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ABSTRACT

We report on a novel approach to fabricate channel (ridge) waveguides (WGs) in bulk crystals using precision diamond saw dicing. The channels feature a high depth-to-width aspect ratio (deep dicing). The proof-of-the-concept is shown for a Tm:LiYF₄ fluoride crystal. Channels with a depth of 200 µm and widths of 10–50 µm are diced and characterized with a confocal laser microscopy revealing a r.m.s. roughness of the walls of about 1 µm. The passive waveguiding properties of the channels are proven at ~815 nm showing almost no leakage of the guided mode into the bulk crystal volume. The laser operation is achieved in quasi-CW regime. The maximum peak output power reaches 0.68 W at ~1.91 µm with a slope efficiency of 53.3% (in ε-polarization). The laser mode has a vertical stripe intensity profile. The proposed concept is applicable to a variety of laser crystals with different rare-earth dopants and it is promising for sensing applications.

Keywords: waveguide lasers, fluoride crystals, thulium ions, microstructuring, dicing.

1. INTRODUCTION

Fluoride crystals doped with rare-earth ions (RE³⁺) are attractive for development of efficient power-scalable waveguide (WG) lasers emitting in the near-mid-infrared (at the wavelength of ~2 µm and beyond) [1,2]. As host matrices, they provide good thermal properties, broadband transparency, low refractive index and low phonon energies. The latter determines weak non-radiative relaxation and long upper laser level lifetimes of the RE³⁺ ions [3]. An example of efficient fluoride laser material is RE³⁺-doped tetragonal lithium yttrium fluoride crystal, LiYF₄ [4,5]. This material belongs to the tetragonal crystal class and it is optically uniaxial. It offers a single rare-earth site (the Y³⁺ one) and can be doped with the RE³⁺ ions in high concentrations [6].

Nowadays, a common way to produce crystalline RE³⁺-doped LiYF₄ WGs is the Liquid Phase Epitaxy (LPE) [1]. In this way, high optical quality thin crystalline films of RE³⁺:LiYF₄ are achieved on undoped bulk LiYF₄ substrates (resulting in a planar WG geometry). Consequently, a microstructuring step is required to fabricate channel WGs with a well-defined transverse profile of the refractive index leading to the single-transverse-mode operation. One known method of microstructuring of LPE-grown crystalline films is the ion beam milling leading to relatively low propagation losses (~0.11 dB/cm) [7]. However, it is rather complicated from the technological point of view. Recently, we demonstrated the suitability of precision diamond saw dicing for microstructuring of LPE-grown Tm³⁺-doped LiYF₄ crystalline thin-films [8]. A Tm³⁺:LiYF₄ channel WG laser generated 1.30 W at 1880 nm with a slope efficiency of 80% with respect to the absorbed pump power and a low laser threshold of 80 mW. The same approach was also used recently for LPE-grown oxide thin crystalline films [9], indicating its potential for a broad variety of materials.

In the present work, we aimed to extend this technology to direct fabrication of optical WGs in bulk crystals. A special geometry of WGs with a high depth-to-width aspect ratio (referred as deep dicing) was selected. In this way, the mode confinement is expected to be provided by the refractive index contrast at the crystal / air interfaces and an additional refractive index variation due to the photo-elastic effects originating from stresses induced by mechanical dicing.

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So far, precision diamond saw dicing was used for fabrication of optical WGs in polymers with embedded nanoparticles of Er$^{3+}$,Yb$^{3+}$,Ce$^{3+}$:NaYF$_4$ [10]. The optical gain at ~1.5 μm was reported in such microstructures. In [11], diamond saw dicing was used for patterning of Nd$^{3+}$:α-Al$_2$O$_3$ (sapphire) films produced by pulsed laser deposition. The WG laser generated 322 mW at 1092 nm with a slope efficiency of only ~12% probably due to high scattering losses of 6 dB/cm. In [12], the authors fabricated ridge WGs in bulk Nd$_3$Al$_5$O$_{12}$ single crystals subjected to swift heavy ion irradiation extracting 84 mW at 1064 nm with a slope efficiency of 43% and a propagation loss of 1.7 dB/cm. Finally, WGs in irradiated LiNbO$_3$ and KTiOPO$_4$ crystals were also fabricated by diamond saw dicing [13-15], featuring WG propagation losses of ~1 dB/cm. These structures were used for second-harmonic generation leading to green emission.

