Improved-index-contrast $KY(WO_4)_2$:Gd, Lu, Yb epitaxial waveguides suitable for highly efficient waveguide lasing

S. Aravazhi, D. Geskus, K. Wörhoff, and M. Pollnau

Integrated Optical MicroSystems Group, MESA+ Institute for Nanotechnology, University of Twente,
P.O. Box 217, 7500 AE Enschede, The Netherlands

High-quality crystalline $KY(WO_4)_2:Yb^{3+}$ layers co-doped with large concentrations of optically inert Gd^{3+} and Lu^{3+} ions were grown by vertical liquid phase epitaxy. The co-doping enhances the refractive index contrast between the active layer and the undoped $KY(WO_4)_2$ substrate to $\sim 7.5\times 10^{-3}$. A $K_2W_2O_7$ solvent was employed for the growth of layers onto undoped (010)-oriented KYW substrates. Single crystalline layers of thickness 5-10 µm were grown at low level of supersaturation and growth temperatures of 920-923°C. The layer quality was studied by X-ray diffraction. The composition of the grown layers was determined by laser-ablation inductively-coupled-plasma mass spectrometry (LA-ICP-MS). Planar waveguide lasers with low laser threshold of 18 mW, record-high slope efficiency of 82.3%, and maximum output power of 195 mW have been achieved.

Introduction

Monoclinic crystals of $KY(WO_4)_2$ (= KYW) doped with different rare-earth ions are among the highly promising materials for building compact solid-state lasers [1]. Optically active rare-earth ions doped into these crystals exhibit large absorption and emission cross sections and broad linewidths, which may be due partly to the high refractive indices and partly to the strong anisotropy [2]. Especially doping with Yb^{3+} provides high absorption and emission cross sections [2]. In thin-film geometry, this material is also suitable for waveguide lasers [3]. Co-doping the layer with appropriate amounts of Lu^{3+} and Gd^{3+} resulted in $KY(WO_4)_2$:Yb (1.7 at%) thin films with increased refractive index contrast of $\sim 7.5\times 10^{-3}$ [4], thus reducing the required layer thickness for waveguiding, while simultaneously providing lattice matching between layer and substrate [4]. Here we report on liquid phase epitaxy (LPE) of high-quality thin layers of KYW co-doped with large concentrations of Lu^{3+} and Gd^{3+} used for the fabrication of planar waveguide lasers. The resulting layers exhibits low laser threshold of 18 mW, slope efficiency of up to 82.3%, and maximum output power of 195 mW.

Experiment and Results

Vertical LPE was employed for the growth of KYW:Gd^{3+},Lu^{3+},Yb^{3+} layers on undoped, (010)-orientated, laser-grade polished KYW substrates of 1 cm^2 size in a $K_2W_2O_7$ solvent by the vertical dipping method. The growth was performed at elevated temperatures of 920–923°C, ensuring low level of supersaturation and slow growth rates and leading to crack-free layers of KYW co-doped with 13 at.% Gd^{3+}, 25.8 at.% Lu^{3+}, and 1.2 at.% Yb^{3+} with thickness of ~5–10 µm (Fig. 1). Subsequently, the layer surface was polished parallel to the layer-substrate interface, creating waveguides with a uniform thickness of ~1–5 µm. Surface profile measurements revealed that the polished surface had a radius of curvature of approximately 6 m. The endfaces of the sample were polished parallel to the N_m optical axis, such that by butt-coupling dielectric mirrors to the waveguide endfaces a monolithic cavity along the N_g optical axis was formed. The active layer used for the laser experiments had a thickness of 4.6 µm and was overgrown by an undoped KYW layer in order to diminish surface scattering and prevent damage and edge rounding of the waveguiding layer during endface polishing.

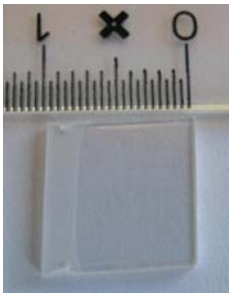

Fig. 1. Crack-free co-doped KYW crystal of 13 at.% Gd^{3+}, 25.8 at.% Lu^{3+}, 1.2 at.% Yb^{3+}

