High index contrast potassium double tungstate waveguides towards efficient rare-earth ion amplification on-chip

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ABSTRACT

Rare-earth ion doped $KY(WO_4)_2$ amplifiers are proposed to be a good candidate for many future applications by benefiting from the excellent gain characteristics of rare-earth ions, namely high bit rate amplification (>Tbps) with low noise figure (<5-6 dB). However, $KY(WO_4)_2$ optical waveguide amplifiers based on rare-earth ions were conventionally fabricated on layers overgrown onto undoped $KY(WO_4)_2$ substrates. Such amplifiers exhibit a refractive index contrast between the doped and undoped layer of typically <0.02, leading to large devices not suited for the high degree of integration required in photonic applications. Furthermore, the large mode diameter in the waveguide core requires high pump input powers to fully invert the material. In this study, we experimentally demonstrate high index contrast waveguides in crystalline $KY(WO_4)_2$, compatible with the integration onto passive photonic platforms. Firstly, a layer of $KY(WO_4)_2$ is transferred onto a silicon dioxide substrate using bonding with UV curable optical adhesive. A subsequent polishing step permits precise control of the transferred layer thickness, which defines the height of the waveguides. Small-footprint (in the order of few microns) high index contrast waveguides were patterned using focused ion beam milling. When doped with rare-earth ions, for instance, Er^{3+} or Yb^{3+}, such high contrast waveguides will lead to very efficient amplifiers, in which the active material can be efficiently pumped by a confined mode with very good overlap with the signal mode. Consequently, lower pump power will be required to obtain same amount of gain from the amplifier leading to power efficient devices.

Keywords: Potassium double tungstate, high-contrast waveguide, bonding, thinning, heterogeneous integration

1. 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 the 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 the active layer and the undoped substrate, typically smaller than 0.02, which leads to large footprint and inefficient pumping of the active core 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.

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2. FABRICATION OF HIGH-INDEX-CONTRAST RIDGE KYW WAVEGUIDES

A new fabrication process flow wase developed to realize high-index-contrast waveguides in KYW. Thes fabrication steps can be summarized in three main stages: (1) bonding the amplifier material with carrier chip, (2) thinning the bonded material to a certain thickness that defines the waveguide height, and (3) 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 demonstration, focused ion beam (FIB) milling was useed in this work to pattern the ridge waveguides. However 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.

2.1. 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.

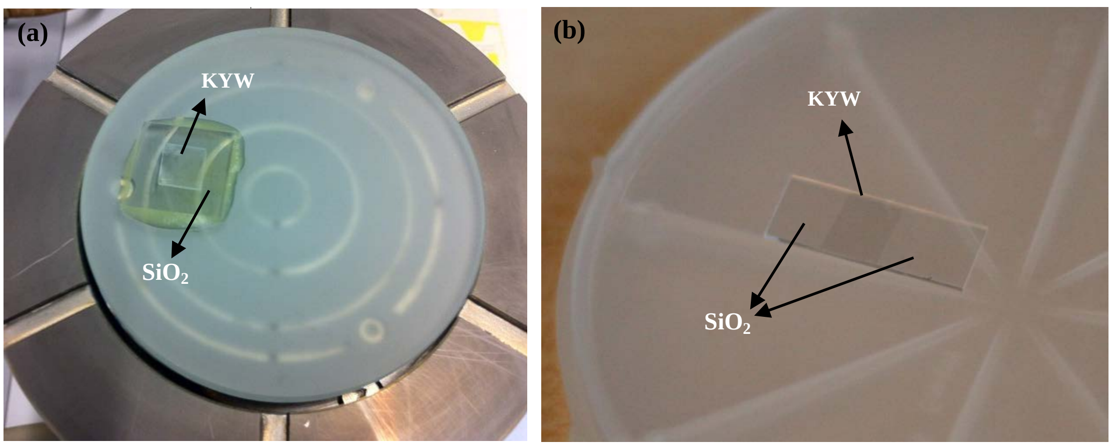

Fig. 1 (a) Mounted KYW/glass plate on metal polishing jig with vacuum; (b) Polished KYW layer on SiO_2 substrate. The thicknesses of adhesive and undoped KYW layers are ~5 µm and ~2 µm respectively. The SiO_2 substrate was diced from two sides to create direct accessibility to KYW layer.

2.2. 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 utilized. 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.

2.3. 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. Ridge waveguides with lengths ranging from 200 to 300 micrometers, with the lateral dimensions given in Fig. 2(c), were 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.