High aspect ratio (e.g., top width: 1 μm, depth: 500 μm) WGs were reported in lithium niobate [13].

2. FABRICATION OF WAVEGUIDES

2.1 Diamond saw dicing

As a reference material for proof-of-the-concept, we selected the tetragonal (sp. gr. $I4_1/a$) Tm$^{3+}$:LiYF$_4$ crystal. It was grown by the conventional Czochralski (Cz) method and doped with 4 at.% Tm ($N_{\text{Tm}} = 5.50 \times 10^{20}$ cm$^{-3}$). A rectangular sample was cut along for light propagation the $a$-axis ($a$-cut) with a thickness ($t$) of 7.0 mm and an aperture of 3.5×10 mm$^2$. The input and output faces and the top surface of the crystal were polished to laser quality and remained uncoated.

Then, the top surface was subjected to precision diamond saw dicing resulting in fabrication of surface channels (ridges) with a depth of 200 μm and a varied width of 10–50 μm (with a step of 10 μm). The channels propagated through the whole length of the sample. For this purpose, very low grit sized blades where selected and many calibration processes occurred to ensure the dimensions of ridges. The channels were separated by about 500 μm. The end-facets of the crystal sample were not repolished after the dicing.

![Figure 1. Scheme of the deep diced ridge WGs in bulk Tm$^{3+}$:LiYF$_4$ crystal.](https://photonicsforenergy.spiedigitallibrary.org/conference-proceedings-of-spie)

The quality and geometry of channels were inspected with a confocal laser microscope (Sensofar S-neox) equipped with a blue light-emitting diode (LED, $\lambda = 405$ nm), Fig. 2. This study revealed well preserved quality of the end-facets and the top surface of the sample. The ridges have smooth side walls and a nearly rectangular transverse profile with only a...
small rounding in the bottom part. There are no cutting debris in the diced areas and no cracks in the ridges and in the bulk part of the sample. The r.m.s. surface roughness of the channel walls was well below 1 μm.

2.2 Waveguiding properties

The passive waveguiding properties of the fabricated channels were studied at the wavelength of ~815 nm. It is close to the pump wavelength for Tm³⁺:LiYF₄ (780 nm, the ³H₆ → ³H₄ Tm³⁺ transition). As a laser source, we used a Ti:sapphire laser (3900S, Spectra Physics). Its output was focused into the WGs using an uncoated CaF₂ lens (f = 40 mm) resulting in a measured spot size ²w of ~30 μm (at the 1/e² level). The mode profile in the near field was measured using a short focal length CaF₂ lens (f = 15 mm) and a CCD camera (BladeCam-XHR, DataRay Inc.). The polarization of the laser beam in the crystal corresponded to π (E || e, vertical). The scale calibration was provided by illuminating the WG using an IR light source.

The guided modes had a vertical stripe intensity profile well confined within the cross-section of the channel, Fig. 3. No leakage of the guided modes into the bulk crystal volume was detected. For the WGs with the widths of 30–50 μm, the beam was spatially multimode along both the vertical and horizontal directions. For smaller WGs (10–20 μm), a single vertical stripe was detected (representing a kind of a rotated planar WG geometry).

![Figure 3. 2D intensity profiles of the guided pump mode at the output WG facet: the WG width is (a) 30 μm and (b) 50 μm.](image)

Under pumping at 780 nm, the channels provided an intense polarized luminescence at ~1.9 μm due to the ³F₄ → ³H₆ Tm³⁺ transition. The spectral properties were similar to those of the bulk crystal.

3. LASER OPERATION

3.1 Laser set-up

The scheme of the WG laser is shown in Fig. 4(a). As a pump source, we used a CW Ti:Sapphire laser delivering about 3.2 W of linearly polarized output at 780 nm in a fundamental mode (M² ≈ 1). This wavelength corresponded to the local peak in the absorption spectrum of Tm³⁺:LiYF₄ crystal (the ³H₆ → ³H₄ Tm³⁺ transition). The pump polarization was set to be vertical (π-polarization in the crystal). The incident pump power was varied by a rotatory λ/2 plate and a Glan-Taylor polarizer. The pump beam was focused by an uncoated CaF₂ lens (f = 40 mm, T = 93.8%) providing a pump spot diameter at the input face of the WG ²wp of 30 μm. For quasi-CW pumping, the pump beam was modulated using a mechanical chopper (frequency: 10 Hz, duty cycles ranging from 1:2 to 1:12).

