$KY(WO_4)_2:Yb^{3+}$ planar waveguide laser

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Abstract: Continuous-wave waveguide lasing in a thin layer of monoclinic $KY(WO_4)_2:Yb^{3+}$ grown by liquid-phase epitaxy is demonstrated at 1024 nm in the fundamental mode with 50% slope efficiency and 290 mW of output power.

OCIS codes: (140.5680) Rare earth and transition metal solid-state lasers; (230.7390) Waveguides, planar

$KY(WO_4)_2$ (hereafter KYW) crystals doped with different rare-earth ions are recognized as very promising materials for solid-state lasers operating at room temperature, both in pulsed and continuous-wave (CW) mode [1,2]. In particular, the Yb^{3+} ion in KYW exhibits an absorption maximum near 981 nm with a cross-section about 15 times larger than that of YAG:Yb. The small absorption length in highly-doped KYW:Yb together with an extremely small laser quantum defect (as low as 1.6% [3]) makes this material a favorable candidate for the thin-disk laser concept [4]. Recently, the growth of KYW:Yb thin layers on KYW substrates and their CW laser operation under longitudinal pumping normal to the layer using a CW Ti:sapphire laser as pump source has been demonstrated [5].

However, as Yb^{3+} is a quasi-three-level system, a significant part (e.g. 5% in YAG:Yb at room temperature [6]) of the total ground-state population is thermally excited in the lower Stark laser level, giving rise to pronounced reabsorption and a rather high pump threshold. One way of decreasing the threshold is the use of a waveguiding structure, in which high pump-power densities and excellent overlap of pump and resonator modes can be achieved. This approach requires fabrication of high-quality KYW:Yb layers on suitable substrates with close-to-perfect interfaces to ensure low-loss propagation. On the other hand, in a waveguiding configuration with end-face pump coupling and pump absorption along the whole waveguide length, the Yb^{3+} concentration can be much smaller than would be required for pumping perpendicular to the layer plane. At low Yb^{3+} concentration, stress due to lattice mismatch between layer and substrate is minimized and large-area, defect-free thin layers can be grown.

Recently, we reported on the liquid-phase epitaxy (LPE) of rare-earth-ion-doped KYW layers employing a low-temperature chloride solvent [7]. However, 3D island nucleation generated insertion defects, which limited the maximum layer thickness to approximately 10 µm and led to non-optimum interface quality. In the present study, we used $K_2W_2O_7$ as solvent [8] and undoped KYW crystals grown by a modified Czochralski method with laser-grade polished (010) faces as substrates. The vertical dipping technique under constant substrate rotation was applied. Single-crystalline layers with thicknesses from 10 to 100 µm and Yb^{3+} concentrations ranging from 1 to 3 at% with respect to Yb^{3+} were produced.

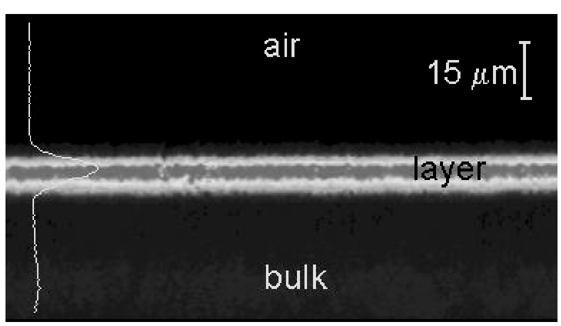

Fig. 1. Image of the guided fluorescence and pump laser light outcoupled from a 15-µm thick KYW:1.8% Yb^{3+} planar waveguide under excitation at 980 nm from a diode laser.

The surface and end-faces of each layer were polished to laser-grade quality and the layers were tested as planar passive and active waveguides under excitation at 633 or 980 nm, respectively. For the particular waveguide shown in Fig. 1, the vertical shape of the guided beam can be fitted with a Gaussian profile, nevertheless the combination of waveguide thickness and refractive-index change of the layer with respect to the substrate (1.0×10^{-3} for a 1.8at% Yb^{3+}-doped layer, as measured by dark m-lines spectroscopy) allows multi-mode propagation.

The planar waveguide used for the laser experiments consisted of a 35-µm thin layer of 1.8at% Yb^{3+}-doped KYW. A 1-mm thick undoped KYW acted as the substrate. The 6-mm long waveguide was placed in an external resonator. To match the resonator waist size with the waist of the transverse fundamental mode of the waveguide, a Z-shaped four-mirror laser resonator was constructed. The KYW:Yb waveguide was positioned between two 10-cm folding mirrors such that the resonator waist is located at both end-faces of the waveguide and negligible diffraction losses occur for the resonator mode at the air/KYW:Yb/KYW interfaces. Our laser scheme was characterized by guiding the pump and the resonator mode over the entire length of the planar waveguide, maintaining a high overlap between pump and resonator mode. The waveguide was positioned at Brewster angle to minimize losses in the laser cavity. Beam propagation was approximately along the N_g principal optical axis and polarization along the N_m axis. The sample was mounted on a copper plate but no special care was taken for active cooling. The KYbW:Yb layer was pumped in single-pass absorption by a tunable CW Ti:sapphire laser with a maximum output power of 3 W near 980 nm. A 62.8-mm focusing lens was used to couple the nearly diffraction limited pump beam through one of the folding mirrors into the planar waveguide. The measured single-pass low-signal absorption of the 1.8at% Yb-doped KYW layer at 980.5 nm amounted to 56%, in good agreement with the calculated value.

