epitaxial crystal occurred regardless of the high power levels (intracavity intensity exceeding 1 MW/cm^2) applied.

3.2 Mode-locked operation

Here we demonstrate for the first time to our knowledge mode-locked operation of an epitaxially grown composite crystal and present results obtained both in the picosecond and the femtosecond regimes. We studied a Z-shaped astigmatically compensated resonator with two RC=-10 cm folding mirrors in the middle. The Ti:sapphire pump beam was launched into the cavity through one of these mirrors. The cavity waist was formed at the position of the Yb:KLuW/KLuW crystal, inserted under Brewster angle. One arm contained an additional focusing mirror (RC=-10 cm) to increase the intensity on the semiconductor saturable absorber mirror (SAM) which was used for passive mode locking. Two dispersion prisms could be inserted in the other arm containing the plane output coupler.

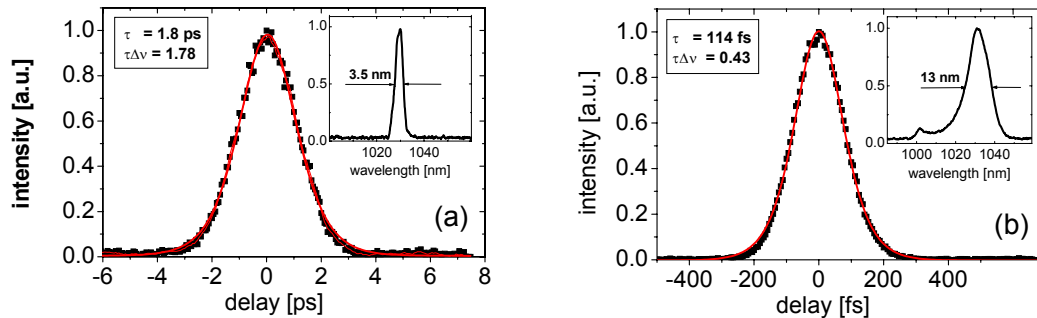


Fig. 2: Mode-locked laser performance of the Yb:KLuW/KLuW epitaxial composite in the picosecond (a) and the femtosecond (b) regimes.

Without intracavity prisms the SAM mode-locked laser operated in the picosecond regime with a pulse repetition frequency of 100 MHz and a maximum average output power of 117 mW ($T_{OC}=3\%$). Assuming a sech^2 -pulse shape the deconvolved FWHM of the pulse, from the autocorrelation trace in Fig. 2a, is $\tau=1.8$ ps.

The femtosecond regime was realized by adding two SF10 Brewster prisms with a separation of 31 cm into the arm containing a $T_{OC}=1.1\%$ output coupler, which resulted in a cavity round trip time of 101 MHz. Pulses as short as 114 fs (Fig. 2b) at 1030 nm could be achieved with an average output power of 31 mW. The time-bandwidth-product of 0.43 is slightly above the Fourier limit which is related to the asymmetric spectrum generated (inset Fig. 2b). We believe, the lower limit for the pulse duration and the observed deviation from the transform-limited pulse performance are related to the reflection characteristics of the folding mirrors which are restricted by the close separation between the pump and lasing wavelengths.

4. Conclusion

In conclusion we studied for the first time to our knowledge lasing in the 1 μm spectral range of Yb³⁺-doped epitaxial layers using the monoclinic KLuW as a substrate and host. Pulse durations as short as 114 fs could be obtained in the initial mode-locking experiments with such a composite crystal. CW output powers exceeding 400 mW with pump efficiencies as high as 55% were achieved without active cooling the crystal. This is an improvement of about one order of magnitude in comparison to the results reported with Yb:KYW/KYW epitaxies [4].

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