the layer surface was polished parallel to the layer-substrate interface with a rms surface roughness of 1.5 nm. A $KY_{0.40}Gd_{0.433}Lu_{0.150}Yb_{0.017}(WO_4)_2$ layer (sample A) was polished to a thickness of 2.4 µm, while a $KGd_{0.490}Lu_{0.485}Yb_{0.025}(WO_4)_2$ layer (sample B) was polished to a thickness of 5 µm. Both layers were microstructured by standard lithography and Ar^+ beam etching [21] to obtain 7-µm-wide, 1.4-µm-deep ridge waveguides along the N_g optical axis. To improve mode overlap with the active region, diminish propagation losses, and facilitate end-face polishing, both samples were overgrown by an undoped $KY(WO_4)_2$ cladding. The end faces of each sample were polished parallel to the N_m optical axis, resulting in a waveguide length of 7.0 mm (re-polished from 7.5 mm after previous investigations [21]) and 6.6 mm [10] for sample A and B, respectively.

The waveguides were end-pumped by a continuous-wave Ti:Sapphire laser operating at ~934 nm with its polarization parallel to the N_m optical axis. The pump laser was mechanically chopped with a 50% duty cycle at a frequency of 200 Hz. Pump light was coupled into the channel waveguide using a × 16 objective lens with a numerical aperture (N.A.) of 0.32. With a variable beam expander in the pump-beam line the pump mode was adapted to the slightly lower N.A. of the channel waveguides. By use of mode-solver software (Phoenix FieldDesigner [22]) a coupling efficiency of 88% and 82% (excluding Fresnel reflection) was calculated for the pump light, of which ~62% and ~80% was absorbed in sample A and B, respectively. The waveguide geometries and calculated [22] fundamental laser modes are presented in the insets of Fig. 3. Sample A additionally supports propagation of a weakly confined higher-order laser mode, while no higher-order modes were found by the mode-solver software for sample B. Considering the higher refractive index contrast and larger waveguide dimensions of sample B, this result is counter-intuitive, but is known from Petermann structures [23]. The cavity of sample A was formed by the 11% Fresnel reflection at the pumped waveguide end-facet and a mirror with 97% reflectivity at 981 nm butt-coupled to the other end-facet by fluorinated oil (Fluorinert FC-70), resulting in R_{out} = 11%. The emitted laser light was collected from the pumped end via a beam splitter placed into the pump beam. A reflective grating was used to separate the laser emission from residual pump light. The cavity of sample B was formed by the Fresnel reflections from both waveguide end-facets, providing R_{out} = 1.2%. Here, the emitted light was monitored only from the unpumped end in order to launch the maximum available pump power. The measured emitted power was multiplied by a factor of two to account for emission from the pumped end. This is a conservative estimation, since according to our rate-equation calculations counter-propagating laser light is more efficiently amplified than co-propagating laser light.

For comparison with the usual lasing situation, experiments were also performed by pumping at 981 nm. In this case mirrors were butt-coupled on both waveguide ends, resulting in R_{out} = 77% at 1028 nm (sample A) or R_{out} = 30% at 1023 nm (sample B).

4. Laser results

The measured laser performance at 981 nm, displayed as green triangles in Figs. 3(a) and 3(b), reveals slope efficiencies of 76% and 72% (green solid lines) versus absorbed pump power and maximum output powers of 77 mW and 650 mW for sample A and B, respectively. The pump threshold was 13 mW and 130 mW of absorbed pump power in case of sample A and B, respectively. The laser emission spectrum from sample B was analyzed by a spectrometer (Jobin-Yvon iHR550) with a resolution of 0.11 nm. The emission peak occurred at a wavelength of 981 nm with a width of 0.5 nm. In comparison, when pumping at 981 nm, lasing occurred at 1023−1028 nm with slope efficiencies of 62% and 72%. Since in these experiments the mirror reflectivities at the laser wavelength were chosen to be significantly higher, hence outcoupling losses were significantly smaller, lower pump thresholds of 5.5 mW and 30 mW resulted for samples A and B, respectively.

#185246 - $15.00 USD Received 11 Feb 2013; revised 13 Mar 2013; accepted 21 May 2013; published 31 May 2013
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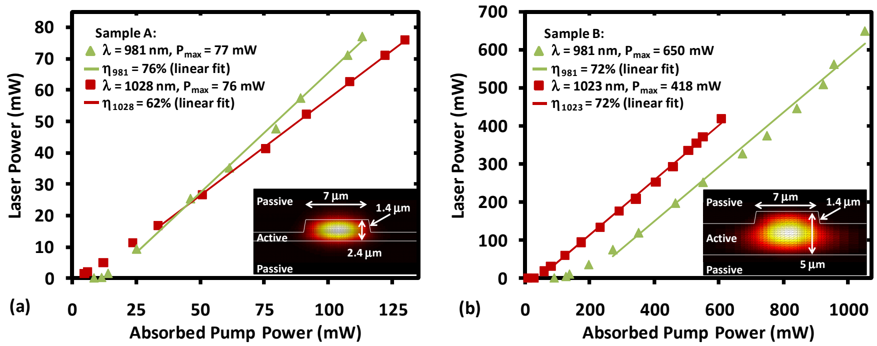

Fig. 3. Measured power characteristics (symbols) and fitted slope efficiencies (lines) of the waveguide lasers based on (a) sample A and (b) sample B for pumping at 934 nm and lasing at 981 nm (green) and comparison with pumping at 981 nm and lasing at 1023–1028 nm (red). The insets show the modeled fundamental-mode profiles in these structures.

Despite the significantly larger reabsorption cross-section on the central line at 981 nm, equal or even higher slope efficiencies are obtained for lasing on this transition (Fig. 3, green triangles) compared to laser performance at longer wavelengths of 1023–1028 nm (Fig. 3, red squares). At first glance this may be counter-intuitive, because reabsorption reduces the efficiency of the laser process. However, there is a large difference in the applied outcoupling efficiency between laser operation at the central line and at longer wavelengths. The much larger outcoupling degree used at the central line laser operation increases the threshold inversion and available gain, thus compensating the accordingly decreased reabsorption losses, while simultaneously increasing the useful outcoupling losses. These effects explain the highly efficient laser operation of these laser devices at the central line. The fact that in sample B the slope efficiency is the same for both operational regimes could be explained by the conservative estimation of monitored laser output power at 981 nm, which was based on the assumption that equal power is emitted from both waveguide ends.

5. Summary

From the calculated emission cross-section spectra and chosen resonator outcoupling degrees, the output wavelength characteristics of Yb^{3+}-doped $KY_{1-x-y}Gd_xLu_y(WO_4)_2$ channel waveguide lasers was analyzed, based on the laser round-trip equation. The large gain which is present on the central line at 981 nm in Yb^{3+}-doped potassium double tungstate channel waveguides under pumping at a shorter wavelength of 934 nm was exploited in open cavities based on Fresnel reflection at one or both waveguide end-facets. In this configuration the large outcoupling efficiency leads to a large population inversion and accordingly reduced reabsorption on the central line. Furthermore, it diminishes the adverse influence of the fairly large intra-cavity propagation loss in a channel waveguide, resulting in the demonstration of a high slope efficiency of 76% and a total extracted laser power of 650 mW. This approach promises high efficiencies also for other laser transitions in rare-earth ions.

Acknowledgment

This work was supported by The Netherlands Organisation for Scientific Research (NWO) through the VICI Grant no. 07207 "Photonic integrated structures".