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Efficient Broadly Tunable Waveguide Lasers in $\text{Yb}^{3+}:\text{CaF}_2$ Produced by Deep Diamond Saw Dicing

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Abstract: High-aspect-ratio ridge waveguides (propagation losses: 0.13 ± 0.05 dB/cm) were fabricated in $\text{Yb}^{3+}:\text{CaF}_2$ by diamond-saw-dicing. The waveguide laser generated 723 mW at 1029-1051 nm with a slope efficiency of 76.0%; wavelength tuning between 1009-1072 nm was achieved. © 2020 The Author(s)

Ytterbium (Yb^{3+}) doped calcium fluoride (CaF_2) is an attractive laser material [1]. The host matrix provides high thermal conductivity ($\sim 9.7 \text{ W m}^{-1} \text{ K}^{-1}$), isotropic thermal expansion, negative thermal lensing and low refractive index ($n = 1.429$ at $\sim 1 \mu\text{m}$). CaF_2 can be easily doped with Yb^{3+} and it features strong ion clustering already at low doping levels (above 0.1 at.%) resulting in significant inhomogeneous broadening of spectral bands (a glassy-like spectroscopic behavior) [2]. The smooth and broad gain spectra of $\text{Yb}^{3+}:\text{CaF}_2$ determine its potential for broadband wavelength tuning and especially generation of femtosecond pulses in mode-locked oscillators at $\sim 1 \mu\text{m}$ [1].

So far, little attention was paid to the development of $\text{Yb}^{3+}:\text{CaF}_2$ waveguide (WG) lasers [3,4]. Ren *et al.* fabricated buried channel WGs in $\text{Yb}^{3+}, \text{Na}^+:\text{CaF}_2$ by ultrafast laser inscription and achieved 174 mW at $\sim 1.01 \mu\text{m}$ with an optical-to-optical efficiency of 45.3% [4]. In the present work, we report on highly-efficient and wavelength-tunable WG lasers fabricated using diamond saw dicing [5] of bulk $\text{Yb}^{3+}:\text{CaF}_2$ crystals.

High aspect ratio (height: 200 μm , width: 10-50 μm) surface channel (ridge) WGs were produced in a bulk 4.5 at.% $\text{Yb}^{3+}:\text{CaF}_2$ crystal by “deep” diamond saw dicing, Fig. 1(a). The guides exhibited no chipping at the facets nor cracks, as well as good verticality of the side walls. The r.m.s. surface roughness of the latter studied using a confocal microscope in an interferometric mode was 0.5 nm, Fig. 1(b). The WG propagation loss δ_{loss} increased for narrower guides, from 0.17 dB/cm for the 50 μm wide guide up to 0.52 dB/cm for the 10 μm wide one (for vertical polarization, at 0.91 μm).

The laser operation was studied in the continuous-wave (CW) regime using a plano-plano cavity. It was formed by a pump mirror (PM) coated for HT at 0.88-0.99 μm and for HR at 1.02-1.20 μm , and a set of output couplers (OCs) having a transmission T_{OC} in the range of 2% - 50% at 1.0-1.1 μm . The $\text{Yb}^{3+}:\text{CaF}_2$ sample containing the WGs was mounted on a Cu-holder and it was passively cooled. As a pump source, we employed a CW Ti:Sapphire laser emitting at 979.5 nm in the fundamental mode ($M^2 \approx 1$) with linear polarization (vertical). Its output was focused using a spherical CaF_2 lens ($f = 40$ mm). For the 40 μm wide WG, the pump coupling efficiency η_{coupl} was 74.2%. With increasing the output coupling, the pump absorption under lasing conditions $\eta_{\text{abs,L}}$ decreased from 92.7% ($T_{\text{OC}} = 1\%$) to 68.2% ($T_{\text{OC}} = 50\%$).

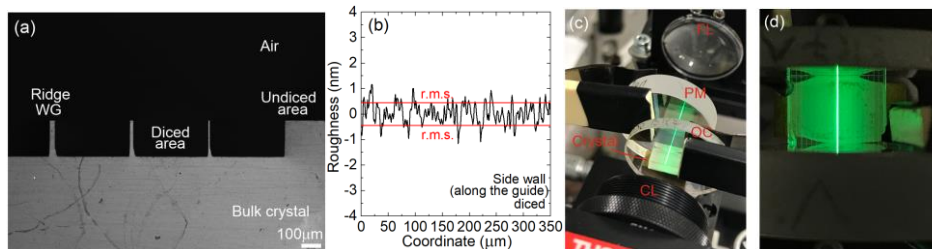


Fig. 1. (a) Confocal laser microscopy image of an end-facet of a 4.5 at.% $\text{Yb}^{3+}:\text{CaF}_2$ sample containing ridge waveguides, bright field, reflection mode, $\lambda = 405$ nm; (b) roughness profile for one of the WG side walls (diced); (c) photograph of the waveguide laser: PM – pump mirror, OC – output coupler, FL and CL – focusing and collimating lenses, respectively; (d) top view photograph of the pumped guide.

The laser performance of the 40 μm wide guide for the pump wavelength of 979.5 nm corresponding to the zero-phonon-line of Yb^{3+} ions in CaF_2 is shown in Fig. 2(a,b). The laser generated a maximum output power of 723 mW at 1029-1051 nm with a slope efficiency η of 76.0% (*vs.* the absorbed pump power) and a laser threshold of 165 mW (for $T_{\text{OC}} = 20\%$). The maximum optical-to-optical efficiency *vs.* the pump power incident on the crystal η_{opt} was 38.9%. With increasing the output coupling, the laser threshold gradually increased, from 52 mW ($T_{\text{OC}} = 1\%$) to 394 mW ($T_{\text{OC}} = 50\%$).

