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Channel waveguide fabrication in $KY(WO_4)_2$ combining liquid-phase-epitaxy and beam-multiplexed femtosecond laser writing

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ABSTRACT

In the present work we propose a 2D-channel waveguide fabrication process based on the microstructuration of the cladding of a planar waveguide by femtosecond laser writing. The core of the waveguide is formed by a layer of $KY_{1-x-y}Gd_xLu_y(WO_4)_2$ epitaxially grown over a $KY(WO_4)_2$ substrate by means of Liquid Phase Epitaxy (LPE). A cladding of $KY(WO_4)_2$ is then grown by LPE over the core waveguide. To obtain lateral light confinement, the cladding is then micromachined using a multiplexed femtosecond laser writing beam, forming a ridge structure. Channel waveguides fabricated following this approach have been characterized in terms of their mode sizes and propagation losses at 0.98 μm and 1.64 μm, which are close to the wavelengths of interest in lasers/amplifiers based on the Er^{3+}/Yb^{3+} system. Experimental data are compared with simulation analysis based on the Effective Index Method and the Beam Propagation Method, showing a good accordance between experimental and numerical results.

1. Introduction

Nowadays the development of active integrated optical devices, such as waveguide lasers, is a very active research field [1]. The fabrication of low loss channel waveguides in dielectric crystals doped with active ions is thus a major point of interest. For this purpose different fabrication techniques have been used, such as metallic in-diffusion, laser writing, ion milling and proton exchange [1]. Among them, femtosecond (fs) laser microstructuring is becoming a promising technique for fabricating integrated photonic devices [2,3]. This technique offers a main advantage compared to other fabrication processes as it enables rapid prototyping with a relatively low production cost. Besides, it does not require a clean room processing to be carried out. Using this technique, low loss waveguides have been fabricated in different types of materials such as glasses or dielectric crystals [4,5]. Recently, active devices, such as waveguide lasers, fabricated with this technique, have been also reported [6].

On the other hand, potassium double tungstates are well known dielectric crystals. They are monoclinic crystals which belong to the *C*2/*c* space group, with the unit cell parameters $a = 10.64$ Å, $b = 10.35$ Å, $c = 7.54$ Å and $\beta = 130.5°$ for $KY(WO_4)_2$ [7]. Crystals of this family, such as $KY(WO_4)_2$, $KGd(WO_4)_2$ or $KLu(WO_4)_2$, have been widely studied for photonic applications due to their unique properties. Their optical transparency from 350 nm up to 5.4 μm, relative high refractive index (~2.0 at 633 nm), and high absorption and emission cross sections when doped with rare ions, make these materials interesting for developing active photonic devices [8,9]. Optically, they are biaxial crystals, with the N_p, N_m and N_g dielectric axis, being $N_p//\boldsymbol{b}$ crystallographic direction (N_g is at 18.5° in $KY(WO_4)_2$ clock-wise rotation when positive $\boldsymbol{b}$ is pointing to the observer [8]) and $n_g > n_m > n_p$.

Waveguide lasers based on these crystals have been reported using different active ions, in both continuous wave [10–12] and pulsed operation [13]. Similarly, waveguide lasers based on Er^{3+} ions have been also proposed and modeled [14]. The main drawback of double tungstates as the matrix for active devices codoped with Er^{3+}:Yb^{3+} is their rather low phonon energy (compared to other Er^{3+}:Yb^{3+} active hosts), around 900 cm^{-1} [8], which makes the design of devices very critical, with the propagation losses being of utmost importance.

In this work a fabrication technique combining liquid-phase-epitaxy (LPE) and fs-laser micromachining is presented in order to develop controllable loss channel waveguides in $KY(WO_4)_2$ crystals. The approach is based on the effect of a load

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waveguide to achieve lateral confinement of light [15,16]. The fs-laser microstructuring process, based on a multiplexing strategy, has been optimized for double tungstates to obtain low loss ridge waveguides. The modal sizes and propagation losses of the fabricated waveguides have been measured, and they have been favorably compared with results from numerical modeling. The characterization has been focused at the pump and emission wavelengths of the Er^{3+}:Yb^{3+} system.

2. Experimental procedure

2.1. Planar waveguide fabrication

$KY(WO_4)_2$ single crystal was obtained by TSSG slow cooling technique [8]. The growth of the crystal was carried out in a tubular furnace from a solution of $KY(WO_4)_2$ in $K_2W_2O_7$, prepared with a ratio of solute:solvent = 12:88 (in mol%) following the procedure explained elsewhere [17–19]. The crystal was grown using a seed parallel to the ***b*** crystalline direction. The substrates for waveguide fabrication were procured from the grown $KY(WO_4)_2$ crystal, where 2 mm slices perpendicular to ***b*** direction were obtained, and then polished up to 0.3 μm roughness. This orientation was chosen because it allows an efficient pump in the waveguides grown over these substrates when doped with rare earths, as it allows pump polarizations parallel to N_m and N_p optical directions which are the ones with higher absorption cross sections [8].

