Segmented Growth of Monoclinic Yb:KY(WO$_4$)$_2$/KY(WO$_4$)$_2$ and its Laser Operation

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Abstract: Composite Yb:KY(WO$_4$)$_2$ grown on KY(WO$_4$)$_2$ substrates by segmented growth showed highly efficient continuous-wave laser operation with slope efficiencies as high as 80% and 375 mW output power was demonstrated.

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Yb-doped materials are well suited for building simple and robust diode-pumped lasers in the 1-µm spectral range. The low temperature monoclinic phases of KY(WO$_4$)$_2$ (KYW), KGd(WO$_4$)$_2$ (KGdW) and KLu(WO$_4$)$_2$ (KLuW) are well known host materials for doping with active rare earth ions. They are strongly anisotropic and, when doped with Yb, exhibit an absorption maximum near 981 nm with a cross section about 15 times larger than that of Yb:YAG [1]. Furthermore, Yb:KYW and Yb:KLuW can incorporate very high concentrations of active ions, up to the stoichiometric composition KYb(WO$_4$)$_2$ (KYbW) [2]. The extremely high absorption and emission cross sections of the Yb-doped monoclinic double tungstates permit the use of very thin crystals, as demonstrated in the case of thin-disk lasers [3]. However, thermo-mechanical limitations impose restrictions on the fabrication and use of stand alone active elements with a thickness in the order of 100 µm corresponding to the absorption length. Two different approaches were investigated to establish such structures: diffusion bonding [4] and liquid phase epitaxy (LPE) [5,6]. Diffusion bonded structures have already proved their potential for laser applications [4], but mainly based on YAG. To our knowledge no reports about diffusion bonding using the strongly anisotropic double tungstates exist. LPE grown Yb-doped monoclinic double tungstates were successfully introduced in the last few years. The first laser operation based on epitaxial double tungstate structures was demonstrated by using a 25-µm thick, 20 at % Yb-doped KYW layer on a KYW substrate [7]. Continuous-wave (CW) lasing at 1030 nm with 40 mW of output power was achieved. Because of the close ionic radii of Lu and Yb, KLuW doped with Yb is potentially interesting for epitaxial composites. Recently, lasing in the 1 µm spectral range of 10 at % Yb-doped epitaxial layers using KLuW as a substrate and host was studied. CW output powers exceeding 400 mW with pump efficiencies as high as 55% were demonstrated [8].

Segmented crystal growth is an alternative method developed at FEE GmbH to obtain composite single crystals. In segmented growth, two or more segments of bulk single crystalline material are grown on top of each other. In the simplest case of two segments, the resulting crystal can be used for the fabrication of composite optical elements with two layers of different concentrations of dopants if these elements are drilled across the interface between the segments. Here we report on segmented growth of Yb-doped KYW on undoped KYW yielding the first double tungstate composite laser crystals based on this technique.

Segmented growth of Yb-doped KYW on undoped KYW was performed in a standard top-seeded solution growth setup. The first-grown segment could be either doped or undoped. The seed orientation was along the monoclinic *b*-axis, thus yielding a flat growth interface. This fact is important for the growth of the second segment which had to start on this very interface. Of course the two segments were grown from two liquid solutions with different Yb concentrations (in our case 0 and 13 mol %). The pulling rates were between 0.05 and 0.1 mm/h. The resulting crystals had typical lengths of 3 to 6 mm for the undoped material and 5 to 10 mm for the doped one. Crack-free boules with 10×10 mm^2 cross-sections were obtained. At the present level, the interface still has inclusions and care must be taken to core drill usable samples in appropriate volumes of high quality material. Away from the interface, the material is of comparable quality to standard top-seeded grown samples: segmented growth is thus able to provide composites with segment lengths of at least 3 to 10 mm.

