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Buried channel waveguides in Yb-doped $KY(WO_4)_2$ crystals fabricated by femtosecond laser irradiation

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Abstract

We report on the fabrication of optical channel waveguides inside $KY(WO_4)_2$ crystals, both undoped and Yb-doped, for applications in compact solid-state lasers and three-dimensional photonic devices. Nonlinear absorption of femtosecond laser pulses has been employed in order to induce refractive-index changes in these crystals. The irradiation damage results in a decrease of the material density compared to the surrounding bulk. In this work, two types of buried channel waveguides have been fabricated in the $KY(WO_4)_2$ crystals. First ones (type I) were formed in the vicinity of the irradiated regions due to the presence of an induced compressive lattice strain, which causes an increase of the local refractive index. Light can be better confined in the second (type II) of channel waveguides that are created between pairs of damaged regions. For the best confined channels (type II), the propagation loss value measured at 1 μm amounted to 2–2.5 dB/cm.

Keywords: Femtosecond-laser writing; Burried channel waveguides; $KY(WO_4)_2$ crystals

1. Introduction

Crystals of monoclinic $KY(WO_4)_2$ (hereafter KYW) doped with different rare earth ions are among the highly promising materials for building compact solid-state lasers operating at room temperature, both in pulsed and continuous wave modes [1,2]. Due to its high refractive index (of the order of 2), good thermal conductivity and versatility in doping with rare earth ions, Yb^{3+} in particular, KYW crystals are ideally suited for high-power laser applications. Recently, laser emission from epitaxially grown KYW:Yb^{3+} planar waveguides with a high slope efficiency of 80% has been reported [3]. Despite these exceptional properties, no effort has been made yet to produce channel waveguide structures or other photonic elements inside KYW bulk crystals.

Ultra-short laser pulses tightly focused inside a transparent material can create localized structural changes. When the laser intensity in the focal volume is high enough, multiphoton absorption, avalanche ionization, optical breakdown and micro-plasma formation can take place, leading to high temperatures and pressures [4–6]. Since the absorption region is buried within the substrate matrix, the ablation of material is not possible. However, the heated material is expanding, creating a strain distribution around it. The exact dynamics of the expansion is determined by the laser characteristics (intensity, pulse duration, focusing conditions, etc.) and, most importantly, by the properties of the matrix material itself. The strain left in the material can result in a very complex distribution of the refractive index around the irradiated region [7–9]. When a continuous line is written using the appropriate laser parameters, a refractive-index profile inside the transparent material can be generated that acts as a waveguide. Despite the ongoing work on laser waveguide production inside glasses and transparent crystals, the structural changes caused by fs-laser pulses have not been thoroughly studied yet.

Optical channel waveguides showing an increase in refractive index in bulk crystals have recently been demonstrated in α-quartz [10], lithium niobate [11] and Ti^{3+}:sapphire [12]. However, the results seem to depend mostly on the crystal properties rather than the fs-writing parameters, since the results differ regarding the localization of the light-guiding regions of higher refractive index, as explained below. Results obtained in fused silica and several other glass systems [13] have shown that the laser irradiation induces a densification of the glass, and hence an increase in the refractive index within the focal volume, which allows one to guide light. In contrast,

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recent results reported in α-quartz [4] and in Ti^{3+}:sapphire [6], as well as in some glasses such as alkaline lead-oxide silicate glass [14], phosphate glass [15] and heavy-metal oxide glass [16], suggest that in these materials the main structural modification consists of an expansion of the focal volume accompanied by a lower local density and refractive index that does not support light guiding. Regions of higher refractive index, where light guiding was shown to occur, are created in the surroundings, as a result of the compression induced by the expansion of the central region. However, direct fs-writing of lithium niobate crystals resulted in an increase of the refractive index within the focal volume which supports light waveguiding [11].

In this paper we report, to the best of our knowledge, the first realization of buried waveguides in KYW and KYW:Yb^{3+} by irradiation with fs-laser pulses. The buried waveguide channels (of type I) are created in the vicinity of the laser-damaged regions, indicating that the guiding is stress-induced, like in α-quartz and Ti^{3+}:sapphire bulk crystals. Highly confined waveguide channels (of type II) can be formed between pairs of fs-laser written parallel lines. We observe no difference of the results obtained on either undoped or Yb^{3+}-doped KYW crystals.

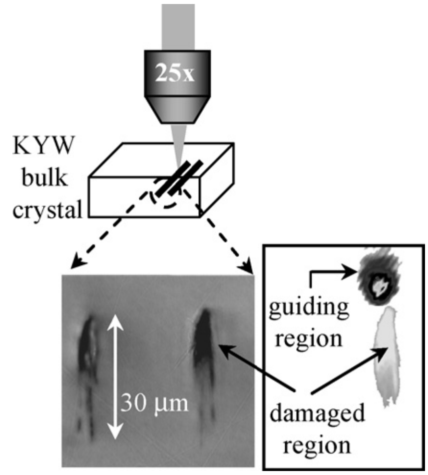

Fig. 1. The schematic diagram of the writing geometry is shown, as well as the white-light trans-illumination image of an end-face showing two fs-laser written lines. The inset shows a superposition of the white-light image of the facet and the recorded near-field intensity profile of a single-mode (type I) waveguide channel excited at 633 nm (the fringes present in the beam profile are artificially induced by the CCD camera).

