

# Methods of Fabricating Surface Undoped and Yb-doped KY(WO<sub>4</sub>)<sub>2</sub> Planar Waveguides

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## ABSTRACT

The paper reports on the fabrication of undoped and Yb-doped double tungstate waveguides for laser applications. Two different methods of fabricating the waveguides are detailed below, one being thin film growth by liquid-phase epitaxy and the other, light ion implantation of undoped double tungstate materials. Highly efficient CW laser emission based on the Yb-doped layers was demonstrated at room temperature.

**Keywords:** optical amplification, ion implantation, optical waveguides, solid-state lasers.

## 1. INTRODUCTION

Yb-doped media for fabricating lasers that emit in the 1- $\mu\text{m}$  near IR spectral region have undergone a resurgence in popularity, due to the development of high-power pumping laser diodes around 980 nm. Yb-doped media have the advantages of a low quantum defect, a simple electronic structure and relatively long fluorescence lifetime. In addition, compared with Nd-doped media, Yb-doped materials have broader emission bandwidths, which make them still more attractive as ultrafast laser media. In particular, the Yb<sup>3+</sup> ion in KY(WO<sub>4</sub>)<sub>2</sub> (KYW) exhibits a cross-section approximately 15 times larger than that of Yb:YAG, which makes lasing easier, and a thermal conductivity that is three fold that of Yb:glass, which permits higher average powers. Besides the bulk KYW:Yb crystal lasers, intensive research is being conducted towards increasing the slope efficiency and decreasing the laser threshold by the use of a waveguiding structure. The advantages of the thin-layer geometry can be fully exploited in a two-dimensional structure, in which high pump-power densities and excellent overlap of pump and resonator modes can be obtained. This approach requires the fabrication of high-quality KYW:Yb waveguides, with close-to-perfect interfaces to ensure low-loss propagation. The paper reports on the fabrication of undoped and Yb-doped KYW waveguides using two different approaches: thin-film growth by liquid-phase epitaxy and creation of an optical barrier by light ion implantation. Highly efficient CW laser emission based on the grown layers, with end-face pump coupling was demonstrated at room temperature.

## 2. KY(WO<sub>4</sub>)<sub>2</sub> WAVEGUIDES BY He-ION IMPLANTATION

Ion implantation can be regarded as a universal tool for fabricating low-loss waveguide structures in optically active oxide materials. Good control of the implantation parameters, such as the dose, energy or type of implanting ion can result in excellent confinement of the light between the crystal's surface and the optical barrier created at the end of the ions tracks [1].

Optically polished undoped KYW crystals, which were kept at a controlled temperature of 30°C and oriented along the [010] axis, were irradiated by use of a Van de Graaf accelerator operating at beam currents in the range of 0.6-0.8 mA/cm<sup>2</sup>. He<sup>+</sup> ions at 1.5 MeV with dose of 2x10<sup>16</sup> ions/cm<sup>2</sup> were implanted into these crystals. The accumulated damage profile created by the implanted ions was calculated by the SRIM simulation code [2] and can be seen in Fig. 1(a). At this energy, an optical barrier is expected approximately 3.5  $\mu\text{m}$  below the surface.

The guided-mode effective refractive index ( $N_m$ ) change presented in Fig. 1(b) was measured at 633 nm by the m-line spectroscopy technique. The Chandler-Lama (reflectivity-matrix) approach was applied to calculate the theoretical values for the effective refractive index such that they reproduce the experimental ones by means of best-fit algorithm [3]. The reflectivity-matrix approach is a more realistic method to describe and to use for correct interpretations for m-line measurements. It takes into account the characteristics of the experiments: the coupling prism, the air gap between the prism coupling and the waveguide and the graded index in the guide. The fit to the observed two waveguiding modes at 633 nm resulted in an  $\Delta n = -1\%$  change in refractive index along the  $N_m$  axis with respect to the bulk value. Annealing at 250°C for 5 hours resulted in better confinement of the modes in the waveguiding region.