Continuous-wave laser operation was obtained for output-coupler transmissions between 1.7 and 13.5%. Independent of the output-coupler transmission, the laser emission was centered near 1024 nm (Fig. 2). Because of the reduced reabsorption due to the high confinement and, therefore, high intensity of the pump beam in the active layer, the spectral emission corresponds to the maximum of the gain curve. Best laser performance was achieved for pumping in the main absorption peak at 980.5 nm. The laser threshold of the 35-µm-thin KYW:Yb layer was reached at an absorbed pump power of about 100 mW. Using an output coupler with a transmission of T_{OC} = 5.1%, the maximum output power amounted to 290 mW, resulting in a slope efficiency of η = 46% with respect to the absorbed pump power, as measured in the lasing state (Fig. 3). The slope efficiency was maximum for T_{OC} = 7.6% and amounted to 50%, corresponding to a pump efficiency of 39%. Applying a chopper with a duty cycle of 10%, the output power decreased ten times. Hence it can be concluded that no thermal problems occur up to the maximum applied pump power of 2 W despite the absence of active cooling. A rough loss estimation based on the detected laser slope efficiencies gave a cavity round trip loss of ≈ 4.8%. The observed far-field intensity distribution indicates that despite the multi-mode waveguide structure, the laser output is close to the diffraction limit and the resonator mode is well matched within the physical dimensions of the planar waveguide.

Our future research will concentrate on establishing a monolithic laser cavity by use of butt-coupled laser mirrors to reduce the resonator round-trip losses, reducing the layer thickness to ensure fundamental-mode laser operation in any pump and resonator configurations, demonstrating diode pumping, exploring surface structuring to demonstrate channel waveguide lasing, and doping or co-doping the KYW lattice with other rare-earth ions to access other wavelengths for laser operation.

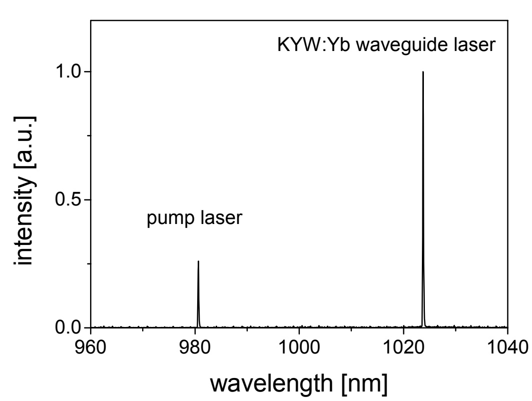

Fig. 2. Spectral record of the KYW:Yb planar waveguide laser emission and the residual pump laser radiation.

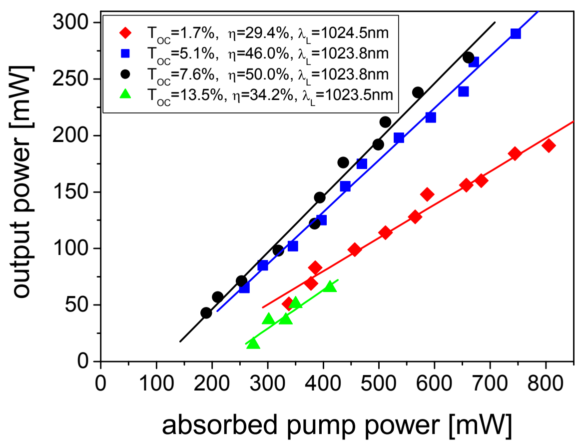

Fig. 3. Continuous-wave output power versus absorbed pump power of the KYW:Yb planar waveguide laser for different transmissions of the output coupler.

In conclusion, epitaxial planar waveguides of monoclinic double tungstates have been manufactured with high optical quality by the LPE method. KYW:Yb layers with thickness from 10 to 100 µm were grown on KYW substrates. Using a 6-mm long planar waveguide with a 35-µm thin, 1.8at% Yb-doped KYW layer, waveguide laser operation based on a monoclinic double tungstate crystal was achieved for the first time. Continuous-wave lasing at 1024 nm with a maximum output power of 290 mW and slope efficiencies as high as 50% were obtained at room temperature. Laser emission close to diffraction-limited performance was achieved.

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