Progress on micro-structured $KY(WO_4)_2$ waveguides for optically active devices

D. Geskus, J.D.B. Bradley, S. Aravazhi, 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
phone: +31-53-4894440, e-mail: d.geskus@ewi.utwente.nl

The optical properties of rare-earth-ion (RE) doped $KY(WO_4)_2$ (KYW) form an excellent basis for the realization of optically active devices such as lasers and amplifiers. External-cavity laser experiments on KYW:Yb planar waveguides confirmed these predictions by high slope efficiencies up to 80%. In-house equipment enables the epitaxial growth of KYW:RE layers and their optical characterization. Combined with micro-structuring of KYW:RE layers using novel reactive-ion-etching methods (to an etch depth of ~390 nm) and use of simulation software (Field Designer), this will lead to novel on-chip integrated lasers and amplifiers and a profound understanding of the physics and optimization of these devices.

Introduction

The demand for smaller and more economic light sources for a number of application is ongoing. The focus of this project is to integrate optically active devices based on rare-earth-ion-doped monoclinic potassium yttrium double tungstate, $KY(WO_4)_2:RE^{3+}$ (hereafter abbreviated KYW:RE) [1]. The challenges of KYW as a host material for rare-earth ions are the reliable growth of high-optical-quality layers and subsequent etching of channel waveguide structures for laser emission or optical amplification. After the growth of a KYW:RE layer onto an undoped KYW substrate the layer has to be polished and structured, e.g. by reactive ion etching (RIE) techniques. The production of planar waveguides is relatively well understood by now, as recent growth experiments have resulted in high-quality epitaxial layers with excellent interfaces, in which waveguide laser emission from KYW:Yb at 1 µm [2] and KYW:Tm at 2 µm [3] was demonstrated. The current work will bring us one step further towards full integration of optical active devices on KYW:Yb.

Crystals of monoclinic KYW 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. Due to its high refractive indices on the order of 2.0-2.1, KYW is highly suitable for the fabrication of integrated optical devices with rather high integration density. Rare-earth ions incorporated into KYW exhibit very high absorption and emission cross sections. In particular, the Yb^{3+} ion in KYW has an absorption maximum at 981 nm with a cross-section, for polarization parallel to the Nm principal optical axis, which is ~15 times larger than that of YAG:Yb. The short absorption length in highly doped KYW:Yb together with an extremely small laser quantum defect as low as 1.6% [4] makes this material not only a favourable candidate for the thin-disk laser concept [5], but also for side-pumped waveguide lasers. In this project doped KYW:Yb layers are grown onto undoped KYW substrates, and waveguiding is obtained due to the slight enhancement in refractive index of the layer due to incorporation of the dopant ion. The obtained refractive index contrast of, e.g., 1.7at% Yb-doped KYW is only $6x10^{-4}$, but can be enhanced to $7x10^{-3}$ by co-doping of waveguide with Lu, Gd [6].

Earlier laser experiments have been performed on a 17-µm-thin layer with a doping concentration of 1.8at% with an refractive index contrast of $6x10^{-4}$, resulting in single-mode laser output despite the multi-mode guiding properties of the waveguide. These experiments were based on an external cavity and resulted in a laser emission power of 29 mW at a wavelength of 1024 nm, while slope efficiencies were up to 80% [2]. Similar experiments confirmed these results and will be used as a basis for further research on a higher integration level.

Experimental Results

Due to its inherent phase transition at 1025°C, which is below the melting temperature of 1080°C, KYW crystals and layers cannot be grown from the melt. To overcome this problem, high-temperature solution growth is employed. Among the different known solvents used for solution growth, the $K_2W_2O_7$ solvent is an excellent choice due its property of single-crystal formation without parasitic phases.

Liquid phase epitaxy (LPE) was employed for the growth of KYW:Yb thin films in $K_2W_2O_7$ solvents by the vertical dipping method. A fully versatile LPE system with a computer-controlled substrate translation and rotation unit was used for the experiments. The growth was performed in a near-equilibrium condition at 895°C for 10-20 minutes. Pure KYW substrates of (010) orientation (good lattice matching) were used for the experiments. Layers of thickness ~35 µm were grown.

