Toward highly confined potassium double tungstate waveguides for laser applications

C.I. van Emmerik, S.M. Martinussen, J. Mu,

M.A. Sefünç, M. Dijkstra, S.M. García-Blanco

Optical Sciences, Twente University, Drienerlaan5, 7552 NB, Enschede, the Netherlands

Very compact, power efficient, tunable on–chip lasers that operate in different wavelength ranges are important for applications in optical sensing, spectroscopy, metrology and telecommunications. In the RENOS project (Rare Earth Novel On-chip Sources) the development of high-contrast, rare-earth ion-doped potassium double tungstate (RE:KY(WO$_4$)$_2$ or KYW) rib waveguides is proposed. Those waveguides are necessary to develop, in a later stage, compact ring resonators. In this work, a fabrication scheme to produce such highly confined waveguides in a controllable and reproducible way is proposed.

Introduction

KYW shows promise as material for solid-state lasers and amplifiers. This is particularly because its high refractive index ($n \approx 2.00 – 2.15$) allows for high confinement when surrounded by typical cladding media like SiO_2 and air. In addition, its long inter-ionic distance (~0.5 nm) allows for high doping concentrations without quenching, which, together with the high absorption and emission cross-sections, leads to high gain per unit length. This allows for highly effective on-chip rare-earth amplifiers [1].

Early work on rare earth doped KYW was based on channel waveguides structured in rare-earth ion-doped (Yb^{3+} [2], Er^{3+} [3], and Tm^{3+} [4]) layers grown on an undoped KYW substrate by liquid phase epitaxy (LPE). Using that approach, amplifiers with modal gain of circa 1000 dB/cm [1], and tunable [5], high-power ultra-efficient lasers [4] have been demonstrated in recent years. However, this approach has a number of disadvantages.

Firstly, the refractive index contrast between the doped and undoped layers is low ($n_{clad} – n_{core} < 0.02$). The low confinement achievable in these waveguides prevents the high integration density required for on-chip applications. Furthermore, it results in increased bend losses and consequently an increased power is needed to achieve non-linear effects such as lasing, Raman scattering and Kerr effects.

Secondly, the LPE process does not allow to grow crystalline KYW on materials with different crystal lattice constant. For this reason, integration of KYW on highly contrasting materials such as SiO_2 is impossible using LPE directly.

The aim of this project is to demonstrate tunable ring lasers in high-contrast KYW waveguides. For this application, waveguides with dimensions less than 1 µm x 1 µm and sub-100 nm precision have to be fabricated. High-confined KYW rib waveguides are demonstrated by Sefünç et al. [6] using focused ion beam (FIB) milling. However, FIB is a very slow process, unsuitable for millimeter long waveguides.

In earlier work a fabrication process has been presented based on reactive ion etching (RIE) to fabricate the ridges of the waveguide, and lapping and polishing to achieve rib waveguides that operate in the single mode regime [7]. However, the fabrication yield of this method was low, and it was too inaccurate to consistently produce single mode waveguides. Therefore we present in this work a procedure that is based on the same techniques but with an additional polishing stop to control the final thickness, as is required for single mode operation of the rib waveguides.

Fabrication

KYW samples (Altechna) with an area of 10 mm x 10 mm and thickness of 1 mm are used for the fabrication of the waveguides. The waveguide structures are first fabricated using a standard photolithography procedure followed by RIE with argon plasma. A pool area of 12 mm x 12 mm is etched in a 20 mm x 20 mm SiO_2 carrier chip with a thickness of 1 mm using a standard lithography procedure and an hydrofluoric acid (HF) etching step (figure 1a-c).
Afterward the KYW sample and SiO_2 sample are bonded with Norland optical adhesive (NOA81). First a precise volume of adhesive is applied on the KYW sample (figure 1d), then the bonding is performed using a Finetech Lambda flip-chip bonder (Finetech GmbH, DE) (figure 1e). After bonding the sample is exposed to UV-light for a total dose of 1 J/cm^2. The entire thinning procedure (figure 1f) is performed using a Logitech PM5 precision lapping and polishing system (Logitech Ltd, UK).

