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Femtosecond laser written waveguides in Dy-doped $Y_3Al_5O_{12}$ for yellow lasers

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Abstract. Depressed cladding waveguides in a Dy:YAG crystal were fabricated by femtosecond direct laser writing. Their μ-luminescence characterization in the visible revealed well-preserved emission properties in the core region, a strong material modification within the damage tracks, and an anisotropic stress field associated with ear-like side structures. The developed waveguides are promising for yellow lasers.

1 Introduction

Among the rare-earths ions exhibiting luminescence in the visible, trivalent dysprosium (Dy^{3+}) is of particular interest for yellow lasers according to the $^4F_{9/2} \rightarrow {}^6H_{13/2}$ transition [1]. One of the main difficulties in developing yellow Dy-lasers comprises of weak absorption of Dy^{3+} in the blue as the corresponding transitions are spin-forbidden ($\Delta S \neq 0$). This problem can be overcome within guided wave configurations, *e.g.*, in fiber or waveguide (WG) lasers [2]. WG lasers fabricated in bulk crystals benefit from good thermal management and monolithic design. They offer high light intensities leading to low laser thresholds, good pump / laser mode overlap, and high laser efficiencies. Femtosecond direct laser writing (DLW) is a powerful method for fabricating 3D photonic microstructures in transparent dielectric crystals [3]. This technique is based on creating a thermally stable, localized material modification within the irradiated area with a controlled change of the refractive index (usually, $\Delta n < 0$ in oxide crystals). It features high precision, and reasonable propagation losses. Visible WG lasers based on DLW have been demonstrated [4]. Yttrium aluminum garnet ($Y_3Al_5O_{12}$, YAG) is a state-of-the-art laser host crystal for rare-earth doping. It combines good thermo-mechanical properties and an attractive spectroscopic behavior of the dopant ions. Laser action in the yellow using Dy:YAG crystals was achieved [5]. However, so far, laser-active Dy waveguides have never been exploited. In the present work, we report on the fabrication of depressed cladding waveguides in Dy:YAG crystals by DLW and their μ-luminescence study with the goal of developing yellow lasers.

2 Dy^{3+} ion spectroscopy

The spectroscopic properties of Dy^{3+} ions in YAG were first revisited. The absorption cross-section, σ_{abs}, spectrum in the blue spectral range is presented in Fig. 2(b). It presents peaks related to the spin-forbidden $^6H_{15/2} \rightarrow {}^4I_{15/2}$ and $^6H_{15/2} \rightarrow {}^4F_{9/2}$ transitions. The maximum σ_{abs} is 0.51×10^{-20} cm^2 at 447.4 nm corresponding to an absorption bandwidth of 1.0 nm (FWHM), in the spectral range well addressed by blue GaN laser diodes.

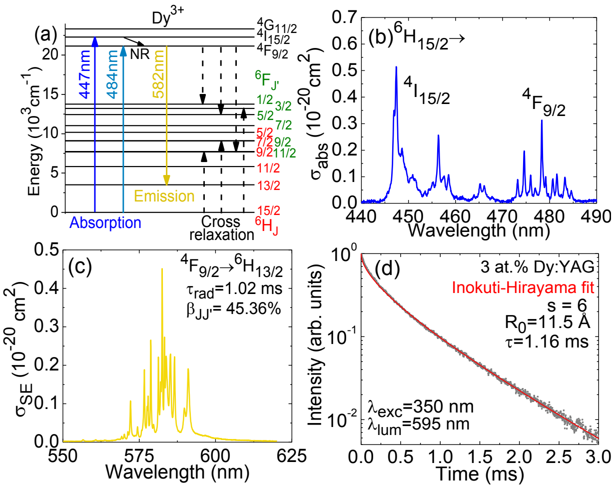

Fig. 1. Spectroscopy of Dy^{3+} ions: (a) Energy-level scheme of Dy^{3+}; (b) Absorption cross-sections, σ_{abs}, in the blue spectral range; (c) stimulated-emission (SE) cross-sections, σ_{SE}, for the $^4F_{9/2} \rightarrow {}^6H_{13/2}$ transition in the yellow; (d) luminescence decay curve from the $^4F_{9/2}$ state in the 3 at.% Dy:YAG crystal, *circles* – experimental data, *curve* – Inokuti-Hirayama fit.

