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Channel waveguides preserving luminescence features in Nd^{3+}:Y_2O_3 ceramics produced by ultrafast laser inscription

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We report on the Nd^{3+}:Y_2O_3 ceramic optical channel waveguides produced by ultrafast laser inscription with a "double-line" scheme. The confocal micro-luminescence images reveal that the original fluorescence emission properties have not been affected by the laser filamentation, which means the original luminescence features have been well preserved in the waveguide volumes. The fabricated micro-photonic structures emerge as promising candidates for integrated laser sources.

1 Introduction Recently transparent ceramics have emerged as promising gain media for high-power solid state lasers [1–10]. Among the host materials, neodymium (Nd) doped $Y_3Al_5O_{12}$ (YAG) transparent ceramics are one of the most promising candidates, and some really excellent works on Nd^{3+}:YAG ceramics have been reported until now [6–8]. At the same time, rare earth ion doped yttria (Re:Y_2O_3), with high melting point (above 2400 °C), high thermal conductivity and excellent laser performance, is also an attractive laser gain medium of special relevance for the development of high-power and ultrashort pulsed lasers [9, 10]. Indeed, highly efficient continuous wave (cw) and pulsed lasers have been reported for neodymium (Nd) or yttrium (Yb) doped Y_2O_3 based oscillating systems [11–15].

Optical waveguides confine light propagation in very small volumes, in which much high optical intensity could be reached. Waveguides in gain media have attracted much attention owing to the compressed active volumes; that open the possibility of the development of low-threshold and high efficient integrated lasers devices. Among all the techniques developed for waveguide fabrication, direct ultrafast laser inscription (ULI) has shown its wide capability for diverse transparent materials for various guiding devices [16–23]. Particularly, by using ultrafast laser inscription (mostly referring to femtosecond (fs) pulses), single-mode waveguides could be easily obtained with relatively low propagation losses [16]. For ceramics, high-quality channel waveguides in Nd^{3+}:YAG ceramics have been successfully produced and highly efficient waveguide lasers have been realized [6–8]. In this work, we report on the fabrication of the first channel waveguide structure in Nd^{3+}:Y_2O_3 ceramic, and show its potential application as laser gain medium.

2 Experimental details The Nd^{3+}:Y_2O_3 ceramic (doped by 2 at.% Nd^{3+} ions, obtained from Baikowski Ltd., Japan) wafers are cut with sizes of 3 × 4 × 8 mm^3 and optically polished. The buried waveguide is fabricated by using the well-known "double line" technique. The laser beam from an amplified Ti:sapphire laser system (100 fs pulses at 800 nm, with 1 kHz repetition rate) is focused by a 20× microscope objective (N.A. = 0.5), and scans the Nd^{3+}:Y_2O_3 ceramic through a three-dimensional motorized sample stage (spatial resolution ~0.2 μm). The linear focus of the objective is located at 150 μm below surface, and two laser filaments (with lateral separation of ~15 μm) are written by translating the sample with a speed of

15 μm/s. The writing pulses' energy at the target is about 0.6 μJ.

The transmission properties of the fabricated waveguides are characterized by using an end-face arrangement at 632.8 nm. Based on the same end-face coupling setup, the propagation loss of the waveguide is measured by the Fabry–Perot resonance method [24].

The confocal micro-photoluminescence (μPL) spectra are obtained by using an Olympus BX-41 fibre-coupled confocal microscope. An argon laser offers 10 mW of continuous wave 488 nm radiation, which is focused into the sample by using a 100× UPlanSApo immersion oil objective with N.A. of 1.4. The back-scattered luminescence signals are collected with the same objective and, after passing blocking filters and a confocal aperture, it was fibre-coupled to a spectrometer.

3 Results and discussion Figure 1(a) shows the optical transmission microscope image of the waveguide cross section, clearly denoting the presence of two laser tracks. We use an end-face coupling system (at 632.8 nm) to measure the guided modes of the $Nd^{3+}:Y_2O_3$ waveguide. Similar to the reported waveguides in other materials by this method [8], the guided modes (Fig. 1(b) and (c) for TE and TM modes, respectively) are located in the waveguide volume between the two filaments, in which the refractive index is increased due to the stress-induced lattice compression. Figure 2 depicts a typical output intensity spectrum (transmitted light intensity vs. the heating time) obtained from the channel waveguide through the Fabry–Perot method [24]. We evaluated that the propagation loss of the ULI waveguide fabricated in $Nd^{3+}:Y_2O_3$ ceramics is around 5 dB/cm. The optical losses depend on the laser parameters and the focusing conditions during the writing process [22, 23]. Lower losses are expected by optimizing the writing process, such as, changing the translation speed, pulse duration, laser polarization, N.A. of the focusing objective.

Figure 3 shows the comparison of the Nd^{3+} fluorescence emission spectra of the $^4F_{3/2} \rightarrow {}^4I_{9/2}$ laser emission obtained from the waveguide, filaments and bulk. We found that, in the waveguide region, the intensity of the

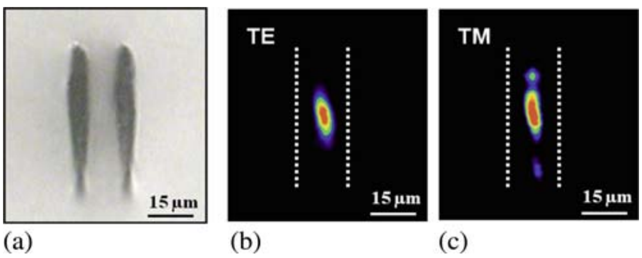

Figure 1 (online colour at: www.pss-rapid.com) (a) Optical transmission micrograph of the "double-line" $Nd:Y_2O_3$ waveguide. Measured near-field intensity distribution of the fundamental (b) TE and (c) TM mode.