2. Experimental

The samples used in this study were crystalline KYW and KYW:(2%)Yb^{3+} substrates, 10 mm × 10 mm × 1 mm in size, having the [0 1 0] direction parallel to the femtosecond laser beam. By means of a XYZ high precision translation stage (with sub-micron resolution), the samples were translated perpendicularly to the laser beam with constant speeds varying from 0.2 to 40 mm/s, thus writing longitudinal waveguides inside the KYW crystal. The symmetry of the irradiated focal region depends strongly on the focusing conditions. In order to avoid surface damage during the writing process, the irradiation was performed while having the beam focus around 200 μm underneath the polished surface plane. The crystals edges were cut and end-polished for optical investigations. A Ti:sapphire laser peaked at 800 nm, coupled to a regenerative amplifier with a repetition rate of 100 kHz, was focused inside the KYW crystals using either 25× or 40× optical microscope objectives with 0.5 or 0.65 numerical apertures, respectively. Investigations were carried out in the 1–20 μJ single-pulse energy regimes, with pulse duration of 200 fs in all cases. Optical loss measurements of the fabricated channel waveguides were performed by launching light at 670 or 980 nm.

3. Results and discussion

To qualitatively study the cross-sectional image and the refractive-index change, an optical contrast microscope was used to record trans-illumination images of the end-faces. Fig. 1 shows the schematic diagram of the writing geometry, as well as the white-light trans-illumination image of an end-face. The inset shows a superposition of the white-light image of the facet and the recorded near-field intensity profile of a single-mode waveguide channel excited at 633 nm, in order to spatially localize the formed channel (of type I). The trans-illumination image shows a dark area in the central part of the laser-modified region, and a bright guiding area in its surrounding. The dark area reflects the dimension of the Gaussian beam which, when focused by an objective lens with NA of 0.5–0.65, has a Rayleigh distance much larger than its beam waist, leading to a longitudinal intensity distribution (as seen in Fig. 1).

Similar results were obtained when varying the fabrication parameters, mainly the average single-pulse energy and the writing velocity. The pulse duration was kept constant at 200 fs. Varying the writing speed from 0.2 to 40 mm/s resulted in insignificant changes of the irradiated regions and waveguiding channels. The damaged regions become darker as the writing speed is decreased. Variation of the pulse energy from 1–20 μJ resulted in more significant changes. Using the same objective lens, at low energies, the damaged volume has a smaller size than the one at higher energies. The resulting waveguiding regions fabricated at low energies and situated in the vicinity of the damaged regions, have a smaller size in comparison with the waveguiding regions obtained at high energies. As the pulse energy increased, the damaged focal volume increased up to a size of 30 μm measured along the vertically elongated axis. The strained surrounding area is also expected to increase in size, facilitating guiding of light in channels of 3–10 μm in diameter. The formed type I-channels are best confined near the tip of the oval damaged region, indicating that the highest refractive-index contrast is obtained in the regions with highest strain of the crystal lattice. Channel waveguides are created around both tips of the elongated irradiated area, where the compressive strain and the refractive index changes are biggest.

In order to improve the light confinement, we fabricated pairs of parallel fs-laser written lines using the highest pulse energy of 20 μJ and a 25× objective lens, in order to produce efficient lateral barriers for the light that propagates in the pristine, unmodified bulk region between the parallel lines (see

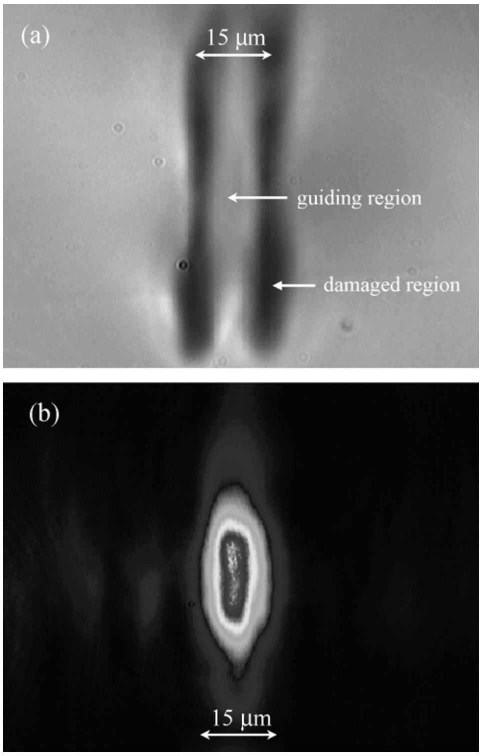

Fig. 2. (a) Pairs of parallel fs-laser written lines with a separation distance of 15 μm between them, in an Yb-doped KYW crystal. (b) Near-field image of 670-nm light out-coupled from such a well-confined channel (of type II) formed between the two lines.

