High-index-contrast potassium double tungstate waveguides enabled by heterogeneous integration

M.A. Sefunc, F. Segerink, S.M. Garcia-Blanco

Optical Sciences Group, MESA+ Institute for Nanotechnology, University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands, e-mail: m.a.sefunc@utwente.nl

Rare-earth-ion doped potassium double tungstate [$KY(WO_4)_2$] waveguide amplifiers are of interest due to high-gain amplification at high-bit rates with low noise figure. The fabrication of such waveguide amplifiers is conventionally based on overgrowing an active layer on a host $KY(WO_4)_2$ crystalline material. These devices exhibit low refractive index contrast, typically <0.02, consequently requiring large optical pump power to invert the active material. In this work, we have successfully demonstrated heterogeneous integration of $KY(WO_4)_2$ ($n \approx 2$) with a silicon dioxide ($n \approx 1.44$) carrier. Focused ion beam milling was used to fabricate high-index-contrast waveguides, permitting the realization of efficient amplifiers when doped with rare-earth-ions.

Introduction

The monoclinic potassium double tungstates, $KGd(WO_4)_2$, $KLu(WO_4)_2$ and $KY(WO_4)_2$ (from now on called KYW), when doped with rare-earth-ions, are recognized as good candidates for solid-state lasers and optical amplifier applications thanks to their high refractive indices (@ $\lambda = 0.4$ µm $n \approx 2.1$-2.15, @ $\lambda = 1.5$ µm $n \approx 2$-2.04) in comparison with other host materials such as SiO_2 or Al_2O_3, large transition cross sections of active ions doped in these hosts materials and reasonably large thermal conductivity (~3.3 $Wm^{-1}K^{-1}$)[1]. In addition to these properties, their crystalline structure helps maintaining long inter-ionic distance between doped active ions in the crystal lattice so that clustering can be prevented in the system even for high doping concentrations. However, the crystalline nature of these materials becomes a disadvantage when the integration with dielectrics (i.e., SiO_2 or Si_3N_4) or semiconductors (i.e., Si or InP) is required for the realization of integrated on-chip waveguide amplifiers and lasers. Heterogeneous integration is the only method to make the integration of such optical devices with other optical devices on passive motherboards possible. Up until now, the fabrication of rare-earth ion doped optical devices in this material system is based on growing a doped layer by liquid phase epitaxy (LPE) on a bulk undoped KYW substrate[2]. The resulting waveguide architecture shows low refractive index contrast between active layer and undoped substrate, typically smaller than 0.02, which leads large footprint and inefficient pumping of the active layer due to the relaxed mode profile supported by the waveguide.

In this work, we demonstrate the heterogeneous transfer of undoped KYW material onto a SiO_2 carrier substrate. By combining the high refractive index host material with a low index substrate, high-index-contrast potassium double tungstate waveguides were successfully realized for the first time.

Fabrication of high-index-contrast ridge KYW waveguides

New fabrication flows were developed to realize high-index-contrast waveguides in KYW. These fabrication steps can be gathered under three main stages: bonding the amplifier material with carrier chip, thinning the bonded material to a certain thickness that defines the waveguide height, and finally milling the ridge waveguide architecture. The crystalline KYW is inert to common etching methods such as wet etching and reactive ion etching (RIE). For proof of concept demonstrations, focused ion beam (FIB) milling technique was considered in this work to pattern the ridge undoped waveguides. However other time-saving, robust etching methods such as ion beam etching (IBE) are also applicable and previously reported [2][3]. All fabrication phases were carried out in MESA+ Nanolab cleanroom facility located at University of Twente.

Bonding

Bonding of KYW onto a SiO_2 carrier substrate was realized by using the epoxy based UV curable optical adhesive NOA 81 (Norland Products, USA). A KYW die (Altechna, LT) with lateral dimensions of 1 cm x 1 cm and 1 mm thick was bonded onto a 2 cm by 2 cm SiO_2 substrate. The adhesive layer was spin coated on a clean KYW surface and the thickness of the corresponding layer was controlled by the spin rate. The substrate and KYW material were aligned and bonded by using a Fineplacer Lambda flip-chip bonder (Finetech, DE). The adhesive layer was cured with flood UV exposure to chemically bond the layers together.