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The stimulated emission (SE) cross-sections, σ_{SE}, for the $^4F_{9/2} \rightarrow {}^6H_{13/2}$ transition in the yellow were calculated via the Füchtbauer-Ladenburg equation, Fig. 1(c). The values of the radiative lifetime of the $^4F_{9/2}$ state (τ_{rad} = 1.02 ms) and the luminescence branching ratio ($\beta_{JJ'}$ = 45.36%) obtained by the Judd-Ofelt theory [6] were used. The peak σ_{SE} is 0.45×10^{-20} cm^2 at 582.5 nm and the corresponding emission linewidth is 0.3 nm (FWHM). The luminescence decay curve from the $^4F_{9/2}$ manifold measured for the 3 at.% Dy^{3+}-doped crystal is shown in Fig. 1(d). It clearly deviates from a single-exponential law due to the cross-relaxation processes between Dy^{3+} ions, see Fig. 1(a). The decay curve was fitted by the Inokuti-Hirayama model for multipolar interactions. The fit indicated dipole-dipole interactions (s = 6), a critical radius R_0 of 11.5 Å and an intrinsic lifetime τ_0 of 1.16 ms. The critical radius represents the distance at which the probability of energy transfer between two Dy^{3+} ions is equivalent to the probability of radiative relaxation.

3 Waveguide characterization

Depressed-cladding (type III) WGs were fabricated in a bulk 3 at.% Dy:YAG single-crystal by DLW. The crystal had a rectangular shape with an aperture of 2.76×2.78 mm^2 and a length of 24.8 mm. It exhibited bright yellow luminescence under UV light illumination, Fig. 2(a). The WG inscription was performed using a Ti:sapphire regenerative amplifier delivering 120 fs / 84 nJ pulses at 795 nm at 1 kHz repetition rate. The wiring optics comprised a 40× microscope objective. The sample translation speed was 650 µm/s, and the track separation - 2 µm. The circular WG cladding had a diameter of 50 µm with ear-like side structures improving light confinement and inducing an anisotropic polarization response of the WG, Fig. 2(b). The damage tracks were continuous along the entire length of the sample.

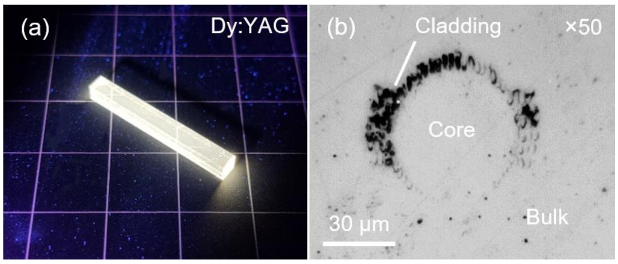

Fig. 2. (a) A photograph of the Dy:YAG sample under UV lamp illumination; (b) A confocal microscope image of the end-facet revealing the femtosecond laser written waveguide.

To characterize the material modification in the irradiated areas of the micromachined WG, a µ-luminescence study was carried out using a Renishaw inVia Reflex confocal laser microscope equipped with a 457 nm Argon laser and a 50× Leica microscope objective. The spatial resolution was 0.5 µm. Three different areas were considered: i) bulk (unmodified) region, ii) a damage track (cladding) and iii) WG core, Fig. 3. The µ-luminescence mapping reveals a decrease in intensity, a red-shift in the peak position and a peak broadening for yellow luminescence of Dy^{3+} ions within the damage tracks indicating a certain loss of crystallinity (a partial amorphization) in this area. In the core area, the emission properties are nearly unchanged. Figure 3(b) also reveals an anisotropic stress field clearly associated with the ear-like side structures. It is expected to affect the polarization response of the WG.

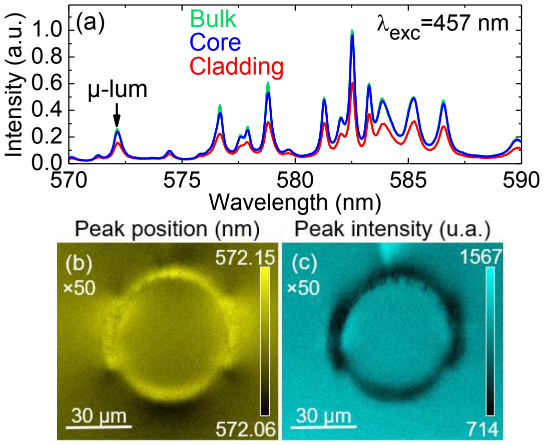

Fig. 3. µ-luminescence study of the depressed cladding buried waveguide in Dy:YAG: (a) emission spectra in the yellow from the bulk (unmodified), core and cladding areas, *arrow* - the peak selected for mapping; (b,c) µ-luminescence maps analyzing (b) the peak position and (c) the peak intensity, λ_{exc} = 457 nm.

4 Conclusion

To conclude, by employing femtosecond direct laser writing, we successfully fabricated depressed cladding waveguides in bulk Dy:YAG crystals featuring intense yellow emission under blue excitation with envisioned polarization response owing to the ear-like side structures. Further work will focus on laser experiments.

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