1.6-W, Highly Efficient Laser at 2 μm in a Potassium Double Tungstate Channel Waveguide

Koop van Dalfsen[1], Shanmugam Aravazhi[1], Christos Grivas[2], Sonia M. García-Blanco[1], Markus Pollnau[1]

[1] *Integrated Optical Microsystems Group, MESA+ Institute for Nanotechnology, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands*
m.pollnau@utwente.nl
[2] *School of Physics and Astronomy, University of Southampton, Southampton SO17 1BJ, UK*
chr.grivas@gmail.com

Abstract: Buried ridge waveguides are microstructured into a monoclinic potassium double tungstate layer with a composition of $KY_{0.40}Gd_{0.29}Lu_{0.23}Tm_{0.08}(WO_4)_2$ grown onto a $KY(WO_4)_2$ substrate by liquid-phase epitaxy. When pumping with a Ti:Sapphire laser at 794 nm, the fundamental-mode channel waveguide produces laser emission with a slope efficiency of ~80% and an output power of 1.6 W at 1.84 µm in a resonator with 89% output coupling.

Introduction: Dielectric channel waveguide lasers are of great interest because of their low pump thresholds and, even more so, high slope efficiencies resulting from the small transverse channel cross-sections which reduce the volume of active medium that needs to be pumped and the excellent overlap between pump and laser modes. In Tm-doped waveguide lasers operating near 2 µm wavelength, highest reported slope efficiencies are 76% in a $LiYF_4:Tm^{3+}$ planar waveguide with an output power of 560 mW,[1] as well as 70% in Tm^{3+}-doped potassium double tungstate channel waveguides with output powers of 300 mW.[2]

Waveguide fabrication: A co-doped layer of $KY_{0.40}Gd_{0.29}Lu_{0.23}Tm_{0.08}(WO_4)_2$ with a thickness of several tens of micrometers was grown onto a pure $KY(WO_4)_2$ (= KYW) substrate by liquid-phase epitaxy at 920-923 °C.[3-5] The layer was lapped and polished to a thickness of 14.3 µm, covered with a photoresist mask, and patterned 1.9-µm-deep by Ar^+-beam milling.[6] Ridge-type channel waveguides with a maximum loss of 0.11 dB/cm at ~2 µm were produced in this way and overgrown with a pure KYW layer as a cladding to further reduce scattering loss.[7] The channels, having a width of 10−25 µm, which support only the fundamental modes for both the pump and laser wavelengths, were diced to a length of 4.2 mm and end-face polished to an optical finish.

Laser experiments: The Tm^{3+}-doped channel waveguides were pumped at a wavelength of 794 nm with a transverse-magnetic (TM, E||N_p) polarization. As the pump source, a Ti:Sapphire continuous-wave laser was used. In-coupling of pump light into the channel waveguides was optimized using cylindrical lenses of 40 mm and 10 mm in the horizontal and vertical directions, respectively. A dielectric mirror with a reflectivity of 99.9% (HR) at 1900–2100 nm and high transmissions at 790–810 nm (due to an anti-reflection coating at this wavelength) was butt-coupled to the pump in-coupling end-facet of the channel waveguides using index-matching oil (Fluorinert). At the other waveguide end-facet, no dielectric mirror was placed such that feedback was only provided by the Fresnel reflection at the KYW-air interface amounting to ~11% reflection. The laser output power was out-coupled from the channel

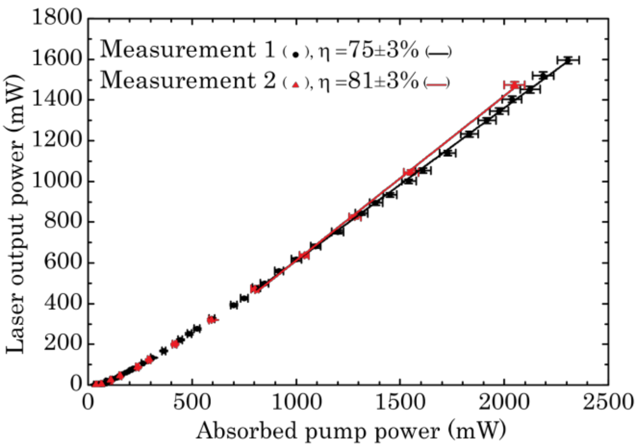

Fig. 1: Laser output power at 1840 nm versus absorbed pumped power at 794 nm in TM-polarization. Shown are two independent measurements (red and black dots), and the linear fits of the laser slope efficiency at higher powers (red and black lines).

