Thulium channel waveguide laser with 70% slope efficiency in a monoclinic double tungstate

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Abstract—**Laser experiments on 1.5at.%, 5at.%, and 8at.% thulium-gadolinium-lutetium-yttrium co-doped, buried, ridge-type channel waveguides in a monoclinic potassium double tungstate demonstrate a maximum slope efficiency of 70% and output powers of 300 mW at ~1.9 µm.**

Keywords-component; thulium; monoclinic double tungstates; channel waveguide; infrared lasers

I. Introduction

Optical sensors for real-time monitoring of gases for environmental, industrial and medical purposes are being widely investigated. For the detection of CO_2 and NH_3 in human breath, a high-power and compact channel waveguide laser, operating in the 2-µm wavelength region is desirable.

Since the emission spectrum of thulium overlaps with the 2-µm wavelength region, thulium is a suitable candidate for detection of gases in this wavelength region. In addition, the availability of inexpensive diode lasers emitting at 800 nm to optically pump the thulium system facilitates the development of these detectors. When pumped at 800 nm, the efficiency of a thulium laser hinges on the efficiency of a nonlinear cross-relaxation (CR) process, where one ion occupying the $3H_4$ manifold transfers part of its energy to an adjacent ion in the $3H_6$ ground manifold, resulting in both ions occupying the $3F_4$ laser manifold. Since, in this way, a pump photon is converted to a maximum of two laser photons, a maximum quantum efficiency of η_q of up to 2 can be obtained. The theoretical maximum slope efficiency for a thulium laser, calculated by multiplying the Stokes efficiency of λ_P / λ_L = 0.8 µm / 2 µm = 40% by the maximum quantum efficiency of of η_q = 2, reaches 80%. The CR efficiency is dependent on the relative population densities of the $^3H_4$ and $^3H_6$ manifold, influenced by the pump and laser intensities, as well as the thulium concentration.

The highest efficiencies for thulium lasers reported in the literature are 68% from a planar YAG laser [1], and 69% from germanate fiber and bulk $KLu(WO_4)_2$ monoclinic double tungstate lasers [2,3]. In channel waveguide lasers, the highest reported slope efficiency is 50% in a ZBLAN glass with femtosecond-written channels [4].

In this paper we demonstrate that the inferior slope efficiencies for channel waveguide lasers in monoclinic double tungstates originates in the relatively low dopant concentrations, which consequently negatively influences the CR efficiency. We compare the slope efficiencies for thulium concentrations of 1.5at.% [5], 5at.% and 8at.% and present a compact channel waveguide laser in an Y^{3+}, Gd^{3+}, Lu^{3+} co-doped potassium double tungstate yielding output powers up to 300 mW and a maximum slope efficiency of 70% [6], which is close to the theoretical maximum of 80%.

II. Sample Fabrication and Experimental Methods

Co-doped layers of $KY_xGd_yLu_{1-x-y-z}Tm_z(WO_4)_2$ with x = 40at.%, and z = 1.5at.%, 5at.% and 8at.%, were grown onto pure $KY(WO_4)_2$ substrates by liquid-phase epitaxy at 920−923°C [7]. Ridge-type channel waveguides 10−25 µm wide and 7.7 µm and 14.3 µm high, for the 5at.% and 8at.% concentrations, respectively, were patterned into surface-polished planar waveguides by Ar^+-beam milling [8]. Afterwards, the channels were overgrown with a pure $KY(WO_4)_2$ cladding layer. The 1.5at.%, 5at.% and 8at.%-doped channels were diced and end-face polished to a length of 8.5, 6.7 mm and 4.2 mm, respectively.

The channels waveguides were pumped by a Ti:Sapphire continuous-wave laser at wavelengths of 794 nm in transverse-magnetic (TM, $E||N_p$), and 802 nm in transverse-electric (TE, $E||N_m$) polarizations. In-coupling of pump light into the waveguides was optimized using a beam expander and cylindrical lenses with focal lengths of 40 mm and 10 mm, for the horizontal and vertical directions, respectively, thereby obtaining a coupling efficiency of 95%. Commercially obtained dielectric mirrors with a reflectivity of R = 99.9% (HR), 98%, and 92% at 1900–2100 nm and high transmission at the pump wavelength of 790–810 nm (due to an anti-reflection coating at this wavelength) were butt-coupled to the end-facets of the waveguides using index-matching oil (Fluorinert). Round-trip out-coupling efficiencies $T_{out} = 1 - R_1R_2$ of 2%, 8%, 89%, and 99% were tested with mirror combinations of R_1 and R_2 equaling HR and 98%, HR and 92%, HR and 11%, and 2 × 11%, respectively. In the latter two configurations, Fresnel reflection of ~11% at one or both bare waveguide end-facets provided sufficient feedback for the laser. Losses of 11% for the pump light due to Fresnel reflection at the in-coupling facet were taken into account for the mirror-less laser configuration. The laser power out-coupled from the waveguides was collimated via a 0.25 NA microscope objective and a RG1000 high-pass filter was used to block any residual pump power.

III. Experimental Results

The measured laser output power versus absorbed pump power when pumping the 8at.%-doped sample at 794 nm in TM polarization and 802 nm in TE polarization is shown in Fig. 1a and 1b, respectively. For both pump polarizations an output power as high as ~300 mW was obtained. Slope efficiencies of 70%, 68%, 48%, and 31% were measured when coupling out 99%, 89%, 8%, and 2%, respectively, while pumping at 794 nm in TM polarization (Fig. 1a). When pumping at 802 nm in TE polarization, slope efficiencies of 69%, 70%, 44%, and 33% for out-coupling efficiencies of 99%, 89%, 8%, and 2%, respectively, were also measured (Fig. 1b).