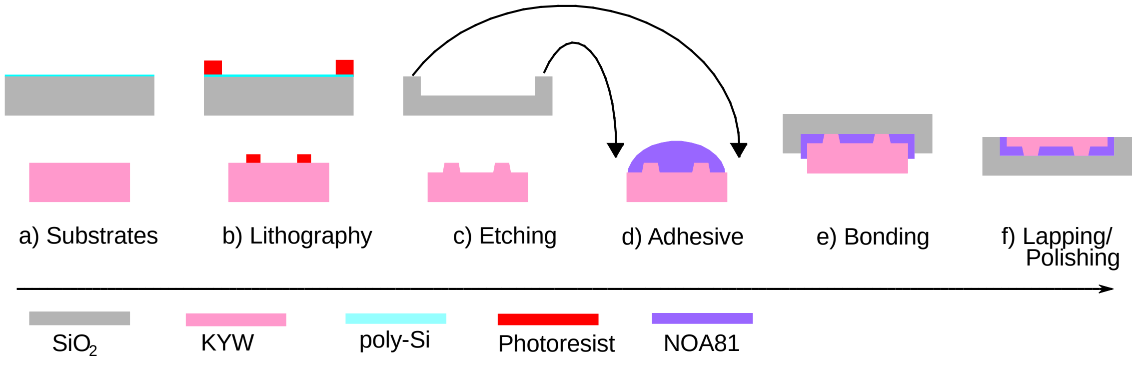

Figure 1: Schematic representation of the fabrication process.

Thickness control

Accurate thickness control of the devices is of great importance for the performance of a device. For a rib waveguide the slab should be fabricated such that a single mode will be guided. If the slab is too thin, higher-order modes will be guided and conversely if it is too thick no mode will be guided at all.
The thinning procedure is divided in a few steps which are optimized for controllability of the sample height and for time consumption. Before starting the thinning process the chip (KYW sample + SiO_2 carrier) are mounted on a thick ultra-parallel glass plate with soft quartz wax (Alcowax, Nikka Seiko, JP) with a high degree of planarity. This glass plate is then positioned inside the polishing jig. The first coarse lapping is performed on an iron disk with 9 µm Al_2O_3 particles. The lapping speed of this first step is ~4-5 µm/min and is performed until the sample has a height of ~50-100 µm.
At this point, the surface of the sample is rough and a finer lapping is performed on the same disk with 1 µm Al_2O_3 particles. The fine lapping has a speed of ~1.0-1.5 µm/min

and is performed until the sample has a height of ~9 µm. With this fine polishing step the thickness of the layer is more controllable than with the coarse lapping and the surface roughness is already reduced.
The last step consists of fine polishing to obtain the desired thickness with optical quality of the surface. This step is performed with 40 nm colloidal SiO_2 particles on a soft polyurethane disk. This process has a polishing speed of ~1 µm/h on the 10 x 10 mm^2 KYW sample. The pool in the SiO_2 is fabricated such that the height of the pool is equal to the sum of the adhesive layer thickness under the waveguides, the height of the waveguides and the height of the slab that is needed (figure 2) for the sample to operate in the single mode regime. When during the polishing the surface of the carrier chip reaches the surface of the polishing plate the total surface area will increase by a factor of ~3.5 compared to only the KYW surface. The additional area will reduce the polishing rate.

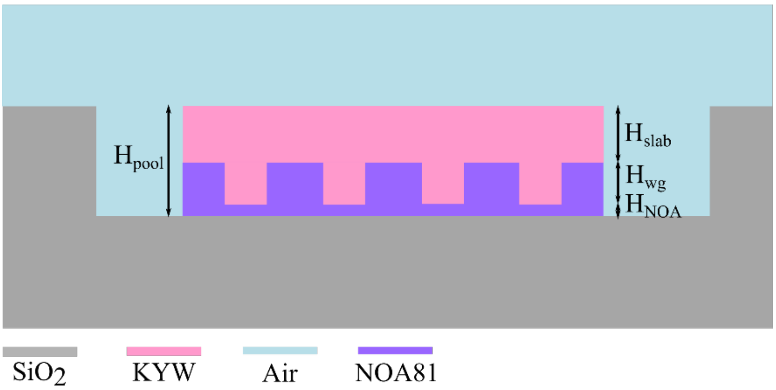

Figure 2: Schematic representation of the polishing stop. The height of the pool (H_{pool}) should be equal to the sum of the height of the adhesive under the waveguides (H_{NOA}), the height of the waveguide (H_{wg}) and the height of the slab (H_{slab}) required for single mode operation.