= 50%). No lasing was achieved when pumping into the bulk area of the sample. With increasing the output coupling, the central emission wavelength experienced a slight blue-shift, from ~1048 nm ($T_{OC} = 1\%$) to ~1029 nm ($T_{OC} = 50\%$), Fig. 2(a). The observed laser efficiencies were analyzed using the Caird approach, i.e., with the formula $1/\eta = 1/\eta_0(1 + 2\gamma/\gamma_{OC})$ where γ is the loss coefficient and γ_{OC} is the output-coupling loss, yielding the intrinsic slope efficiency η_0 of $75.0 \pm 4\%$ and δ_{loss} of 0.13 ± 0.05 dB/cm, Fig. 2(c). The laser mode was localized near the top part of the guide and it was elliptical, Fig. 2(d). The measured beam quality factors were $M^2_x = 1.05 \pm 0.05$ and $M^2_y = 1.3 \pm 0.1$.

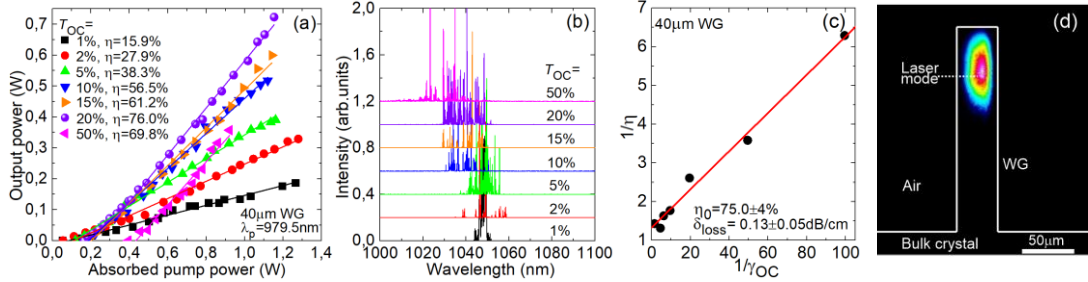


Fig. 2. Laser performance of the deep-diced $\text{Yb}^{3+}:\text{CaF}_2$ waveguide (width: $40 \mu\text{m}$): (a) input-output dependences, η – slope efficiency; (b) typical spectra of laser emission measured at maximum P_{abs} ; (c) Caird analysis of propagation losses; (d) near-field profile of the laser mode, $T_{OC} = 20\%$, $P_{\text{abs}} \sim 0.5$ W. Pump polarization: vertical, $\lambda_p = 979.5$ nm. In (c), white lines mark the air / crystal interfaces.

To demonstrate wavelength tuning of the $\text{Yb}^{3+}:\text{CaF}_2$ WG laser, the flat OC was replaced by a concave one (RoC = -100 mm) with $T_{OC} = 2\%$ resulting in a nearly hemispherical cavity. As a tuning element, we used an uncoated quartz birefringent plate with the optical axis lying in the plane of the plate. It was placed at the Brewster angle near the output facet of the sample. A continuous wavelength tuning between 1009.2 and 1072.4 nm was demonstrated, Fig. 3. This corresponded to a tuning range of ~63 nm. The maximum of the tuning curve was observed at ~1052 nm corresponding to an output power of 118 mW.

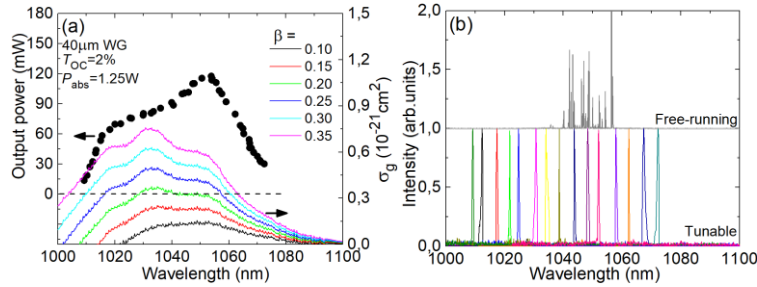


Fig. 3. Tunable deep-diced $\text{Yb}^{3+}:\text{CaF}_2$ ridge waveguide laser (WG width: $40 \mu\text{m}$): (a) tunability curve, $T_{OC} = 2\%$, $P_{\text{abs}} = 1.25$ W, the gain cross-section, σ_g , spectra for several inversion ratios $\beta = N_2(^2F_{5/2})/N_{\text{Yb}}$ are shown for comparison; (b) typical spectra of laser emission from the tunable laser; the spectrum for the free-running laser is shown for comparison.

To conclude, deep diamond saw dicing is a powerful approach to fabricate ridge WGs in bulk $\text{Yb}^{3+}:\text{CaF}_2$ crystals. Such guides ensure low propagation losses (down to 0.13 ± 0.05 dB/cm at $\sim 1 \mu\text{m}$), small surface roughness and good verticality of the side walls and the lack of cracking / chipping. No post-processing polishing is required for the ridges. The combination of good thermal properties of CaF_2 with the broadband emission of Yb^{3+} ions determine the power scaling capabilities of deep-diced $\text{Yb}^{3+}:\text{CaF}_2$ WG lasers, as well as the broadband wavelength tuning. The fabricated guides are promising for compact mode-locked oscillators at $\sim 1 \mu\text{m}$ operating at high repetition rates (GHz-range).

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