Rare Earth Doped Epitaxial Layers of $KY_{1-x-y}Gd_xLu_y(WO_4)_2$ as Active Waveguides

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***Abstract*—Active planar waveguides based on monoclinic double tungstates doped with Er^{3+} and Tm^{3+} are presented. The incorporation of these ions into the lattice matched $KY_{0.59}Gd_{0.19}Lu_{0.22}(WO_4)_2$ epitaxial layers grown on $KY(WO_4)_2$ substrates was successfully achieved without loss of optical quality, and keeping a high refractive index contrast between the epitaxial layer and the substrate. Both spectroscopic and waveguiding properties of the epitaxial layers have been characterized. Results indicate that high performance waveguide lasers operating at the IR can be realized in these dielectric media.**

Keywords- active waveguides, lasers, liquid phase epitaxy

I. INTRODUCTION

A wide range of dielectric materials, such as oxides, fluorides, glasses [1], and more recently monoclinic double tungstates, $KRE(WO_4)_2$ [2,3] and rare-earth doped sesquioxides [4], have been studied to develop waveguide lasers. The main advantages of lasers in waveguide configuration are the reduction of the cavity mode-volume, high optical gain, low threshold and easy on-chip integration with other photonics components. Since the family of monoclinic double tungstates, $KRE(WO_4)_2$, includes a rare earth ion in its structure, it is an excellent host materials for active lanthanide ions such as Yb^{3+}, Tm^{3+}, and Er^{3+}, for laser applications [5–8], including thin disk configuration [9]. In addition, $KRE(WO_4)_2$ crystals containing different rare earths present different refractive indices, and therefore by choosing a suitable combination of the constitutive rare earth ions in these materials, active waveguide with good refractive index contrast can be fabricated. We have chosen Er^{3+} and Tm^{3+} as active ions for doping the passive layer, due to their attractive characteristics for several integrated optical applications.

II. EXPERIMENTAL DETAILS

Er^{3+} and Tm^{3+} doped $KY_{1-x-y}Gd_xLu_y(WO_4)_2$ bulk single crystals were grown by the Top Seeded Solution Growth method (TSSG) in a vertical tubular furnace using **b**-oriented seeds of $KY(WO_4)_2$. $K_2W_2O_7$ was used as solvent in a ratio solute:solvent 12:88 mol%. The crystals were grown cooling by 15 K the temperature of the solution from the saturation temperature at a cooling rate of 0.03 K/h. The lattice parameters of Er^{3+} and Tm^{3+} doped $KY_{1-x-y}Gd_xLu_y(WO_4)_2$ single crystals were determined by X-ray powder diffraction using a Bruker-AXS D8-Discover diffractometer.

Liquid Phase Epitaxy was used to grow Er^{3+} and Tm^{3+}-doped $KY_{1-x-y}Gd_xLu_y(WO_4)_2$ epitaxial layers on **b**-oriented $KY(WO_4)_2$ substrates. The solution prepared for the epitaxial growth was composed of 7 mol% solute and 93 mol% solvent ($K_2W_2O_7$). Once the T_s was established, the $KY(WO_4)_2$ substrate was introduced into the furnace, and it was kept at 1 mm above the surface of the solution for 45 min to reach the same temperature that the solution used for growing the epitaxial layer. After that, the substrate was submerged into the solution at 1 K above T_s, during 5 min. Then, we decreased the temperature of the solution suddenly by 4 K below T_s, to reach the growth temperature, T_g. After 3 h, the substrate was taken out from the solution, and the furnace was cooled down to room temperature at 20 K/h to prevent cracking of the epitaxies by thermal shocks. Chemical composition of the samples was determined by Electron Probe Microanalysis (EPMA) with a CAMECA SX 50 equipment, performed at 20 mA of beam current, 20 kV of acceleration voltage.

Optical absorption spectra were taken with a VARIAN CARY-5E-UV–VIS–NIR 500 Scan Spectrophotometer, while photoluminescence spectra were performed by using a Ti:sapphire laser as excitation source and recorded in a 90º configuration by a double monochromator with a focal length of 0.46 m, by means of a cooled NIR photomultiplier.

Refractive indices of the Er^{3+} and Tm^{3+} doped $KY_{1-x-y}Gd_xLu_y(WO_4)_2$ epitaxial layers as well as those of the substrates were measured by the prism-film coupling technique using a Ti:sapphire laser and a He-Ne laser. The TE polarization allowed us to measure the refractive indices, n_g and n_m, associated to the N_g and N_m principal dielectric directions, respectively, while the TM polarization was used to determine the refractive index n_p, associated to the third principal dielectric direction, N_p.