The laser was found to operate at 1842 nm when high out-coupling efficiencies of 89% and 99% were used. The laser shifted via 1950 nm for 8% out-coupling, to a maximum operating wavelength of 2037 nm in case only 2% of the laser was out-coupled. The laser was found to operate on multiple longitudinal modes, but single-transverse mode.

Fig. 2. compares the maximum slope efficiency of the 8at.%-doped sample with the maximum slope efficiencies of 53% obtained in this study in the 5at.%-doped sample with the results previously reported in a 1.5at.%-doped sample [5]. A trend toward higher slope efficiencies is clearly visible with

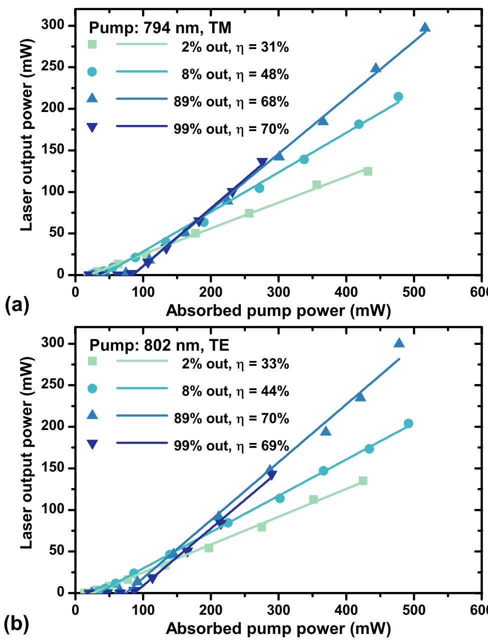

Fig. 1. Output power versus absorbed pump power of a 8at.% thulium-doped channel waveguide laser pumped at (a) 794 nm in TM polarization and (b) 802 nm in TE polarization.

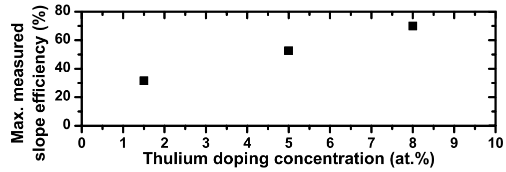

Fig. 2. Maximum measured slope efficiencies for thulium-doped monoclinic double tungstate channel waveguide lasers with different doping levels.

increasing thulium concentrations. Although the result of 70% slope efficiency is close to the theoretical maximum, a slight improvement can be expected when choosing a dopant concentration higher than 8at.%.

Conclusions

Thulium-co-doped monoclinic double tungstate layers have been micro-structured by Ar^+-beam milling, yielding ridge-type channels, and overgrown with a pure $KY(WO_4)_2$ cladding. Lasers operating around 2 µm with excellent slope efficiencies of up to 70% and 300 mW of output power have been demonstrated due to efficient CR resulting from the high doping concentration of 8at.%. The highest efficiency was obtained in a mirror-less laser. Operation of the laser was demonstrated between 1842 nm and 2037 nm. The authors believe that the demonstrated laser is the most efficient thulium channel waveguide laser reported to date, and comparable to the best results in other thulium laser configurations.

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References

[1] A. Rameix, C. Borel, B. Chambaz, B. Ferrand, D. P. Shepherd, T. J. Warburton, D. C. Hanna, and A. C. Tropper, "An efficient, diode-pumped, 2-µm Tm:YAG waveguide laser," Opt. Commun. vol. 142, pp. 239–243, October 1997.

[2] J. Wu, Z. Yao, J. Zong, and S. Jiang, "Highly efficient high-power thulium-doped germanate glass fiber laser," Opt. Lett. vol. 32, pp. 638–640, March 2007.

[3] X. Mateos, V. Petrov, J. Liu, M. C. Pujol, U. Griebner, M. Aguiló, F. Díaz, M. Galan, and G. Viera, "Efficient 2-µm continuous-wave laser oscillation of Tm^{3+}:$KLu(WO_4)_2$," IEEE J. Quantum Electron. vol. 42, pp. 1008–1015, October 2006.

[4] D. G. Lancaster, S. Gross, H. Ebendorff-Heidepriem, K. Kuan, T. M. Monro, M. Ams, A. Fuerbach, and M. J. Withford, "Fifty percent internal slope efficiency femtosecond direct-written Tm^{3+}:ZBLAN waveguide laser," Opt. Lett. vol. 36, pp. 1587–1589, May 2011.

[5] K. van Dalfsen, S. Aravazhi, D. Geskus, K. Wörhoff, and M. Pollnau, "Efficient $KY_{1-x-y}Gd_xLu_y(WO_4)_2$:$Tm^{3+}$ channel waveguide lasers," Opt. Express vol. 19, pp. 5277–5282, March 2011.

[6] K. van Dalfsen, S. Aravazhi, C. Grivas, S. M. García-Blanco, and M. Pollnau, "Thulium channel waveguide laser in a monoclinic double tungstate with 70% slope efficiency," Opt. Lett., in press.

[7] F. Gardillou, Y. E. Romanyuk, C. N. Borca, R. P. Salathé, and M. Pollnau, "Lu, Gd codoped $KY(WO_4)_2$:Yb epitaxial layers: towards integrated optics based on $KY(WO_4)_2$," Opt. Lett. vol. 32, pp. 488–490, March 2007.

[8] D. Geskus, S. Aravazhi, C. Grivas, K. Wörhoff, and M. Pollnau, "Microstructured $KY(WO_4)_2$:Gd^{3+},Lu^{3+},Yb^{3+} channel waveguide laser," Opt. Express vol. 18, pp. 8853–8858, April 2010.