During the experiment the substrates were partially immersed into the solution - leaving a small strip (1-2 mm) of the substrate without the film allowing subsequent orientation of the sample by means of an autocollimator to ensure polishing of the layer surface parallel to the layer-substrate interface, creating waveguides with a uniform thickness within ~10-20 µm. Surface profile measurements of the polished surface show a curvature of approx 5.9 meters with a surface roughness below the resolution of the Dektak surface profiler.

First experimental etched results have been obtained with an inductively coupled RIE system. Channel waveguides in KYW:Yb were fabricated with Ar as the process gas and using a sputter-deposited Al_2O_3 layer as the mask. The sloped sidewalls of the etched waveguides and the trenches indicate that further optimization is required.

New equipment enables the options for thorough optical characterization of the waveguides. Experiments are currently performed to determine the background loss, gain, and laser performance with monolithic cavity using butt-coupled mirrors. The background loss is obtained by irradiance of the sample with a relative short wavelength (~940 nm), far away from the absorption peak around 981 nm. The intensity decay of the luminescence observed over the length of the waveguide is a measure for the absorption and propagation losses of the waveguide. With the knowledge of the absorption losses from absorption measurements in bulk samples it is possible to derive the propagation loss of the channel waveguide. Simultaneous coupling of pump and signal into the waveguide reveals the optical amplification characteristics of the waveguide. By measuring the signal gross enhancement when switching on the pump source, the net gain is obtained by subtraction of the background loss and the absorption loss of the signal.

The intermediate step to integration will be butt-coupling of mirrors to the waveguide end faces. In combination with simulations of the active waveguide using the spectroscopic parameters of KYW:Yb, this will expand the understanding of this material towards improved device functionality.

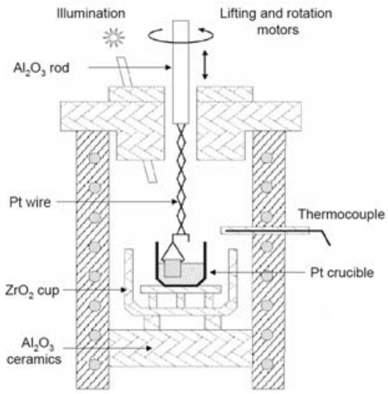

Figure 1. Schematic of LPE crystal growth, together with photograph of the setup

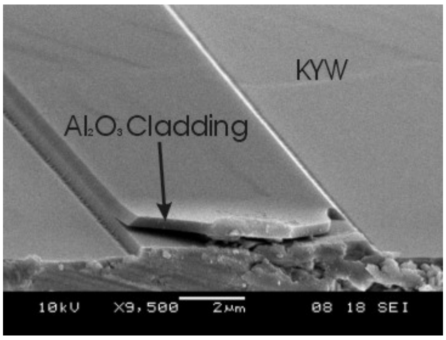

Figure 2. SEM micrograph of a KYW channel waveguide etched by Ar RIE

Conclusions

Earlier reported results on optically active devices in KYW:Yb reveal the promising properties of KYW:Yb as a basis for optically active integrated devices. The in-house production of the LPE-grown KYW:Yb thin films has been successful and will soon be extended towards further integration of optical active devices. The combination of these results and the expertise in further micro-fabrication and characterization of integrated optical devices will lead to novel developments in active devices based on KYW:Yb.

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., vol. 13, pp. 661-671, 2007.

[2] 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., vol. 31, pp. 53-55, 2006.

[3] S. Rivier, X. Mateos, V. Petrov, U. Griebner, Y.E. Romanyuk, C.N. Borca, F. Gardillou, and M. Pollnau, “Tm:$KY(WO_4)_2$ waveguide laser”, Opt. Express, vol. 15, pp. 5885-5892, 2007.

[4] P. Klopp, V. Petrov, and U. Griebner, “Potassium ytterbium tungstate provide the smallest laser quantum defect”, Jpn. J. Appl. Phys., vol. 42, L246, 2003.

[5] F. Brunner, T. Südmeyer, E. Innerhofer, F. Morier-Genoud, R. Paschotta, V.E. Kisel, V.G. Shcherbitsky, N.V. Kuleshov, J. Gao, K. Contag, A. Giesen, and U. Keller, “240-fs pulses with 22-W average power from a mode-locked thin-disk Yb:KY(WO4)2 laser”, Opt. Lett., vol. 27, pp. 1162-1164, 2002.

[6] 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., vol. 32, pp. 488-490, 2007.