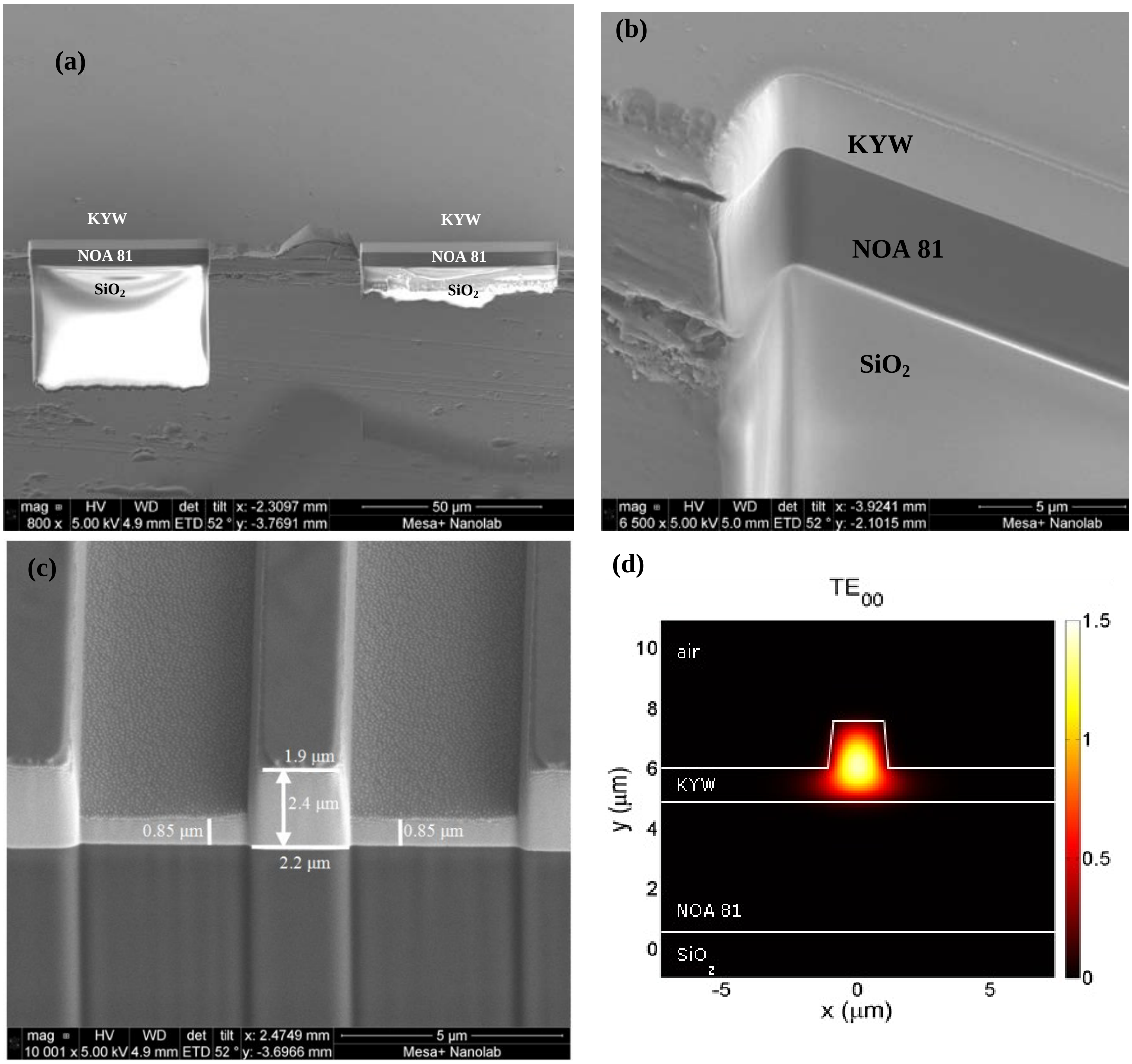

Fig. 2 (a) Scanning electron microscope (SEM) image of polished cross-section. The sample consists of four layers: SiO_2 as substrate, NOA 81 as an adhesive layer, undoped KYW and a thin Ti layer (~40 nm) to avoid any charging effect during FIB milling and SEM imaging; (b) Closer look at the corner of 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.