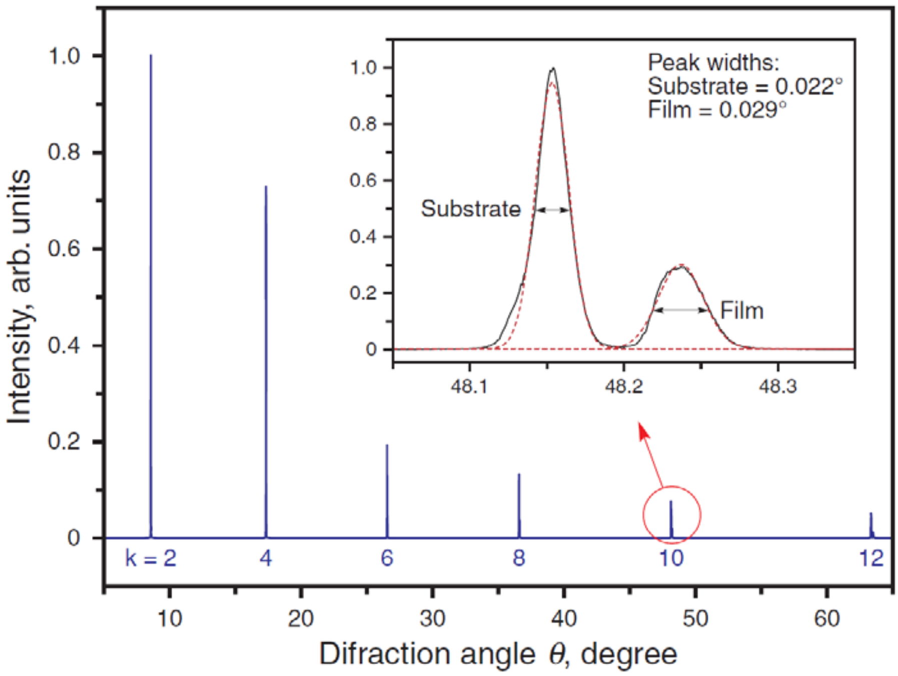

Fig. 2. XRD spectrum of a 13 at.% Gd^{3+}, 25.8 at.% Lu^{3+}, 1.2 at.% Yb^{3+} co-doped KYW layer grown on an undoped KYW substrate showing the 0 k 0 reflections. An expanded view of the 0 10 0 Bragg diffraction together with the FWHM values derived for the film and the substrate are shown in the inset.

The layer quality was investigated by X-ray diffraction (Fig. 2). Although the measurement confirms the single-crystalline character of the grown layer, the full width at half maximum (FWHM) of the diffraction peak originating from the grown film is slightly larger (0.029°) compared to that of the undoped substrate peak (0.022°), which is due to the co-doping and to a certain extent also a result of the small thickness of the layer. The offset between the two diffracted peaks originates from the difference between the out-of-plane crystal lattice parameters of the film and the substrate.

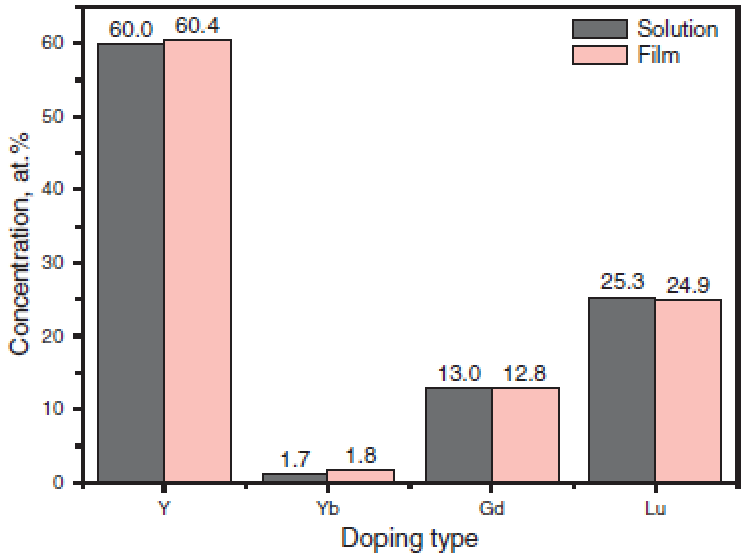

Fig. 3. Dopant concentrations in the solution and in the grown KYW:Gd^{3+}, Lu^{3+}, Yb^{3+} layer as obtained from LA-ICP-MS measurements. The relative standard deviation of the determined concentration was <0.6–1.3%.