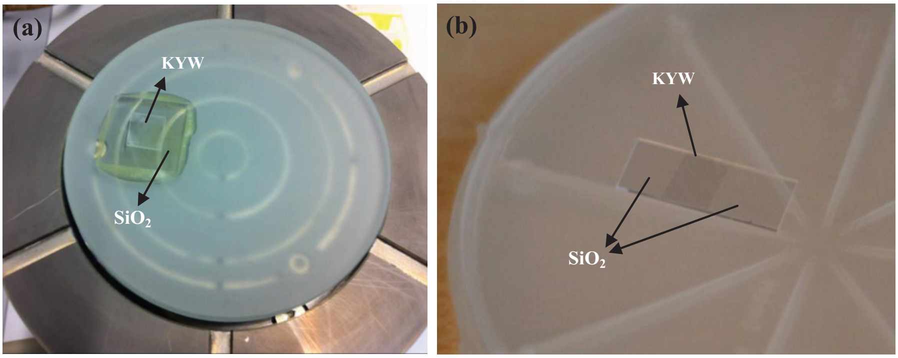

Fig. 1 (a) Mounted KYW/glass plate on metal polishing jig with vacuum; (b) Polished KYW layer on SiO_2 substrate. The thicknesses of adhesive and undoped KYW layers are ~5 μm and ~2 μm respectively. The SiO_2 substrate was diced from two sides to create direct accessibility to KYW layer.

Thinning

The lapping process was developed using a Logitech PM-5 polishing system (Logitech, UK). The objective of this step was to decrease the thickness of the bulk bonded KYW substrate in order to define the waveguide height. The bonded sample was fixed on a flattened 83 mm thick glass plate with wax as depicted in Fig. 1(a). The corners of the bonded sample were also covered with same wax to avoid cracks during the lapping and polishing processes. In the lapping step, a slurry (OP-U oxide polishing suspension from Struers, DE) with particles with a diameter of 3 μm were consumed. This coarse lapping process was followed by a fine polishing step, where a slurry with 40 nm particle size was used to obtain an optical quality surface. The bonded layer thickness was tuned to support a single mode at the wavelength of interest, 1.55 μm, for which a calculated maximum value of 2.5 μm is required. Fig. 1(b) shows an image of a polished KYW on SiO_2 substrate.