waveguides via a 0.25 NA microscope objective and any residual pump power was blocked by a RG1000 filter. The measured laser output power from two independent experiments when pumping at λ_P = 794 nm in TM-polarization is shown in Fig. 1. The highest output power measured is 1594 mW at an absorbed pump power of 2181 mW and the slope efficiency amounts to ~80%. The laser operates at an output wavelength of λ_L = 1840 nm.

Slope efficiency: If ground-state bleaching is absent, from spectroscopic lifetime data[8,9] we derive that the "2 for 1" cross-relaxation process[10] in Tm^{3+} provides a quantum efficiency of η_q = 1.94 for the relevant Tm^{3+} concentration of 5.07 × 10^{20} cm^{-3}. Furthermore, this laser has a mode overlap of η_{mode} = 1, because the laser-beam size is larger than the pump-beam size, and a Stokes efficiency of $\eta_{St} = \lambda_P / \lambda_L$ = 794 nm / 1840 nm = 0.432. With an out-coupling efficiency equaling the ratio of useful resonator losses, given by the outcoupling transmission of T_{out} = 89%, to total resonator losses, in which also the intrinsic round-trip losses L = 0.015, equaling $\eta_{out} = \ln[1-T_{out}]/\ln[(1-T_{out})(1-L)]$ = 0.993, the theoretical limit of the slope efficiency is

$$\eta_{slope} = \frac{dP_{out}}{dP_{abs}} = \eta_{mode}\eta_{St}\eta_q\eta_{out} = 83.2\% \,. \qquad (1)$$

Thanks to the channel waveguide geometry and the resulting strong confinement of pump and laser modes, the laser overcomes the reabsorption losses from the ground state and is indeed able to operate close to the theoretical slope efficiency, see Fig. 1.

Conclusions: We have demonstrated a 2-μm channel waveguide laser with a slope efficiency exceeding 80% and an output power of 1.6 Watt. At this performance level it may be applied as a compact and inexpensive laser source for real-time monitoring of gases for environmental, industrial, and medical purposes.

References

1. W. Bolaños, F. Starecki, A. Benayad, G. Brasse, V. Ménard, J.-L. Doualan, A. Braud, R. Moncorgé, P. Camy, *Opt. Lett.* **37**, pp. 4032−4034 (2012).
2. K. van Dalfsen, S. Aravazhi, C. Grivas, S. M. García-Blanco, M. Pollnau, *Opt. Lett.* **37**, pp. 887−889 (2012).
3. Y. E. Romanyuk, C. N. Borca, M. Pollnau, S. Rivier, V. Petrov, U. Griebner, *Opt. Lett.* **31**, pp. 53−55 (2006).
4. F. Gardillou, Y. E. Romanyuk, C. N. Borca, R. P. Salathé, M. Pollnau, *Opt. Lett.* **32**, pp. 488−490 (2007).
5. S. Aravazhi, D. Geskus, K. van Dalfsen, S. A. Vázquez-Córdova, C. Grivas, U. Griebner, S. M. García-Blanco, M. Pollnau, *Appl. Phys. B* **111**, pp. 433−446 (2013).
6. D. Geskus, S. Aravazhi, C. Grivas, K. Wörhoff, M. Pollnau, *Opt. Express* **18**, pp. 8853−8858 (2010).
7. K. van Dalfsen, S. Aravazhi, D. Geskus, K. Wörhoff, M. Pollnau, *Opt. Express* **19**, pp. 5277−5282 (2011).
8. F. Güell, Jna. Gavaldà, R. Solé, M. Aguiló, F. Díaz, M. Galan, J. Massons, *J. Appl. Phys.* **95**, pp. 919−923 (2004).
9. O. Silvestre, M. C. Pujol, M. Rico, F. Güell, M. Aguiló, F. Díaz, *Appl. Phys. B* **87**, pp. 707−716 (2007).
10. E. W. Duczynski, G. Huber, V. G. Ostroumov, I. A. Shcherbakov, *Appl. Phys. Lett.* **48**, pp. 1562−1563 (1986).