CW laser oscillation in Nd:YAG ceramic waveguides fabricated by femtosecond laser writing

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Abstract. *In this work, the laser oscillation at 1.06 μm in Nd:YAG ceramic channel waveguides fabricated by femtosecond direct laser writing is reported. Stable laser oscillation has been achieved by using the natural Fresnel reflection for optical feed-back. Output laser power in excess of 80 mW and a laser slope efficiency of 60 % have been demonstrated.*

Introduction

Nowadays the use of ultrafast lasers to write lightwave circuits has been revealed as a promising technique to define microstructures in dielectric materials. In particular, femtosecond (fs) direct laser writing (DLW) offers the possibility of three dimensionally modifying the optical properties of the irradiated media. When fs pulses are focused inside a dielectric material a local and permanent refractive index change is produced, in such a way that channel waveguides could be generated. This possibility has been already demonstrated in a great variety of glasses and crystals [1-3]. On the other hand, ligthwave circuits can be performed by using DLW without the expensive clean-room envioronment, in contrast to most waveguide fabrication approaches in which different photolithographic steps are needed to define the channels.

Neodymium doped YAG transparent ceramics are attracting materials because of its advantages over the traditionally used Nd:YAG crystals. These advantages are the lower manufacturing costs, the possibility of high Neodymium contents without any decrease in the optical quality of the gain medium and also the possibility of direct composite fabrication [4]. As a matter of fact, the laser performance of Nd:YAG ceramics has been found to be equal or even superior to that corresponding to Nd:YAG crystals [5]. Recently, authors reported on the fabrication of near surface channel waveguides in Nd:YAG ceramics by taking advantage of the permanent induced modifications created around the focal volume after fs ablation [6]. Nevertheless, up to date no attempt has been made, to the best of our knowledge, for the fabrication of buried channel waveguides in Nd:YAG ceramics by fs DLW. The possible application of such waveguides as reliable and integrated laser sources is, therefore, still unexplored.

In this work, the fabrication of buried channel waveguide lasers in Nd:YAG ceramics by using a two line confinement approach is reported. Light confinement has been achieved between two parallel tracks due to filamentation of the fs laser pulses. The spectroscopic properties of Nd^{3+} ions within the guiding region have been investigated by Time-resolved Confocal Microscopy. The quality of the channel waveguides has allowed to obtain highly efficient and stable laser oscillation under continuous wave conditions.

Waveguide fabrication

The Nd:YAG ceramic sample used in this work was provided by Baikowski Ltd. (Japan). The sample was a 5x5x5 mm^3 cube with all its faces polished up to optical quality (λ/4). The nominal Nd^{3+} concentration was 2 at.%. The waveguide laser was fabricated by using a CPA Ti:Shappire laser system providing 120 fs pulses at 796 nm and 1 kHz of repetition rate. The laser beam was focused with a 10x microscope objective (NA=0.3).

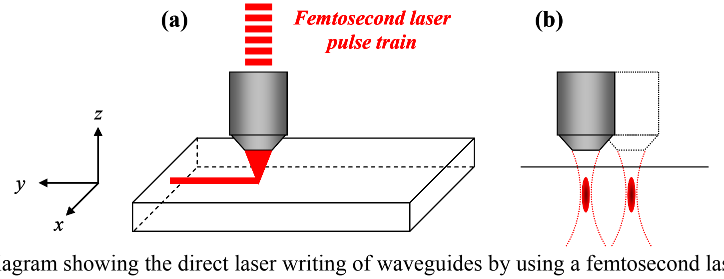

Fig. 1: (a) Diagram showing the direct laser writing of waveguides by using a femtosecond laser. (b) Two parallel lines, separated 20 μm, were written by translating the sample in the x-direction.

The waveguide was written by translating the sample with an XYZ motorized stage with a spatial resolution of 0.8 μm, the situation is sketched in Fig. 1(a). With the linear focus of the objective located 500 μm below surface, 29 μm long filaments were written with a pulse energy of 11 μJ, which corresponds to a laser power of 85 MW, well above the YAG threshold power for self-focusing (≈1 MW) which has been estimated by $\lambda^2/2\pi n_0 n_2$ where n_0=1.8 and n_2 = 6.22×10^{-16} cm^2/W are the linear and nonlinear refractive indexes of YAG. Two parallel lines were written separated 20 μm by translating the sample with a speed of 50 μm/s, see Fig. 1(b).

Experimental results and discussion

The ability of the written structure as an optical waveguide was firstly investigated by end-coupling a He-Ne laser (632.8 nm). Light confinement between the two inscribed channels was observed for both TM and TE polarizations, electric field parallel and perpendicular to the filaments, respectively. Fig 2 (a) shows an optical transmission image of the end face.

The spectroscopic properties of Nd^{3+} ions in the guiding region have been checked, and compared with the bulk. For that purpose an Olympus BX41 Confocal Microscope was used to perform time-resolved micro-photoluminescence (μPL) experiments. Fig. 2(b) shows the room temperature $^4F_{3/2}\rightarrow{}^4I_{11/2}$ μPL spectra measured at the waveguide region and that at the bulk, points A and B in Fig. 2(a), respectively, after excitation at 808 nm by using fiber coupled pulsed diode.