The end-faces of implanted crystals were polished and the waveguiding properties of the obtained planar structures were investigated using a laser diode at 980 nm, a He-Ne laser at 633 nm, and a CCD camera. The waveguiding properties were observed using coupling by microscope objectives as well as by prism coupling. Near-field images of light guided coupled through the multimode He-implanted waveguide were

recorded after coupling 980-nm light from a single-mode laser diode into the 3.5- $\mu\text{m}$  layer with 40x microscope objectives. Fig. 1(c) shows the profile of a near-field image obtained after thermal treatment at 250°C for 5 hours. The results are, to the best of our knowledge, the first obtained on He-implanted waveguides in undoped KY(WO<sub>4</sub>)<sub>2</sub> crystals. Similar results have been published on He implantations into NaY(WO<sub>4</sub>)<sub>2</sub> crystals [4,5]. It is interesting to note that proton implantations into KY(WO<sub>4</sub>)<sub>2</sub> crystals resulted in a layer with very high losses and no waveguiding properties due, probably, to the chemical interaction effects between the proton charges and the target material [6].

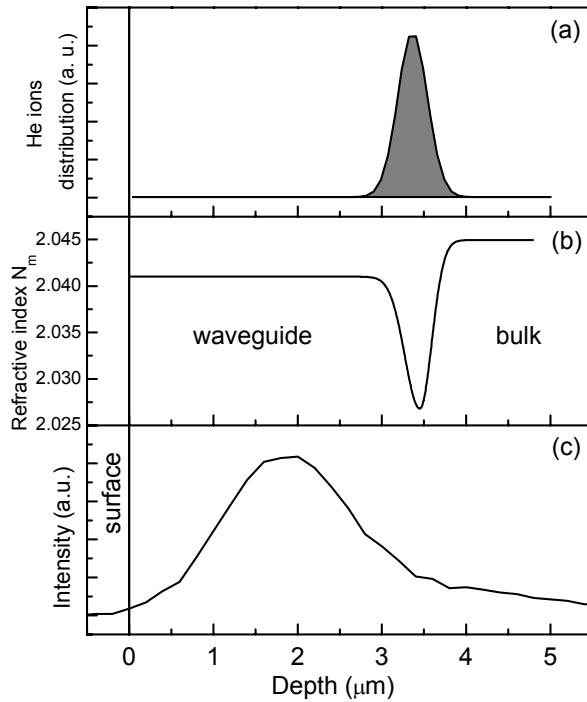


Figure 1. Surface planar waveguide in KY(WO<sub>4</sub>)<sub>2</sub> formed by He-ion implantation.

(a) Accumulated damage profile calculated by SRIM simulations for He ions at 1.5 MeV;

(b) Change in effective refractive index measured by dark m-line spectroscopy and reconstructed by the reflectivity method;

(c) Near-field intensity profile along the  $N_m$  axis experimentally recorded at 980 nm.

### 3. KY(WO<sub>4</sub>)<sub>2</sub>:Yb WAVEGUIDES BY LIQUID PHASE EPITAXY

Liquid-phase epitaxy (LPE) is a well-known technique to produce high-quality oxide films for laser applications, in which a single crystal layer can be grown from a molten solution on a flat oriented single crystal substrate [7]. Recently, we reported on the LPE of rare-earth-ion-doped KYW layers employing a low-temperature chloride solvent [8]. The tungstate solvent K<sub>2</sub>W<sub>2</sub>O<sub>7</sub> seemed to offer larger thicknesses and a good layer quality [9,10] and it was successfully used to obtain our thin films. Single-crystalline layers with thicknesses from 10 to 100  $\mu\text{m}$  and Yb<sup>3+</sup> concentrations ranging from 1.2 to 2.4 at% with respect to Y<sup>3+</sup> were grown on undoped KYW crystalline substrates. The end-faces of each layer were polished parallel to each other to laser-grade quality. Yb<sup>3+</sup> concentration in the layer was nearly the same as in the initial growth solution because the distribution coefficient of the Yb<sup>3+</sup> ion in the K<sub>2</sub>W<sub>2</sub>O<sub>7</sub> solvent is close to unity [9]. The layers were tested as planar passive and active waveguides under excitation at 633 or 980 nm, respectively. The laser light was coupled into an active layer along the crystallographic c-axis by focusing with a 10x microscope objective. The out-coupled light was imaged onto the sensor of a CCD camera with a 16x microscope objective. For the particular waveguide shown in Fig. 2, the Yb<sup>3+</sup> fluorescence was guided together with the pump laser light in the surface KYW:Yb layer after the excitation with an InGaAs laser diode at 980 nm.

