Ridge waveguide structures in KYW crystals produced by beam-multiplexed fs-laser writing

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Abstract: Femtosecond laser structuring using a multiplexed beam has been used to produce ridge waveguides in KYW crystals. The initial structure consists on a planar waveguide where a cladding is added by LPE technology. Then, the cladding is structured by fs-laser processing is such a way that lateral confinement of the light is achieved by a local increase of the effective refractive index of the planar waveguide. The proposed waveguide geometry allows the propagating mode to be confined in a region far from the lateral walls of the ridge, thus avoiding losses that could arise from the roughness of the walls at the high-index material/air interfaces.

Introduction. Double tungstates, such as $KY(WO_4)_2$, have been widely studied for photonic applications[1,2]. In particular, their optical transparency, high refractive indices, and the high absorption and emission cross sections when doped with rare earths, make them good candidates for developing integrated optical devices. Combining Liquid Phase Epitaxial (LPE) with Reactive Ion Etching (RIE) o Ar milling techniques for the surface micro-structuring, low losses (< 0.25 dB/cm) waveguides have been reported, and efficient waveguide lasers have been demonstrated[3]. Alternatively, channel waveguides can be structured by fs-laser writing[4], although wall roughness can induce undesired propagation losses. Here we propose and study numerically a ridge waveguide structure which avoids losses from the roughness at the high-index material/air interface. These structures have been fabricated in KYW crystals by LPE followed by fs-laser processing structuring. Experimental results have been then compared with predictions based on numerical modelling.

Ridge structure. Figure 1 shows the cross-section of the proposed ridge structure with the relevant size parameters. It consists of a film of refractive index n_{core} and thickness h_1, which acts as the waveguide core, sandwiched by a uniform substrate (n_{subs}) and a structured cladding made with of the same material ($n_{clad} = n_{subs}$). In the figure h_2 represents the residual cladding thickness.

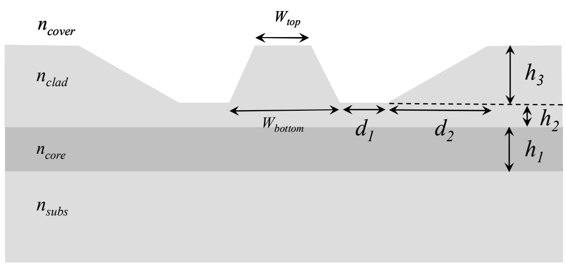

Fig. 1: Transversal section of the ridge structure.

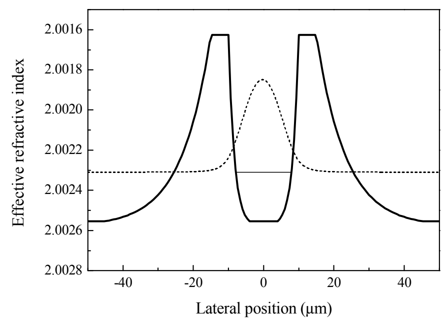

Fig. 2: Effective index and mode profiles using EIM.

The transversal structure has been analyzed by means of the effective index method[5] (EIM). For such a purpose, the effective index corresponding to the fundamental mode of the asymmetric planar waveguide obtained by vertical cuts from the original structure is obtained as function of the total cladding thickness (h_2+h_3 in figure 1), and then it is parameterized to an exponential function. In the model, $n_{clad} = n_{subs} = 2.000$ (KYW crystal), and $n_{core} = 2.005$, that is, a 5×10^{-3} index increase respect to the substrate index, which is a typical value obtained in LPE epitaxial layers. The core thickness is h_1 = 4 µm, and the working wavelength is λ = 1.55 µm. Figure 2 plots the effective index profile (thick line) along the horizontal direction obtained by the EIM. That index profile was obtained with: h_2 = 0.5 µm, h_3 = 8 µm, W_{bottom} = 20 µm, W_{top} = 10 µm, d_1 = 5 µm and d_2 = 30 µm. The modal intensity profile of the fundamental mode (dashed line) and its effective index (horizontal line) are also plotted in figure 2. As the resulting 2D-waveguide consists on light confinement between two low-index optical barriers, some losses are expected coming from tunneling through the low-index barriers, similar to those found in ion implanted waveguides. In this case, the calculated propagation loss of the mode at 1.55 µm is 0.25 dB/cm. The losses can be reduced either by increasing the residual cladding (h_2) or by increasing the lateral distance d_1 (or even d_2).

Following this concept, a ridge waveguide has been fabricated on an oriented KYW substrate grown by the TSSG method[1]. A layer of 0.5% Er^{3+}-0.5% Yb^{3+} KYW was deposited by LPE[6], with a final thickness of 4 µm. After that, a 8 µm cladding of pure KYW was additionally grown. The three-layer sandwich was then processed with a multiplexed fs-laser beam, using a spatial light modulator, as described in Ref.4, in order to produce ridge structures similar to those shown in figure 3 (left, center). After end-face polishing, the mode profile of the waveguides at 1640 nm was measured (figure 3, top-right) showing a good mode confinement of the ridge structure and negligible propagation losses. In the same figure (bottom-right) the mode intensity profile obtained by imaginary-distance 3D-BPM has been included, using the parameters derived from the experimental profile dimensions and the refractive indices of the substrate and core layers. Also, the measured losses at this wavelength are lower than 0.5 dB/cm.

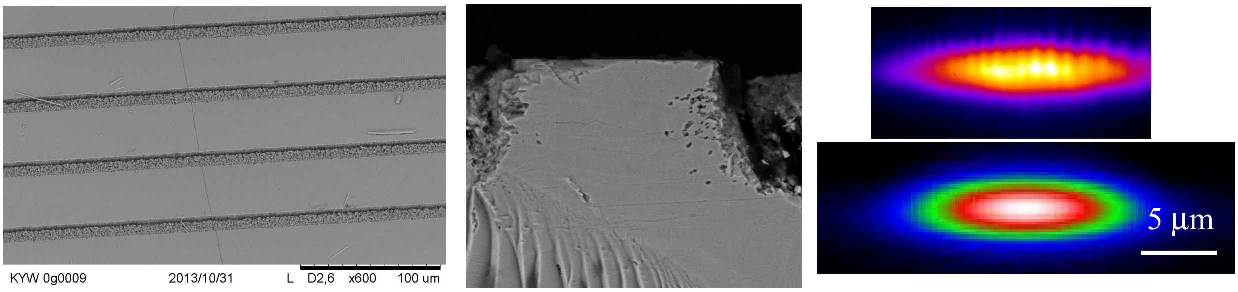

Fig. 3: Left and center: Typical SEM images appearance of the ridge structures produced before end facets polishing. Right: measured (top) and simulated (bottom) waveguide mode at 1640 nm.

Conclusions. A waveguide ridge structure has been proposed to generate lateral confinement on planar structures grown by KYW crystals fabricated by the LPE. This structure has been fabricated by fs-laser processing, and the results of light propagation have been compared with numerical simulations. The good accordance between experiments and simulations indicate that this a promising route for fabricating channel waveguides in KYW crystals and its isostructural family.

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