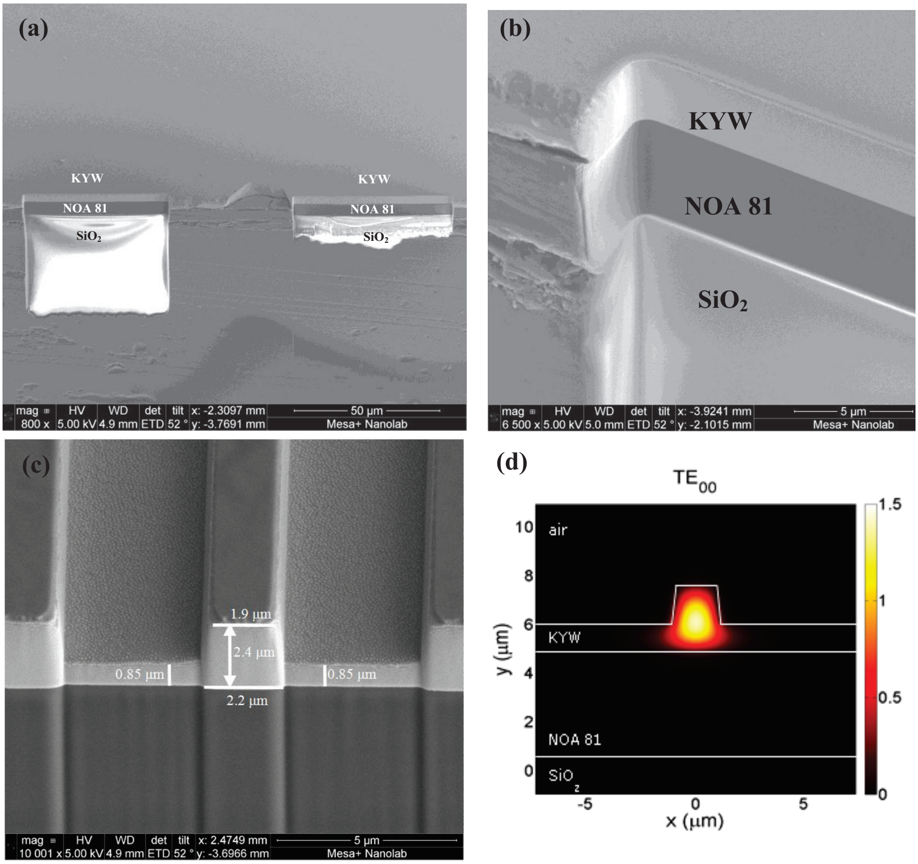

Fig. 2 (a) Scanning electron microscope (SEM) image of polished cross-sections. The sample consists of four layers: SiO_2 as substrate, NOA 81 as an adhesive layer, undoded KYW and a thin Ti layer (~40 nm) to avoid any charging effect during FIB milling and SEM imaging; (b) Closer look at the corner of a cleaned cross section depicted in image (a); (c) FIB milled ridge KYW waveguide. The waveguide dimensions are given on the image. A layer of Ti with the thickness of ~40 nm on top of the KYW layer is clearly visible on this SEM image; (d) Calculated 2-D mode profile (shown as the real part of the dominant electrical field component, E_x) at λ = 1.55 μm for the patterned ridge waveguide. The refractive indices of the layers are set as follows; $n_{SiO2} = 1.44$, $n_{NOA81} = 1.56$, $n_{KYW} = 2.01$ and $n_{Air} = 1$ at 1.55 μm wavelength.

Patterning of high-index-contrast ridge KYW waveguides

After a successful thinning step, the cross section of the material stack was polished to investigate the thickness of the different layers and to find out the suitable FIB beam current value for patterning the device. Fig. 2(a) and (b) depicts the quality of the polished interface under SEM. No indications of undesired effects were observed neither on the adhesive layer nor on the KYW layer. The final step in the fabrication was the patterning of the ridge waveguide architecture on the thin layer of KYW. A 300 micrometer long ridge waveguide with the lateral dimensions given in Fig. 2(c) was patterned by using the optimized FIB milling method. The milling current was always kept at 2.7 nA to obtain low surface roughness on the waveguide side walls with reasonable amount of processing time, in this specific case less than an hour. The lateral dimensions of the waveguide were carefully chosen to avoid excitation of high order modes in the channel [Fig. 2(d)]. The patterning was finalized by polishing the end facets with FIB to achieve effective light in- and out- coupling to the waveguide.

Conclusion

We demonstrated high-index-contrast undoped KYW waveguides enabled by heterogeneous integration. Such waveguides permits not only the realization of efficiently pumped optical amplifiers but also allow to reduce their footprint due to the highly confined mode propagation in the channel once the undoped material is exchanged with active material doped with rare-earth-ions; such as Er^{3+}, Yb^{3+} or Lu^{3+}. The fabrication steps reported in this article will be repeated in the near future for doped KYW to create high-index-contrast waveguide amplifiers integratable to photonic boards by flip-chip bonding. The optical characterization of the fabricated structures is still under way and will be published in a separate manuscript.

Acknowledgment

The authors acknowledge financial support from “Stichting voor de Technische Wetenschappen” (STW) under the project number STW-12832 named “HiReAmp”.

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. Sel. Topics Quantum Electron., 13-3, 661-671 (2007).

[2] S. Aravazhi, D. Geskus, K. van Dalfsen, S.A. Vázquez-Córdova, C. Grivas, U. Griebner, S.M. García-Blanco, and M. Pollnau, “Engineering lattice matching, doping level, and optical properties of $KY(WO_4)_2$:Gd,Lu,Yb layers for a cladding-side-pumped channel waveguide laser,” Appl. Phys. B, 111-3, 433-446 (2013).

[3] 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 18, 8853-8858 (2010).