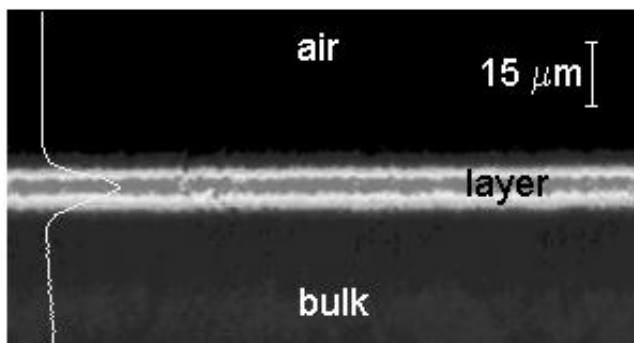


Figure 2. Image of the guided fluorescence and pump laser light outcoupled from a 17- $\mu\text{m}$  thick KYW:1.2% Yb<sup>3+</sup> planar waveguide under excitation at 980 nm from a diode laser.

Following the characterization of the grown Yb-doped films, the lasing properties were investigated. The planar waveguide used for the laser experiment consisted of a 17- $\mu\text{m}$  thin layer of 1.2 at%  $\text{Yb}^{3+}$ -doped KYW [11]. A 1-mm thick undoped KYW slab acted as the substrate. The 6-mm long waveguide was placed in an external resonator. To match the resonator waist size with the waist of the transverse fundamental mode of the waveguide, a Z-shaped four-mirror laser resonator was constructed. The KYW:Yb waveguide was positioned between two 10-cm folding mirrors such that the resonator waist is located at both end-faces of the waveguide and negligible diffraction losses occur for the resonator mode at the air/KYW:Yb/KYW interfaces. Our laser scheme was characterized by guiding the pump and the resonator mode over the entire length of the planar waveguide, maintaining a high overlap between pump and resonator mode. The waveguide was positioned at Brewster angle to minimize losses in the laser cavity. Beam propagation was approximately along the  $N_g$  principal optical axis and polarization along the  $N_m$  axis. The sample was mounted on a copper plate but no special care was taken for active cooling. The KYW:Yb layer was pumped in single-pass absorption by a tunable CW Ti:sapphire laser with a maximum output power of 3 W near 980 nm. A 62.8-mm focusing lens was used to couple the nearly diffraction limited pump beam through one of the folding mirrors into the planar waveguide. The measured single-pass low-signal absorption of the 1.2 at% Yb-doped KYW layer at 980.5 nm amounted to 56%, in good agreement with the calculated value.

