Mode-locked laser operation of epitaxially grown $Yb:KLu(WO_4)_2$ composites

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Mode locking based on an epitaxial composite of the monoclinic double tungstate crystal $Yb:KLu(WO_4)_2$ is realized. A 100 μm thin $Yb:KLu(WO_4)_2$ layer grown on a $KLu(WO_4)_2$ substrate is used as an active medium in a laser passively mode locked by a semiconductor saturable absorber. Pulse durations of 114 fs have been achieved for an average power of 31 mW at 1030 nm. Results in the femtosecond and picosecond regimes of the $Yb:KLu(WO_4)_2/KLu(WO_4)_2$ laser are presented. The great potential of Yb-doped tungstate composite structures as active elements for mode-locked laser systems is demonstrated. © 2005 Optical Society of America

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There is a strong trend toward simplification and miniaturization of Yb-based ultrashort-pulse solid-state lasers operating in the 1 μm spectral region. Yb-doped monoclinic $KRE^{3+}(WO_4)_2$ (RE=Y, Gd, Lu) single crystals are host–dopant combinations that are interesting for highly efficient laser operation.[1] The doping level can reach the stoichiometric structure[2] $KYb(WO_4)_2$ (KYbW), but thermomechanical limitations do not allow the fabrication and use of active elements with a thickness less than 100 μm. The absorption length, for operation in the absorption maximum at 981 nm and with polarization parallel to the N_m dielectric axis, reaches 13.3 μm for KYbW. Epitaxial growth of highly Yb-doped layers on passive substrates is especially interesting for such strongly anisotropic hosts, where the extremely large cross sections would permit the utilization of the thin disk laser concept.[3] Furthermore, for operation at higher power levels, the undoped part of the epitaxial structure can act as a heat sink to reduce the temperature in the crystal. 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 $KY(WO_4)_2$ (KYW) layer on a KYW substrate crystal.[4] However, the crystal lattice mismatch seems to be the inherent limitation on the achievable interface quality in the case of KYW and KYbW, and the mismatch relative to $KGd(WO_4)_2$ (KGdW) is even larger. The closer ionic radii of Lu and Yb make potassium lutetium tungstate, $KLu(WO_4)_2$ (KLuW), potentially interesting as a passive host because of the possibility not only of doping with very high concentrations of Yb^{3+} but also of the growth of KYbW/KLuW epitaxial structures. The maximum absorption σ_a and emission cross sections σ_e of Yb:KLuW and many other relevant laser properties are very close to those reported for Yb-doped KGdW and KYW.[1] The better match of the unit cell parameters of KYbW and KLuW with an average mismatch of 0.33% compared with 0.64% between KYbW and KYW can be seen as a prerequisite for the growth of high-quality epitaxial structures. Highly efficient cw[5] and mode-locked laser operation[6] with this novel Yb-doped monoclinic double tungstate was achieved by using a 2.8 mm thick, 5 at. % Yb-doped KLuW bulk sample. Output powers of the order of 1 W with pump efficiencies as high as 50% and pulse durations down to 81 fs with a saturable absorber mirror (SAM) used for mode locking were obtained at room temperature. The pulse durations achieved with bulk Yb:KLuW are slightly longer than the 71 fs once obtained with a Kerr-lens mode-locked Yb:KYW laser[7] but consistently shorter than the ≈100 fs limit reported for SAM mode-locked Yb:KGdW and Yb:KYW lasers.[8,9]

In this Letter we report for the first time to our knowledge mode-locked operation of Yb:KLuW/KLuW epitaxially grown composite crystal, and we compare its performance to the bulk Yb:KLuW laser.

Yb-doped KLuW layers have been grown with high crystalline quality by the liquid-phase epitaxy method. The thickness of the Yb:KLuW layer with an Yb-doping concentration of 10%, grown on the (010) face of a 1.1 mm thick KLuW substrate, amounted to 100 μm. The maximum σ_a and σ_e of Yb:KLuW for $E \parallel N_m$ amount to $\sigma_a = 1.18 \times 10^{-19}$ cm^2 and $\sigma_e = 1.47$

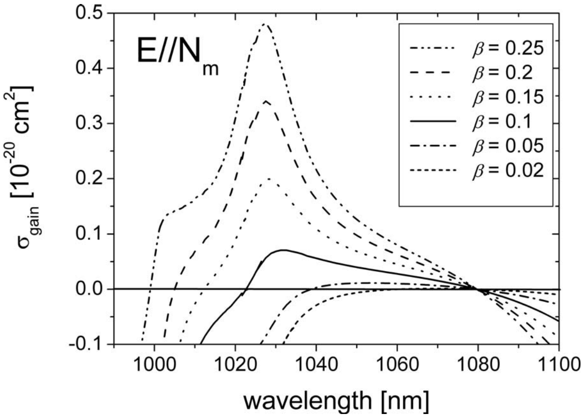

Fig. 1. Calculated gain cross section $\sigma_{\text{gain}}=\beta\sigma_e-(1-\beta)\sigma_a$ for polarization along the N_m principal optical axis of Yb:KLuW and various population inversions β.