Fig. 2a). Indeed, using a separation distance of 15 μm between the lines in an Yb-doped KYW crystal, single-mode waveguides at 670 nm were obtained. Fig. 2b shows the near-field image of the end facet of such a well-confined channel (of type II).

In order to analyze the guiding properties, we measured the total power losses in the two types of fabricated channel waveguides (shown in Figs. 1 and 2). The laser irradiation of a pigtailed diode at 670 nm was coupled into the single-mode channel waveguides formed in an undoped KYW crystal and the total transmitted power was measured by projecting the out-coupled light onto a powermeter through a 40× objective lens. A normalization measurement was performed without the sample to determine the total loss value (including propagation and coupling). Taking into account the Fresnel losses, the total loss value of the channel waveguide shown in Fig. 1 (of type I) was estimated to be 8.5 dB at 670 nm. If we assume low coupling losses and a $1/\lambda^4$ dependence of scattering losses on wavelength, this value corresponds to ~4 dB/cm at 1 μm. For the well-confined channel (of type II) shown in Fig. 2b, the total power loss amounted to 5.3 dB at 670 nm, corresponding to a propagation loss of ~2.6 dB/cm at 1 μm.

These values were confirmed when measuring only the propagation losses by the streak-of-fluorescence method for the 2% Yb-doped crystals. Fig. 3 shows the Yb fluorescence streak imaged onto a CCD camera placed on top of the type II channel waveguide. The scattered pump light at 981 nm from a

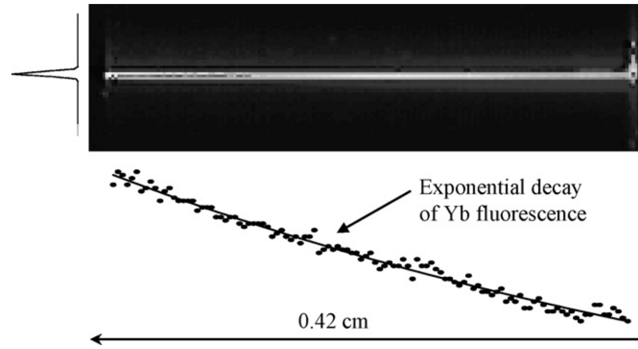

Fig. 3. The Yb fluorescence streak imaged on a CCD camera placed on top of the type II channel waveguide and the exponential decay profile. The loss extracted from the fit for the single-mode channel amounted to a value of 2 dB/cm at 1 μm for a 2% Yb-doped KWW crystal.

Ti:sapphire tunable laser was cut off using a specially designed filter, with >99.9% reflection at 981 nm.

Knowing the pump light absorption during propagation along the waveguide, one can estimate α_{scat} from the equation:

$$I_l = I_{\text{in}} \exp[-(\sigma(\lambda_{\text{p}})N_1 + \alpha_{\text{scat}})l],$$

where I_{in} is the initial coupled intensity, I_l the residual pump intensity after the propagation length l, $\sigma(\lambda_{\text{p}})$ the effective absorption cross-section at the selected pump wavelength, N_1 the ground-state population and α_{scat} is the additional extinction coefficient that corresponds to the waveguide propagation loss.

The decay was fitted by an exponential function, containing one term due to absorption of the 981 nm pump light (according to 2% Yb-doping concentration of the bulk crystal), and one term due to scattering losses. The loss extracted from the fit for the single-mode type II channel amounted to a value of 2 dB/cm at 1 μm.

The direct femtosecond writing of buried channel waveguides in KYW crystals is a highly nonlinear process. The unknown dynamics of the expanding material in the focusing region is determined mainly by the pulse energy and the focusing conditions. A precise control of these two parameters could lead to lower propagation losses for both types of waveguiding channels. Precise tailoring of the shape and size of the modified volume of material, as well as a more uniform distribution of the refractive-index profile may bring the optical propagation losses below 1 dB/cm. This value could be low enough so that complex 3D photonic devices fabricated by this methods to be both efficient and reproducible.

4. Conclusions

We have demonstrated for the first time that fs-laser pulses can be used to fabricate buried channel waveguides in $KY(WO_4)_2$ crystals, both undoped and Yb-doped. We find that optical waveguides cannot be formed in the focal region of the fs-laser beam, but rather in the region surrounding the irradiated region. This behavior is similar to the results reported in crystalline α-quartz [10] and in crystalline Ti^{3+}:sapphire [12], as well as in some heavy-metal oxide glasses [13]. Highly confined buried waveguide channels can be obtained between pairs of parallel fs-laser written lines, with propagation losses as low as 2–2.5 dB/cm. These Yb-doped double tungstate crystals are recognized as very promising materials for solid-state lasers due to their favorable spectroscopic and laser characteristics. Femtosecond laser writing provides the possibility of implementing three-dimensional photonic devices in such crystals.

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