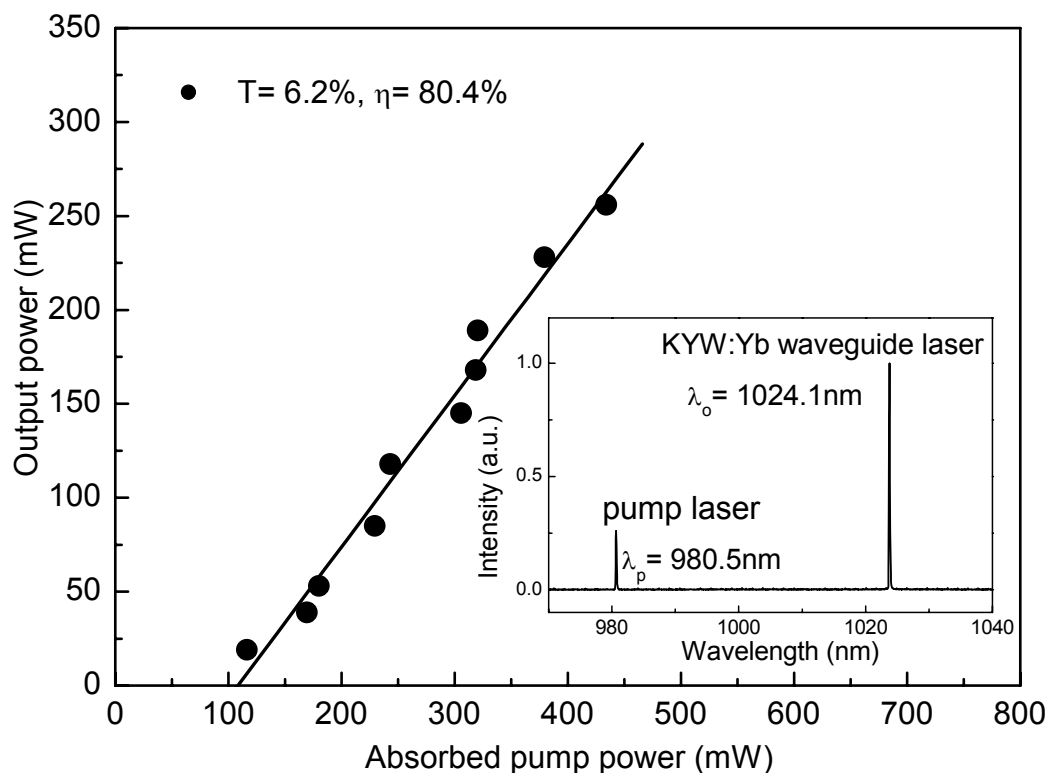


Figure 3. Output power versus absorbed pump power of a surface KYW:Yb planar waveguide laser using an output coupler with transmission of  $T = 6.2\%$ . The inset shows the spectral record of the waveguide laser emission at 1024.1 nm and the residual pump laser at 980.5 nm.

Continuous-wave laser operation was obtained for output-coupler transmissions between 1.7 and 13.5%. Independent of the output-coupler transmission, the laser emission was centered near 1024 nm (Fig. 3, inset). Because of the reduced reabsorption due to the high confinement and, therefore, high intensity of the pump beam in the active layer, the spectral emission corresponds to the maximum of the gain curve. Best laser performance was achieved for pumping in the main absorption peak at 980.5 nm. Applying a chopper with a duty cycle of 10%, the output power decreased ten times. Hence it can be concluded that no thermal problems occur up to the maximum applied pump power of 2 W despite the absence of active cooling. A rough loss estimation based on the detected laser slope efficiencies gave a cavity round trip loss of 4.8%, which assumes maximum waveguide losses below  $0.2 \text{ dBm}^{-1}$ . The observed far-field intensity distribution indicates that despite the multi-mode waveguide structure, the laser output is close to the diffraction limit and the resonator mode is well matched within the physical dimensions of the planar waveguide. Complementing results have been recently obtained proving that the resonator mode is a waveguide mode [12].

The laser threshold of the 17- $\mu\text{m}$ -thin KYW:Yb layer was reached at an absorbed pump power of about 80 mW. Using an output coupler with a transmission of  $T = 6.2\%$ , the maximum output power amounted to 260 mW, resulting in a slope efficiency of  $\eta = 80\%$  with respect to the absorbed pump power, as measured in the lasing state (see Fig. 3). This is the highest value of the slope efficiency ever reported for a KYW:Yb waveguide laser.

#### 4. CONCLUSIONS

Undoped KYW waveguides were successfully produced using He-ion implantation. Passive waveguiding has been demonstrated at 633 and 980 nm. Epitaxial planar waveguides of Yb-doped KYW have been manufactured with high optical quality by LPE method. Passive and active waveguiding was recorded at 633 and 980 nm. Continuous wave-lasing at 1024 nm with a maximum output power of 260 mW and a remarkably high slope efficiency as high as 80% were obtained at room temperature. These results are the building blocks for potential applications of rare-earth doped crystals in the Telecom research area.

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