3. CHARACTERIZATION OF PROPAGATION LOSSES USING FABRY-PEROT METHOD

In the literature, various methods such as measurement of scattered light along the waveguide, optical fiber scanning, transmission measurements, cutback method are considered to measure the propagation losses of optical waveguides. However, those methods mainly suffer from accuracy or from being dependent on measurement parameters, i.e. input coupling efficiency, which is hard to estimate. In order to alleviate such problems, estimating the propagation losses by measuring the Fabry-Perot fringes in the waveguide cavity is a widely accepted method for accurate propagation loss measurements[4][5]. This method only requires the facet reflectivity, which can be typically estimated either from effective refractive index measurement or from simulations. For more accurate approximation, in this study, we created identical waveguides with different waveguide lengths to approximate the unknown parameter, the facet reflectivity, accurately. As mentioned in the previous section, FIB was chosen to pattern high-contrast passive KYW waveguides as well as to polish their input and output facets. Since FIB offers accurate and stable end-facet polishing, the facet reflectivity can be assumed constant for each waveguide end-facet so that the unknown facet reflectivity parameter can be estimated precisely.

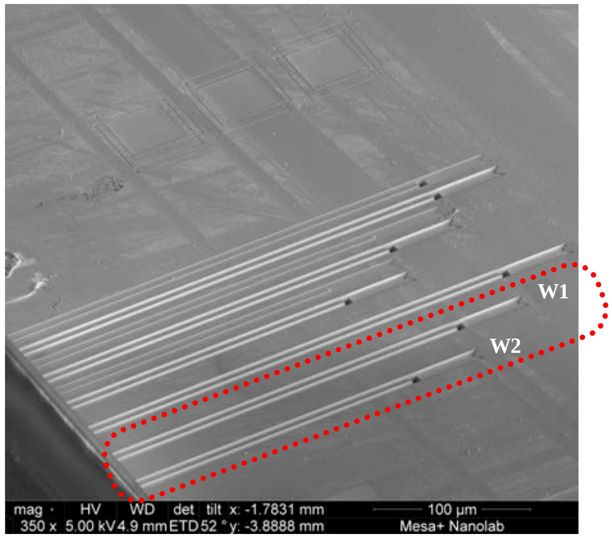

Fig. 3 Tilted SEM image of waveguides patterned on thin KYW layer by FIB method. The waveguides that were characterized in this study are covered by a dashed line. The lengths of the top (W1) and bottom (W2) waveguides are 250 µm and 200 µm, respectively.

Since the length of the waveguides, ranging from 200-300 micrometers, is much smaller than the total length of the KYW layer, ~0.9 mm, the output end facet cannot be reached to measure the transmission of light from the waveguides. Therefore, only the reflection from the waveguide cavity formed between the input and output facets was utilized for the characterization. Both of the facets were polished under constant FIB milling parameters, ion acceleration voltage and beam aperture, to obtain same reflectively at the input and output facets. The experimental setup consists of a tunable laser source with a high-sensitive InGaAs power detector attached (Agilent 8164B Lightwave measurement system), and an optical circulator (OC) to separate the input signal from the reflected signal from device under test (DUT). The schematic of the characterization setup is shown in Fig. 4. The first port of the OC was connected to the tunable laser by a PM fiber. The light comes from port 1 was guided to port 2 and then was coupled to the waveguide using a bare PM fiber. The reflected light from waveguide was circulated to port 3 of the OC. Before measuring the response of the waveguide, a reference measurement was taken to detect the reflection originating from the various cavities formed in the system, including the fiber connections in between the light source and port 1 and the optical interfaces inside the OC. This reference measurement was subsequently filtered out from the measured Fabry-Perot reflection of the waveguide.

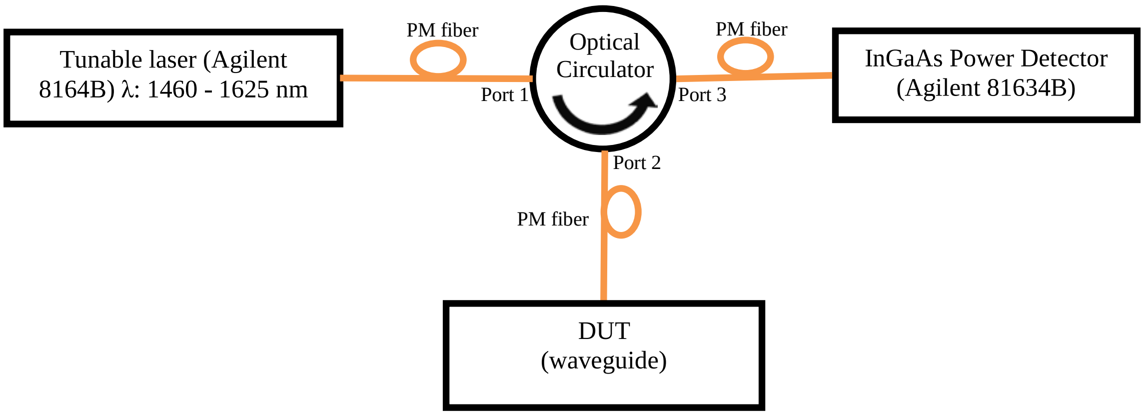

Fig.4. Schematic of the optical setup built for the characterization of the propagation losses using the Fabry-Perot method @ λ=1550 nm. The mode generated in the tunable laser is coupled to the waveguide with a base PM fiber and the reflected light from the waveguide cavity is directed to power detector by using an optical circulator.