For the laser experiments, the {010} face (i.e., the monoclinic *b* face) of the segmented grown Yb:KYW crystal portion was polished down to 200 µm with high optical quality. It is by definition normal to the N_p-principal optical axis. The undoped segment was subsequently polished parallel to give a total thickness of 1.4 mm. The crystal was oriented for polarization parallel to the N_m-optical axis and propagation approximately along the N_p-optical axis. The uncoated Yb:KYW/KYW segmented grown sample with an aperture of 3.6×4.1 mm^2 was positioned at Brewster angle between the two folding mirrors of a Z-shaped resonator. The laser was longitudinally pumped through one folding mirror using an f=6.28 cm lens by a tunable CW Ti:sapphire laser, delivering more than 3 W near 980 nm focused to a beam waist of about 30 µm at the position of the crystal. The optimum pump wavelength corresponds to the absorption peak at 981 nm. The measured single pass low-signal absorption of the 10 at % Yb:KYW segment at this wavelength amounted to 58%.

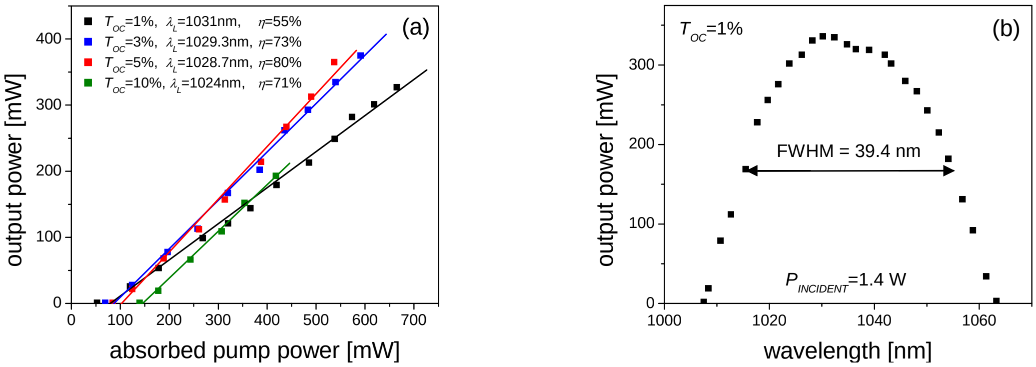

Fig. 1. Continuous-wave laser performance of the segmented grown Yb:KYW/KYW composite. (a) Output power versus absorbed pump power for four output couplers (T_{OC}: output coupler transmission, η: slope efficiency). (b) Output power versus laser wavelength (λ_L).

CW laser operation was obtained for transmissions (T_{OC}) of the plane output coupler between 1% and 10%. The output power versus the absorbed pump power (P_{abs}), measured in the lasing state for four T_{OC}, is shown in Fig. 1a. The laser threshold achieved with the 200-µm thick Yb:KYW segment was as low as P_{abs}≈52 mW for T_{OC}=1%. The maximum measured output power of 375 mW corresponds to a maximum pump efficiency of 63% with respect to P_{abs}. The slope efficiency changes with T_{OC} reaching a maximum value of η=80% for T_{OC}=5%. The actual absorption depends on the bleaching 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 bleaching. The dependence of the laser wavelength λ_L on T_{OC} in Fig. 1a can be explained by stronger absorption bleaching. Both the pump and the slope efficiencies are slightly higher than those we recently reported for a LPE-grown 130-µm thick 10 at % Yb-doped KLuW layer in a similar pump and laser configuration [8]. This confirms the high quality of the segmented grown Yb:KYW composites. It is interesting to note that even without cooling no damage of the segmented grown crystal occurred regardless of the applied high intracavity intensity of >1 MW/cm^2. The tuning operation of the laser was investigated inserting a Lyot filter under Brewster angle close to the output coupler (Fig. 1b). Under optimum alignment the power reduction with the filter inside the cavity did not exceed 10%. Tunability extending from 1007 to 1063 nm at the zero-level was obtained corresponding to a FWHM of 39.4 nm.

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