Once the $KY(WO_4)_2$ substrates were obtained, an epitaxial layer of (0.5 at.% Er, 0.5 at.%Yb): $KY_{0.75}Gd_{0.18}Lu_{0.07}(WO_4)_2$ was deposited by LPE technique over (010) oriented $KY(WO_4)_2$ substrates following the process previous reported [17–19]. In this case, the solute/-solvent ratio was 7:93, as this composition offers better control over the process [20]. The doped epitaxial layer was polished up to ~4 μm thickness. After that, a cladding of undoped $KY(WO_4)_2$ was grown by means of LPE under the same conditions before explained. Finally, the surface was polished again, in order to enable the fs-laser microstructuring of the cladding layer. The end-faces were cut and polished to allow light propagation along N_g direction.

2.2. Ridge structure fabrication

The ridge structure for light confinement in two dimensions was fabricated by means of the fs-laser writing technique. To obtain the rib structures two parallel channels were micromachined by fs-laser ablation. The setup used is explained elsewhere [4]. Briefly, a Tsunami pulsed fs laser in combination with a Spitfire amplification system was used as source. Then, a spatial light modulator (Hamamatsu X8267) was used to select the most suitable wave-front, and an image relay system was used to transfer the beam at the spatial-light-modulator (SLM) to the focusing objective. The sample was mounted on a three axes programmable stage.

The generated laser pulses with 1 kHz repetition rate have a duration around 100 fs. The wavelength of the pulses was centered at 800 nm. Three subsequent scans were carried out to micromachine each channel with energies between 2 and 2.6 μJ, depending on the required depth. The micromachining properties were found to be stable in terms of depth vs speed up to 200 μm/s scanning speeds.

The beam wave-front was modulated in order to generate a multiplexed focused beam at the surface, leading to the so-called approximation scanning technique to structure the surface [21]. This technique is based on performing several parallel scans, partially overlapped, each one slightly closer to the ridge. With this technique it is possible to obtain stepper walls with lower roughness, and partially avoids the re-deposition of the ablated material over the walls. In the present work, a configuration with seven spots was used. The multiplexed array was generated by modulating the wave-front of the beam using a Spatial Light Modulator (SLM). In this way, the spots were displaced diagonally, which allows performing the structuring of an asymmetric trench in a single scan process, instead of performing seven individual, as in the conventional approach. The phase mask imprinted in the SLM to generate the multiplexed beam array was obtained using a weighted Gerchberg-Saxton algorithm [22].

2.3. Waveguide characterization

Passive characterization of the fabricated waveguides was carried out, including mode field analysis and determination of propagation losses. Near field modal analysis was performed to determine the lateral light confinement of the fabricated waveguides. For this purpose, two diodes operating at 980 and 1640 nm were coupled to a SM980 single mode fiber that was subsequently coupled to the waveguide under test. Guided light was collected by using a MIR-AR coated microscope objective, and imaged onto a cooled InGaAs CCD by a tube lens.

Propagation losses were measured using an Optical Spectrum Analyzer (OSA) and a diode emitting at 1640 nm. Losses at 980 nm were not measured because the samples were co-doped with Er^{3+} and Yb^{3+} ions that present strong absorption cross section at this wavelength, especially in double tungstates. The 1640 nm diode was coupled to the selected waveguide using a SM980 fiber, and the guided light was collected by a similar fiber and transferred to an OSA. Insertion losses, including Fresnel and coupling losses were taken into account in order to determine the propagation losses. To determine the insertion losses the near field image of the mode of the SM980 fiber and the waveguide mode under test were considered. The overlap between both modes was analyzed for each waveguide and therefore a coupling losses value was determined for each case and wavelength [23]. Using this method the lower limit that is possible to determine in propagation losses is around 0.5 dB/cm.

3. Numerical analysis

The proposed waveguide structure is based on the effective index modification suffered by a planar waveguide when loading a material with different refractive index, which causes lateral confinement of the light. With this aim, a ridge structure has been fabricated starting from a four-layered planar waveguide, as depicted in Fig. 1a. In this way, a lateral variation of the effective index is induced, which depends on the geometry and refractive index of the top-structured region. As a consequence, a 2D effective index distribution is obtained, which under some conditions is able to laterally confine the light. Fig. 1a shows the cross-section of the proposed ridge structure, where the relevant parameters are indicated. It consists of a film of refractive index n_{core} and thickness h_1, which acts as the waveguide core, sandwiched by an uniform substrate (n_{subs}) and a structured cladding made with of the same material ($n_{clad} = n_{subs}$). The upper region is assumed to be air ($n_{air} = 1$). In the figure h_2 represents the residual cladding thickness remaining after fs-laser processing.

The light confinement of this structure can be understood and analyzed by means of the effective index method (EIM) [24]. For such a purpose, the effective index corresponding to the fundamental mode of the four-layered planar waveguide obtained by vertical cuts from the original structure is obtained as function of the total cladding thickness ($h_2 + h_3$ in Fig. 1a), and then it is fit to an exponential function. In this simulation we have taken