![Figure 4. (a) Scheme of the waveguide laser set-up: λ/2 – half-wave plate, P – Glan-Taylor polarizer, FL and CL – focusing and collimating lenses, respectively, PM – pump mirror, OC – output coupler, F – cut-off filter; (b) top view photograph of the 50 μm wide WG pumped at 780 nm, Pinc = 1.0 W, the bright trace corresponds to Tm³⁺ upconversion luminescence.](image)
The Tm$^{3+}$:LiYF$_4$ crystal with the surface guides was mounted on a Cu-holder using a silver paste to improve the thermal contact from the bottom part of the sample. The crystal was placed in a simple linear plano-plano cavity. It was formed by a flat pump mirror (PM) coated for high transmission (HT, $T = 99.4\%$) at $\sim$0.78 μm and for high reflection (HR, $R > 99.9\%$) at 1.60–2.02 μm, and a set of flat output couplers (OCs) with a transmission at the laser wavelength $T_{OC}$ ranging from 2% to 50%. Both cavity mirrors were gently pressed towards the WG end-facets. No index-matching liquid was used. The geometrical cavity length was 7.0 mm. The pump beam was focused into the WGs through the PM.

The laser threshold was at $P_{th} = 381$ mW for the 50 μm wide WG. The pump coupling efficiency $\eta_{coup} = P_{launch}/P_{inc}$ ($P_{launch}$ is the launched pump power) was determined by coupling into the WGs the laser beam from the Ti:Sapphire laser tuned to 830 nm (out of the Tm$^{3+}$ absorption band) and monitoring the power at the output facet. We determined $\eta_{coup}$ for all WGs and, as expected, it decreased for smaller widths of the guides, namely from $\eta_{coup} = 77.9\%$ for the 50 μm wide WG down to 13.2% for the 10 μm wide one. This value includes the Fresnel losses at the uncoated input facet of the crystal ($T_{Fr} = 96.4\%$, as calculated using a refractive index of LiYF$_4$: $n_e = 1.4722$ at 830 nm), as well as the propagation losses in the WG $\delta_{loss}$. An upper estimation for $\delta_{loss}$ can be obtained by subtracting the Fresnel factor, e.g., $\delta_{loss} \leq 1.3 \pm 0.1$ dB/cm for the 50 μm WG.

For the 4 at.% Tm:LiYF$_4$ crystal, the small-signal pump absorption $\eta_{abs,0}$ at 780 nm is close to unity. Indeed, $\eta_{abs,0} = 1 - \exp (-\delta_{abs,NL}) = 96.2\%$, where $\delta_{abs} = 0.85 \times 10^{-20}$ cm$^2$ is the absorption cross-section at the pump wavelength $\lambda_p$ for $\pi$-polarized light. The pump absorption under non-lasing conditions, $\eta_{abs,NL} = P_{abs}/P_{launch}$ ($P_{abs}$ – absorbed pump power) was determined from the pump-transmission (end-fire) measurements, see Fig. 5 for the particular case of the 50 μm wide WG. $\eta_{abs,NL}$ slowly decreased with the incident pump power due to the ground-state bleaching. For estimating the absorbed pump power under lasing conditions $P_{abs}$, we have taken the $\eta_{abs,NL}$ at the laser threshold (for each of the studied OCs). For example, for the 50 μm wide WG, the pump absorption slightly decreased from 91.4% for $T_{OC} = 2\%$ down to 90.4% for the highest studied $T_{OC} = 50\%$.

![Figure 5. Measured pump absorption under non-lasing conditions, $\eta_{abs,NL}$, in a 50 μm wide ridge WG in 4 at.% Tm$^{3+}$:LiYF$_4$ as a function of the incident pump power.](https://photonicsforenergy.spiedigitallibrary.org/conference-proceedings-of-spie)

To filter out the residual (non-absorbed) pump after the OC, a long-pass filter (FEL900, Thorlabs) was used. The laser emission spectra were measured using an optical spectrum analyzer (AQ6375B, Yokogawa).