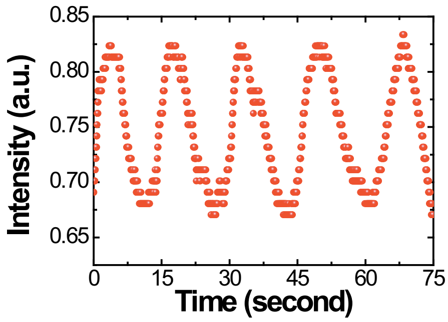

Figure 2 (online colour at: www.pss-rapid.com) Relative intensity of the transmitted light versus heating time obtained from the ULI waveguide in $Nd^{3+}:Y_2O_3$ ceramics at wavelength of 632.8 nm.

emitted fluorescence signals reaches 90% of the bulk values, whilst it decreases down to 70% at the filaments. This means that the original PL features have been well preserved in the waveguide, which suggests potential applications of the $Nd^{3+}:Y_2O_3$ system for laser generation.

We measured the fluorescence images of the waveguide's cross section by analyzing the spatial variation of the fluorescence properties of the hyper-sensitive 892 nm emission line. Figure 4(a) and (b) show the obtained 2D μ-PL images based on the spatial distribution of the intensity, and spectral shift of this emission line, respectively. In order to give a clear presentation, we also provide the linear profiles as obtained along the dashed lines (vertical scan crossing both damage tracks through their middle point). As one can see from Fig. 4(a) and (c), clear fluorescence quenching occurs in the filaments whilst in the waveguide volumes (between the two damage tracks) the fluorescent features are well preserved with respect to the bulk (in good accordance with the results of Fig. 3). Figure 4(b) and (d) clearly denote that the emission line has been shifted to larger energies at the damage tracks whereas it suffers a slight red-shift in their surroundings. Such spectral shifts suggest that different structural modifications have been induced at filaments and in their sur-

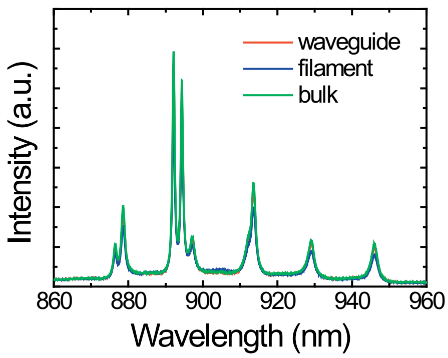

Figure 3 (online colour at: www.pss-rapid.com) Comparison of the room temperature micro-photoluminescence spectra corresponding to Nd^{3+} ions at $^4F_{3/2} \rightarrow {}^4I_{9/2}$ transition obtained after 488 nm excitation at the waveguide, filament and bulk.

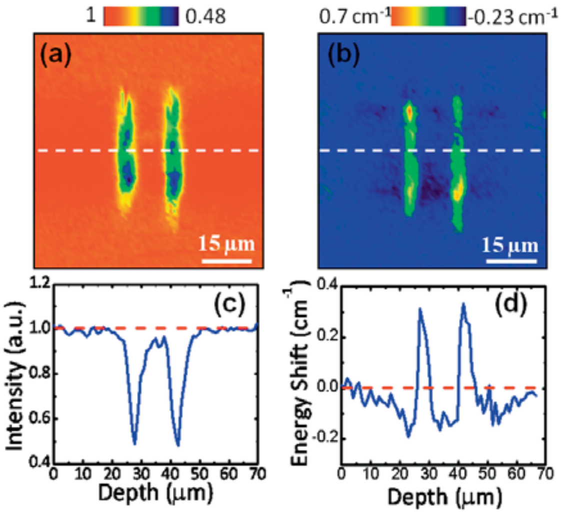

Figure 4 (online colour at: www.pss-rapid.com) Spatial distribution of the (a) emitted intensity and (b) spectral shift of the Nd^{3+} emission line at around 892 nm as obtained from the $Nd^{3+}:Y_2O_3$ ceramic end face. (c) and (d) are the corresponding profiles of the selected white lines in the above pictures (a) and (b), respectively.

roundings. This is, indeed, at opposite to the case of ULI waveguides fabricated in Nd^{3+}:YAG ceramics. In that case the YAG network was compressed at the filaments and between them [8]. Data of Fig. 4 clearly indicates that in the particular case of $Nd^{3+}:Y_2O_3$ ceramic, the structural modification induced at damage tracks is completely different to that induced at the waveguide volume. A similar effect was observed in ULI waveguides fabricated in lithium niobate crystal [20]. We state that the different induced modifications are caused by the material dependent response of the original network modified after ultrafast laser irradiation. A detailed analysis of the energy levels of Nd^{3+} ions in Y_2O_3 ceramic suggests that the observed blue shift of the 892 nm luminescence line can be attributed to a local decrease in the crystal field and, hence, to a local dilatation. Following the same argument we concluded that a slight local compression has been induced between damage tracks this leading to the appearance of a waveguide [8].

4 Summary We have reported the formation of the channel waveguides in $Nd^{3+}:Y_2O_3$ ceramic by using ultrafast laser inscription. The µPL features have been well-preserved in the waveguide volumes compared with the bulk. This work suggests promising $Nd^{3+}:Y_2O_3$ ceramic waveguides as cost-effective integrated laser source.

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