Figure 5 shows the measured Fabry-Perot resonances from the waveguides with different lengths depicted in Figure 3; 200 µm (Fig 5 (a)) and 250 µm (Fig 5 (b)). The separation between the adjacent reflection peaks, the free spectral range, changes with cavity length as expected. A slowly-varying envelope due to the gap in between the waveguide input end-facet and fiber tip was convoluted to the Fabry-Perot reflections. The high frequency noises on the signal are mainly attributable to the cavity formed in the long fiber attached to port 2. The raw data was processed to eliminate the effect of slowly-increasing trend by making a linear trend approximation. Then, a Butterworth filter was applied for removing the high frequency noises on the measured data. The filtered data were fitted to a theoretical expression (eq. 1) given for the power reflected from a Fabry-Perot cavity to extract the propagation loss [6].

$$P_R = E_o^2 \frac{r^2 - 2r^2 e^{-2\alpha L} \cos\delta + r^2 e^{-4\alpha L}}{1 - 2r^2 e^{-2\alpha L} \cos\delta + r^4 e^{-4\alpha L}} \qquad (1)$$

Here L is the cavity length, r is the facet reflectivity and α represents the propagation loss in the system. Estimating free parameters: r and α, using a fitting to measured Fabry-Perot reflections yielded a propagation loss, α = 1,71 ± 0.04 dB/cm @1.55 µm.

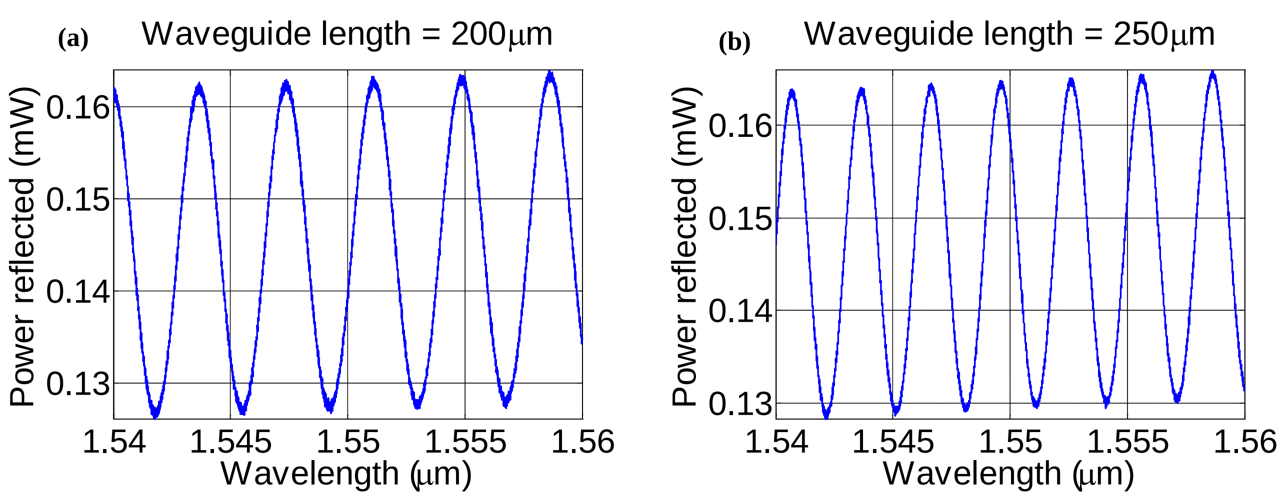

Fig 5. Measured Fabry-Perot reflections from the waveguides with the length of (a) 200 µm and (b) 250 µm.

4. CONCLUSION

We demonstrated high-index-contrast undoped KYW waveguides enabled by heterogeneous integration. The propagation losses of the fabricated waveguides were estimated as low as 1,71 ± 0.04 dB/cm by using Fabry-Perot method. 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+}.

5. ACKNOWLEDGMENT

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