### 3.2 Laser performance

The laser operation was achieved for all the WGs. The experiments were first performed in quasi-CW regime (duty cycle: 1:2) to diminish the thermal effects in thin passively-cooled ridges. The input-output dependences for the largest studied WG (width: 50 μm) are shown in Fig. 6(a). For $T_{OC} = 50\%$, the laser generated a maximum output peak power of 381 mW at 1901-1929 nm (a broad emission spectrum) with a slope efficiency $\eta$ of 42.2% with respect to the absorbed pump power. The laser threshold was at $P_{th} = 0.25$ W and the optical-to-optical efficiency $\eta_{opt}$ was 18.6% (as calculated vs. the pump power incident on the guide). For smaller output coupling, the laser threshold gradually decreased reaching $P_{th} = 0.16$ W for $T_{OC} = 2\%$. For $P_{abs}$ exceeding ~1 W, a thermal roll-over was observed in the input-output dependences. Thus, $P_{abs}$ was limited to about 1.5 W to avoid thermal fracture of the guides.

The typical spectra of laser emission for various transmissions of the output coupler are shown in Fig. 6(b). For all the OCs, the laser emission was linearly polarized ($\sigma$); the polarization was naturally selected by the gain anisotropy. The emission occurred at around ~1.91 μm for all OCs in agreement with the gain spectra of Tm$^{3+}$:LiYF$_4$ for $\sigma$-polarization and high inversion ratios [3].

Note that for the same output coupling ($T_{OC} = 50\%$), the polarization state of the output mode changed with the width of the guides: it was $\sigma$ for larger WGs (30–50 μm) and $\pi$ for smaller ones (10–20 μm). The laser emission was observed at...
the wavelengths around ~1.91 μm and 1.88 μm, respectively. This is assigned to higher propagation losses for the WGs with a smaller width.

![Figure 6](image_url)

**Figure 6.** Deep-diced Tm$^{3+}$:LiYF$_4$ ridge waveguide laser: (a) input-output dependences, $\eta$ – slope efficiency; (b) typical laser emission spectra measured at $P_{\text{abs}}$ ~ 1.0 W. Quasi-CW regime of operation with a duty cycle of 1:2. The channel width is 50 μm. The laser polarization is $\sigma$.

To verify our consideration about the thermal effects in the guides, we studied the laser performance of the 50 μm WG with the same output coupling ($T_{\text{OC}} = 50\%$) but under different pump regimes, ranging from true CW to quasi-CW with various pump duty cycles (between 1:2 to 1:12), see Fig. 7. The CW laser generated only 34 mW and the lasing was ceased for $P_{\text{abs}} > 0.5$ W. For the quasi-CW operation regimes with decreasing the duty cycle down to 1:12 (thus reducing the heat loading), the input-output dependence gradually approached the linear one, so that the power scaling was limited only by the available pump. For the 1:12 duty cycle, the maximum peak output power reached 684 mW with $\eta = 53.3\%$. Note that the laser threshold was almost independent on the pump modulation. This value of the slope efficiency exceeds the Stokes limit under lasing conditions, $\eta_{\text{St,L}} = \lambda_P/\lambda_L = 40.8\%$ ($\lambda_L \sim$1910 nm is the laser wavelength) indicating the action of cross-relaxation for adjacent Tm$^{3+}$ ions increasing the pump quantum efficiency.

![Figure 7](image_url)

**Figure 7.** Evidence of thermal effects in deep-diced Tm$^{3+}$:LiYF$_4$ ridge waveguide laser: input-output dependences measured for true CW and quasi-CW operation regimes. WG with a width of 50 μm, $T_{\text{OC}} = 50\%$. $\eta$ – slope efficiency for the duty cycle of 1:12.

### 4. CONCLUSIONS

To conclude, we report on a novel approach to fabricate ridge WGs with a large surface area in bulk fluoride crystals. The performance of such deep-diced WGs in the case of Tm$^{3+}$:LiYF$_4$ can be improved by better thermal management, e.g., by applying active cooling. Other strategies may involve using higher Tm$^{3+}$ doping levels for more efficient cross-relaxation reaching a pump quantum efficiency of 2 (for the conventional pumping at ~780 nm) or employing in-band pumping directly to the $^3F_4$ upper laser level [16]. A single-transverse-mode operation is expected with a proper design of the geometrical profile of the channels. The proposed concept is applicable to a variety of laser crystals with different RE$^{3+}$ dopants. Regarding fluoride crystals, the proposed methodology of deep diamond saw dicing can be easily applied to materials for which the LPE is still poorly developed, e.g., calcium fluoride (CaF$_2$) [17]. It is also useful for passive WGs for sensing applications through evanescent-field coupling, as the diced canals can be filled with a liquid.
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