Preliminary results show a polishing rate of the whole structure (KYW + SiO_2) of ~200-300 nm/h. This gives an indication that with the SiO_2 around the KYW sample the thickness can be controlled more accurately. The sample processed in this trial is shown in figure 3.

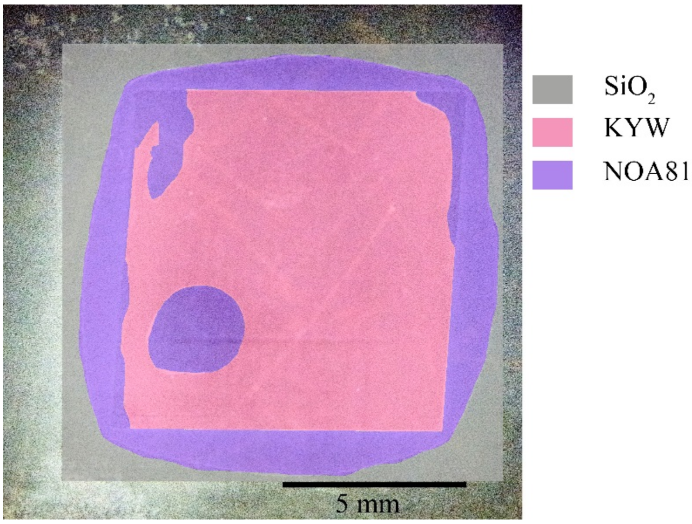

Figure 3: Artificially colored photograph of a KYW sample bonded with adhesive in the polishing stop pool. The larger square is the pool bottom, with the KYW sample sitting inside, surrounded by residual adhesive.Some damage has occurred on the corners and on top of air bubbles formed during bonding.

Conclusion

We propose a method for fabricating high contrast ridge waveguides in KYW.
Such waveguides will enable further research aimed at producing power efficient tunable lasers. Our novel approach is a modified carrier wafer that will stop mechanical thinning at a predetermined thickness. This technique will make it possible to fabricate higher contrast strip waveguides, which can be used for ring resonators.

Acknowledgements

The authors acknowledge support from the European Research Council Consolidator Grant under the project abbreviation RENOS.

References

[1] D. Geskus, S. Aravazhi, S. M. García-Blanco and M. Pollnau, "Giant Optical Gain in a Rare-Earth-Ion-Doped Microstructure," *Advanced Materials*, vol. 24, pp. OP19-OP22, 2012.

[2] D. Geskus, S. Aravazhi, C. Grivas, K. Wörhoff and M. Pollnau, "Microstructured KYW(WO4)2:Gd3+, Lu3+, Yb3+ channel waveguide laser," *Optical Express*, vol. 18, pp. 8853-8858, 2010.

[3] S. Vázquez-Córdova, M. Dijkstra, E. Bernhardi, F. Ay, K. Wörhoff, J. Herek, S. García-Blanco and M. Pollnau, "Erbium-doped spiral amplifiers with 20 dB of net gain on silicon," *Optical Express*, vol. 22, pp. 25993-26004, 2014.

[4] K. v. Dalfsen, S. Aravazhi, C. Grivas, S. G. Blanco and M. Pollnau, "Thulium-doped channel waveguide laser with 1.6 W of output power and exceeding 80% slope efficiency," *Advanced Solid-State Laser Congress*, 2013.

[5] D. Geskus, S. Aravazhi, K. Wörhoff and M. Pollnau, "High-power, broadly tunable, and low-quantum-defect KGd 1-x Lu x (WO 4) 2: Yb 3+ channel waveguide lasers," *Optical Express*, vol. 18, 2010.

[6] M.A. Sefunc, F. Segerink and S. M. García-Blanco, "High index contrast potassium double tungstate waveguides towards efficient rare-earth ion amplification on-chip," in *Proc. SPIE 9365, Integrated Optics: Devices, Materials, and Technologies XIX,*, 2015.

[7] M. Sefünç, "New architectures for integrated optics: low-loss tight bends and on-chip high-indexcontrast potassium double tungstate waveguides," Enschede, Ph.D. dissertation, Optical Sciences, Universiteit Twente, 2016, pp. 47-74.