$\times 10^{-19}$ cm^2 at 981 nm.[5] In order to estimate the potential gain bandwidth for mode-locked operation, the gain cross section for various population inversions β is calculated and presented in Fig. 1. β is the ratio of the excited ion density to the total Yb-ion density.

We studied a Z-shaped astigmatically compensated resonator similar to that used in Ref. 6. 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 N_m. The Yb:KLuW/KLuW crystal was positioned between two folding mirrors at the Brewster angle. The laser was pumped by a cw Ti:sapphire laser, delivering more than 3 W at the pump wavelength of 981 nm, focused to a beam waist of about 30 μm. The used semiconductor SAM was grown by metal organic vapor-phase epitaxy and consisted of a bottom Bragg mirror. The absorber was a 10 nm thick InGaAs surface quantum well structure[10] with a saturable absorption of ≈1%. Its relaxation time was measured by the pump–probe technique to be less than 5 ps.

The measured single-pass low-signal absorption of the 10% Yb:KLuW layer at 981 nm was 64%. Initially the cw laser performance without SAM and prisms in a three-mirror cavity was investigated. The maximum output power of 415 mW corresponds to a maximum optical conversion efficiency of 55% with respect to the absorbed pump power. Note that even without cooling the Yb:KLuW/KLuW composite, no thermal problems and no damage occurred. The pump and slope (up to 66%) efficiencies achieved both exceed those obtained with a 2.2 mm thick bulk KLuW doped with 10 at. % Yb in a similar pump and laser configuration.[5] This is attributed to the strongly reduced reabsorption.

Without intracavity prisms the SAM mode-locked laser operated in the picosecond regime at a pulse repetition frequency $f_{\text{rep}}=100$ MHz. In Fig. 2(a) the autocorrelation function is shown together with the emission spectrum centered at 1030 nm. Assuming a sech^2 pulse shape, the deconvolved FWHM of the pulse is 1.8 ps. The output power versus the absorbed pump power P_{abs} in the picosecond configuration, below and above the mode-locking threshold, is shown in Fig. 2(b). Mode-locked operation was obtained with a maximum output power of 119 mW, applying an output coupler transmission $T_{\text{OC}}=3\%$. From these experimental data the measured slope efficiency amounted to 27%, and the optical conversion efficiency reached 17%. We attribute the overall reduction of the efficiency caused by the presence of the SAM to the cavity realignment connected with the additional focusing mirror. The femtosecond regime was realized by inserting two SF10 Brewster prisms with a separation of 31 cm into the arm containing $T_{\text{OC}}=1.1\%$, which resulted in an $f_{\text{rep}}=101$ MHz. The measured autocorrelation traces are well fitted, assuming a sech^2 pulse shape. Pulses as short as 114 fs [Fig. 3(a)] at a central wavelength of 1030 nm were generated with an average output power of 31 mW for $P_{\text{abs}}=632$ mW. The time–bandwidth product $\tau\Delta\nu=0.43$ is slightly above the Fourier limit [spectrum, inset Fig. 3(a)]. We believe that 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 the lasing wavelengths. This entails a high transmission <980 nm and a high reflection >1020 nm. The output power could be increased by using $T_{\text{OC}}=3\%$, and 94 mW were obtained, again at 1030 nm, for $P_{\text{abs}}=671$ mW. The generated pulses