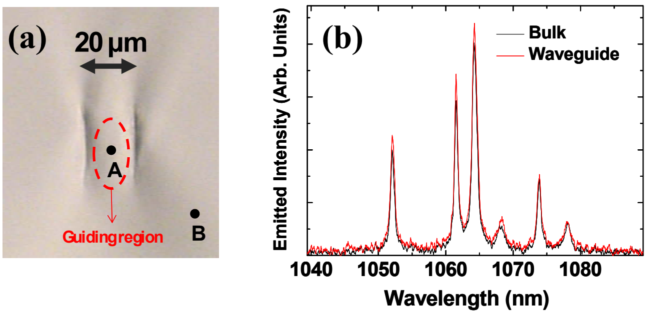

Fig. 2: (a) Optical transmission image of the end face, the guiding region has been indicated. (b) $^4F_{3/2} \rightarrow ^4I_{11/2}$ Nd^{3+} emission band measured at the waveguide and at the bulk, points A and B in Fig. 2(a), respectively.

As it can be observed, the emission spectra were coincident and only slight differences in the peak intensities were detected. The fluorescence lifetime of the $^4F_{3/2}$ metastable state inside the waveguide was also measured. A fluorescence lifetime of 141 µs was found, in good agreement with that obtained at position B (140 µs). The invariance of both spectral shape and lifetime indicates that the spectroscopic properties of Nd^{3+} are basically preserved by this waveguide fabrication technique.

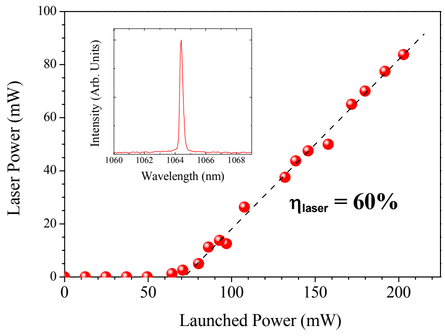

Fig. 3: Experimental output efficiency curve. The inset shows the laser line, obtained for TM excitation at 748 nm.

The laser oscillation, under continuous wave conditions, was investigated by forming a single pass laser cavity. For that purpose a plane dielectric mirror was attached to the entrance end face (T > 80% @ λ = 748 nm and T > 99 % for 1020 nm < λ < 1100 nm). The optical feedback, at the exit end face, was provided by Fresnel reflection. In this case, Nd^{3+} ions were excited at 748 nm, $^4I_{9/2} \rightarrow ^4F_{7/2}$ absorption band, by end coupling the beam from a Ti:Sapphire laser. The geometry of the experiment was adopted to couple the pump beam into the channel waveguide as a quasi-$TM_{0,0}$ propagating mode.

Fig. 3 shows the 1.06 µm laser power as a function of the launched pump power. For all the pump powers explored in this work laser oscillation was found to be quasi-$TM_{0,0}$ polarized and single-line, inset in Fig. 3. A best fit to the experimental points gives a laser slope efficiency with respect to launched power as high as 60 %, and a laser threshold of 68 mW. This laser slope efficiency is, up to the best of our knowledge, the highest ever reported in a Nd:YAG based waveguide laser. As a matter of fact, it is close to 6 times the laser slope efficiency previously reported for a fs written waveguide laser fabricated in a Nd:YAG crystal, and 1.5 times larger than the laser slope efficiency achieved with an epitaxially grown Nd:YAG waveguide laser [7,8]. The high laser slope efficiency here reported is achieved due to the absence of any output coupler. Assuming a complete absorption of the launched pump power and a 100% pumping efficiency, the laser slope efficiency, η_{laser}, can be approximately written as [9]:

$$\eta_{laser} = \frac{\lambda_{pump}}{\lambda_{laser}} \frac{Ln\left(\frac{1}{R}\right)}{2\alpha l + Ln\left(\frac{1}{R}\right)} \frac{dS}{dF} \qquad (1)$$

where λ_{pump} = 748 nm is the pumping wavelength, λ_{laser} = 1064 nm is the laser wavelength, $R \approx 0.08$ is the output reflectance (given, in our case, by the Fresnel reflection), α is the loss coefficient, $l = 5$ mm is the waveguide length and ds / dF is the mode-overlap factor defined in [9]. Considering negligible population in the terminal laser level, due to the four level scheme, and pump beam waist smaller than laser beam waist, it can be assumed that $ds / dF \approx 1$ [9]. By substituting the experimental value found for the laser slope efficiency in expression (1), a value of α = 0.4 cm^{-1} (1.7 dB/cm) was found for the loss coefficient. According to expression (1) the laser slope efficiency the waveguide laser can be even improved by using longer pump wavelengths, since they would lead to a significant reduction in the quantum defect between pump and laser photons which, in turn, will be accompanied by a reduction in the pump induced thermal loading and, therefore, in the undesirable thermal effects [10].

Acknowledgements

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