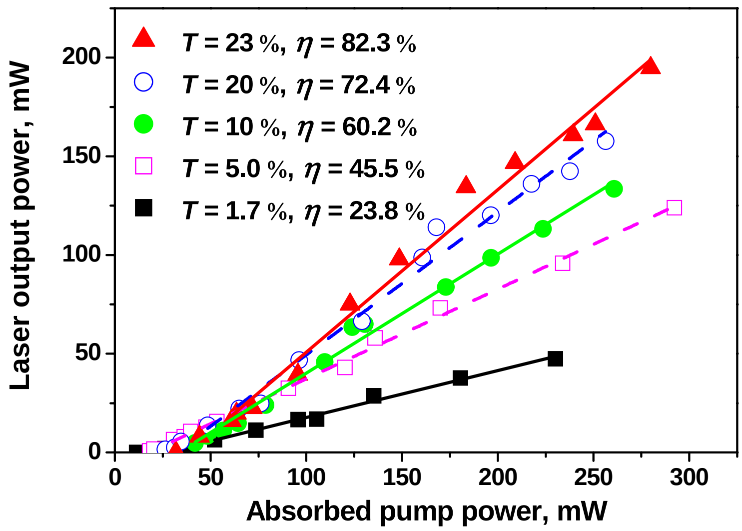

Fig. 4. Laser output power as a function of absorbed pump power for various outcoupling mirror transmissions

The composition of the grown layers was determined by laser-ablation inductively-coupled-plasma mass spectrometry (LA-ICP-MS) [5]. The result presented in Fig. 3 indicates that the composition of the grown layer is close to that of the initial solution and reveals that the segregation coefficients of all incorporated ions are close to unity. Room-temperature laser operation was investigated under continuous-wave Ti:Sapphire pumping at the Yb^{3+} absorption peak near 981 nm with pump polarization parallel to the N_m optical axis of the waveguide layer [5]. Figure 4 shows the laser output characteristics as a function of absorbed pump power. The highest slope efficiency of 82.3%, which represents the highest value yet reported for a planar waveguide laser to date, and a maximum extracted laser power of 195 mW for an absorbed pump power of 280 mW were obtained using the 23% outcoupling mirror.

Conclusions

LPE growth of KYW layers co-doped with 13 at.% Gd^{3+}, 25.8 at.% Lu^{3+}, and 1.2 at.% Yb^{3+} was optimised. Crack-free, high-quality layers of thickness 5-10 μm were successfully grown. The high quality and homogenous doping concentration of the layers were confirmed by X-ray diffraction and inductively-coupled-plasma mass spectrometry (LA-ICP-MS) investigations. Planar waveguide lasers with low laser threshold of 18 mW, slope efficiency of up to 82.3%, and maximum output power of 195 mW have have been demonstrated. These results confirm the suitability of KYW:Gd,Lu,Yb thin layers for highly efficient waveguide lasers.

Acknowledgment

This work was supported by the Netherlands Organisation for Scientific Research via a "Vici" personal research grant to M. Pollnau.

References

[1] M. Pollnau, Y.E. Romanyuk, F. Gardillou, C.N. Borca, U. Griebner, S. Rivier, and V. Petrov, “Double tungstate lasers: From bulk toward on-chip integrated waveguide devices”, IEEE J. Select. Topics Quantum Electron. **13**, 661-671, 2007.

[2] N.V. Kuleshov, A.A. Lagatsky, V.G. Shcherbitsky, V.P. Mikhailov, E. Heumann, T. Jensen, A. Diening, and G. Huber, “CW laser performance of Yb and Er,Yb doped tungstates”, Appl. Phys. B **64**, 409 (1997).

[3] Y.E. Romanyuk, C.N. Borca, M. Pollnau, S. Rivier, V. Petrov, and U. Griebner, “Yb-doped $KY(WO_4)_2$ planar waveguide laser”, Opt. Lett. **31**, 53-55 (2006).

[4] F. Gardillou, Y.E. Romanyuk, C.N. Borca, R.P. Salathé, and M. Pollnau, “Lu, Gd co-doped $KY(WO_4)_2$:Yb epitaxial layers: Towards integrated optics based on $KY(WO_4)_2$”, Opt. Lett. **32**, 488-490 (2007).

[5] D. Geskus, S. Aravazhi, E. Bernhardi, C. Grivas, S. Harkema, K. Hametner, D. Günther, K.Wörhoff, and M. Pollnau, “Low-threshold, highly efficient Gd^{3+}, Lu^{3+} co-doped $KY(WO_4)_2$:Yb^{3+} planar waveguide lasers” Laser Phys. Lett. **6**, 800-805 (2009).