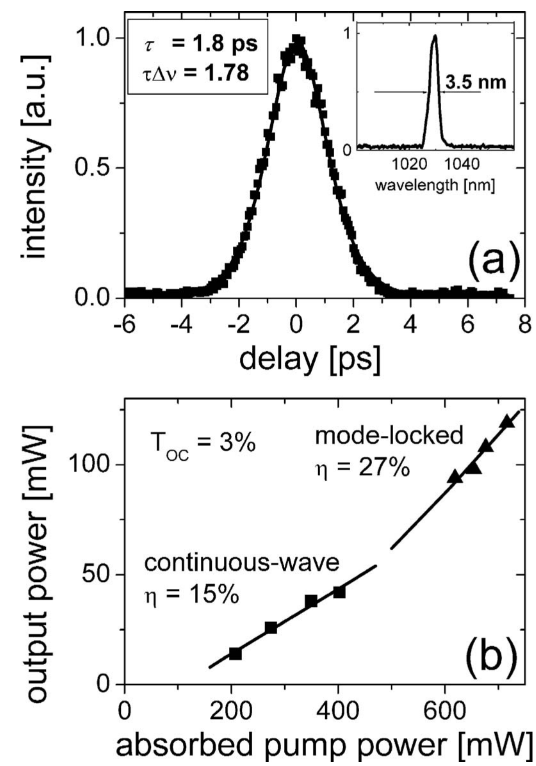

Fig. 2. Mode-locked laser performance of the Yb:KLuW/KLuW epitaxial composite in the picosecond regime; T_{OC}, output coupler transmission. (a) Autocorrelation trace and (inset) spectrum; τ, pulse duration; $\tau\Delta\nu$, time–bandwidth product. (b) Output power versus absorbed pump power above and below the mode-locking threshold (cw); η, slope efficiency.

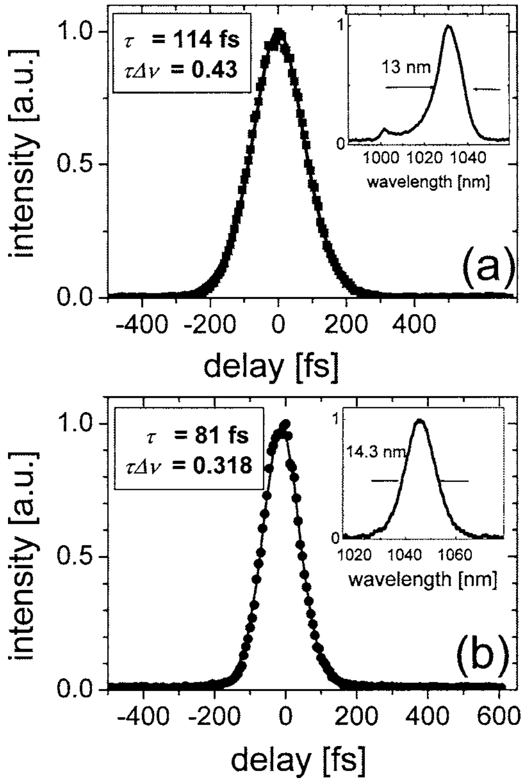

Fig. 3. Autocorrelation traces and (inset) spectra in the femtosecond regime. (a) Epitaxial composite, 100 μm thin Yb(10%):KLuW layer on a 1.1 mm thick KLuW substrate. (b) 2.8 mm thick Yb(5%):KLuW bulk single crystal; τ, pulse duration; $\tau\Delta\nu$, time–bandwidth product.

had a FWHM of 200 fs in this case and were almost bandwidth limited ($\tau\Delta\nu=0.32$).

To illustrate that the 114 fs pulse duration is not the limit, we compare the femtosecond laser performance of the epitaxial Yb:KLuW with that of the bulk Yb(5%):KLuW (2.8 mm thick) single crystal [Fig. 3(b)] under the same experimental conditions. We expect a larger gain bandwidth for the epitaxial structure due to the reduced reabsorption, leading to a higher average population inversion β. Such behavior can be clearly observed in Fig. 1, visualizing the estimated gain bandwidth for various β. From the central wavelength of 1045 nm for spectrum of the bulk Yb:KLuW laser [inset Fig. 3(b)], $\beta\approx 0.08$ can be deduced. The pulse spectrum of the epitaxial composite is centered at 1030 nm with a broadened shape of the short-wavelength wing extending beyond 1000 nm. Both the central wavelength and the spectral shape can be associated with larger population inversion in Fig. 1 ($\beta>0.2$), corresponding to broader gain bandwidths. Thus the strongly reduced reabsorption of the epitaxial Yb:KLuW, resulting in potentially broader gain bandwidths, is expected in the future to allow pulse lengths below 80 fs to be produced, by use of specially designed dichroic coatings for the folding mirrors.

For the development of composite-based femtosecond oscillators the use of epitaxial structures, where the layer and the substrate consist of the same crystal host, have essential advantages compared with heterocomposite structures like bonded crystals of Yb:YAG on sapphire.[11] They can reduce the problem of parasitic reflections and birefringence effects,[12] which could strongly affect the femtosecond regime and have to be taken into consideration. Neither in the emitted spectrum nor in the field distribution of the Yb:KLuW/KLuW laser could we detect any indications of modulations.

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