III. RESULTS AND DISCUSSION

Crack-free and macroscopic defect free epitaxial layers of $KY_{0.60}Gd_{0.18}Lu_{0.21}Er_{0.01}(WO_4)_2$ and $KY_{0.59}Gd_{0.18}Lu_{0.22}Tm_{0.01}(WO_4)_2$ on **b**-oriented $KY(WO_4)_2$ substrates were obtained by the LPE technique. The chemical composition of these epitaxial layers was analyzed by EPMA. The scheme of the

atomic percent of Gd^{3+}, Lu^{3+}, Er^{3+} and Tm^{3+} measured by this technique across the substrate and the epitaxial layer shows no diffusion of these ions from the epitaxial layer to the substrate (see Fig. 1). The as-grown epitaxies had an epitaxial layer on every {010} face of the substrate. So, to fabricate waveguides, we removed one of the epitaxial layers, preferably that grown on the (0-10) face. Then, the epitaxial layer grown on the (010) face of the substrate was lapped and polished to a final thickness of 10 μm. The resulting sample was cut as a slab with dimensions of 5x5x2 mm^3 along the N_g, N_m and N_p directions, respectively. Finally, the four lateral edges of the sample were polished to high quality to facilitate the coupling of light into the epitaxial layer through the edge. The refractive indices of the substrate and the epitaxial layers were measured at different wavelengths with a Ti:sapphire laser coupled to a prism-film coupler system.

At 632.8 nm the refractive index contrast between the doped films and the substrate is, in both cases, of the order of 10^{-3}, which is high enough to guide light along the three principal optical directions of the epitaxial layer. For the Er^{3+} emission wavelength at 1533 nm, the n_g refractive index of the film, estimated by the Cauchy fitting, seems to be lower than that of the substrate. This means that light would be not guided when the electric field of the incident beam oscillates parallel to N_g direction. On the contrary, the n_m and n_p refractive indices of the film seem to be greater than those of the substrate. This would indicate the possibility to demonstrate an erbium-based waveguide laser for light oscillating parallel to N_m and N_p directions. In the case of the Tm^{3+} emission wavelength at 1769 nm, it seems that we would only expect to obtain a Tm-based waveguide laser for light polarized parallel to N_m direction since the estimated n_g and n_p refractive indices of the film seem to be lower than those of the substrate. According to the results, a $KY_{0.60}Gd_{0.18}Lu_{0.21}Er_{0.01}(WO_4)_2/KY(WO_4)_2$ waveguide will be monomode for guided light at λ = 1533 nm when the thickness of the film is around 6 μm, while at λ = 1769 nm the $KY_{0.59}Gd_{0.18}Lu_{0.22}Tm_{0.01}(WO_4)_2/KY(WO_4)_2$ waveguide will only guide one mode when the thickness of the film is ~5 μm.

Through the same prism-film coupler system we recorded the dark-mode spectra for the doped layers. At λ = 633 nm we observed five and four TE guided modes for 10 μm-thick epitaxial films when the electric field oscillates parallel to the N_g and N_m optical directions, respectively, and five TM guided modes when the magnetic field oscillates parallel to the N_p optical direction. The guided modes observed in the dark-mode spectra at λ = 632.8 nm were excited and visualized by the end-coupling technique using a 40x microscope objective to focus the laser beam at the input of the waveguide and a 60x microscope objective at the opposite edge to collect the near field intensity on a CCD camera.

We finally established an upper limit for propagation losses of the waveguides by measuring the intensity of the scattered light along the waveguide with a CCD camera. The upper limit in the two waveguides studied was about 1 dB/cm for the three principal optical directions.

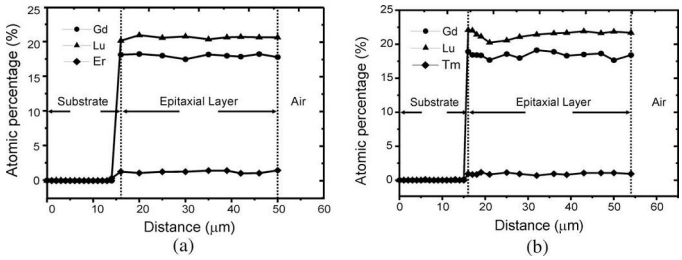

Fig. 1.- Extended profiles of the chemical composition across the interface substrate/epitaxial layer in (a) $KY_{0.60}Gd_{0.18}Lu_{0.21}Er_{0.01}(WO_4)_2$ and (b) $KY_{0.59}Gd_{0.18}Lu_{0.22}Tm_{0.01}(WO_4)_2$ samples.

IV. CONCLUSIONS

We have successfully introduced Tm^{3+} and Er^{3+} ions in $KY_{1-x-y}Gd_xLu_y(WO_4)_2$ epitaxial layers without loosing optical quality and keeping a low lattice mismatch and a high refractive index contrast with the $KY(WO_4)_2$ substrate. The Er^{3+} and Tm^{3+} ions concentrations in these epitaxial layers were $7.8x10^{-19}$ and $6.4x10^{-19}$ cm^{-3}, respectively, high enough to allow laser generation. Finally, the waveguiding properties of these epitaxial layers at λ = 632.8 nm were studied by dark-mode spectroscopy. It was found that these waveguides can support up to four TE and TM modes, allowing monomode propagation at the IR. Experiments to demonstrate planar waveguides lasers and routes for fabricating channel waveguide configuration in this material are ongoing at present.

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