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CLADDING WAVEGUIDES REALIZED IN Nd:YAG LASER MEDIA BY DIRECT WRITING WITH A FEMTOSECOND-LASER BEAM

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We report on realization of buried cladding waveguides in Nd:YAG single crystal and ceramic media by direct femtosecond (fs)-laser writing technique. A classical technique that moves the laser medium transversally to the fs-laser beam, as well as a new scheme in which the laser medium has a motion on a helical trajectory during the inscribing process was used. The waveguides laser emission performances at 1.06 and 1.3 μm have been investigated under the pump at 807 nm with a fiber-coupled diode laser that was operated both in quasi-continuous wave (quasi-cw) and in cw regimes. Laser pulses with energy of 3.45 mJ at 1.06 μm and of 1.05 mJ at 1.3 μm (with overall optical-to-optical efficiency of 0.26 and 0.08, respectively) were obtained from a 50 μm in diameter circular waveguide that was inscribed by the helical-moving techniques in a 5.0-mm long, 1.1-at.% Nd:YAG ceramic medium. Characteristics of the laser emission recorded in cw operation are discussed.

Key words: lasers, solid-state lasers, diode-pumped lasers, neodymium, optical waveguides.

1. INTRODUCTION

Due to their unique features like small dimensions, low threshold of operation and good output performances, the waveguides lasers present high interest in optoelectronics. Various methods can be used to obtain such a laser device [1]. Extensive research has been carried out recently on realizing waveguides by writing directly with a fs-laser beam. Within this approach a focalized fs-laser pulse produces modifications at micro or sub-micrometric scale inside the material, thus inducing changes of the refractive index. For the first time such a method was used to inscribe waveguides in glasses [2]. It is worth to emphasize that in this kind of material the irradiated volume melts during the process and then it re-solidifies. Finally, the inscribing process delivers a track with an increased index of refraction compared with that of the bulk (the free or the unmodified) glass, and the track is used itself for light propagation.

The direct fs-laser writing technique is nowadays recognized as a powerful tool for obtaining waveguides with various geometries in many laser media [3]. In this case, the irradiated region of the material can be even damaged during the writing process and an increase of the refraction index in the adjacent zones results by stress. Consequently, the light propagates in the medium that remains unmodified between two such tracks [4]. Laser emission was reported from two-wall type waveguides that were inscribed in well-known active media, like Nd:$Y_3Al_5O_{12}$ (Nd:YAG) [5], Yb:YAG [6, 7], or Nd-vanadates [8, 9]. In the experiments, the pump was made with tunable Ti:sapphire lasers. Thus, while the efficiency of such a waveguide laser is high, the output power is limited and the device compactness is restricted by the pump source dimensions.

A compact waveguide laser should include also the pump source, which usually is an array or a fiber-coupled diode laser. A step forward to realization of such a laser device was the proposal of a new inscribing procedure in which many tracks are written around a defined contour [10, 11]. This process delivers a structure that is called “depressed-cladding waveguide”: A principal feature of the inscribed tracks is that it is no damage of the irradiated material and the change of the refractive index averaged on the cross-section of a track is negative. Buried, depressed-cladding waveguides with rectangular or nearly-circular shapes were inscribed in Nd:YAG single crystals [10, 12], in Nd:YAG ceramic media with hexagonal, circular, and trapezoidal aspects [13], circular with double cladding in Nd:YAG [14], rhombic in a Pr:$YLiF_4$ (Pr:YLF) crystal [15], or circular shapes in Tm:YAG ceramic [16] and in Tm:ZBLAN [17].

Because it can be realized with different tubular shapes and sizes, such a waveguide enables the pump with diode lasers. For the first time, a diode laser with emission at 809 nm was used to pump a rectangular depressed-cladding waveguide [10]; the device yielded more than 150 mW cw output power at 1064 nm for nearly 1.5 W of absorbed pump power. Furthermore, a nearly-circular waveguide that was inscribed by the same authors in a Nd:YAG single crystal was pumped with a fiber-coupled diode laser (about 1 W power at 809 nm) and delivered 180-mW cw output power at 1.06 μm [12]. Few tens of mW power level into orange and deep-red visible spectra was demonstrated from a rhombic cladding Pr:YLF waveguide using the pump at 444 nm with an array diode laser [15]. Recently, our group has obtained laser emission at 1.06 μm from two-wall type and cladding waveguides using quasi-cw and cw pumping with a fiber-coupled diode laser. Furthermore, for the first time to the best of our knowledge, laser emission at 1.3 μm was reported from such kind of waveguides that were inscribed in Nd:YAG single crystals [18].

In this work we present results on laser emission at 1.06 μm and 1.3 μm yielded by buried cladding waveguides that were inscribed directly by a fs-laser beam in Nd:YAG single crystals and ceramic media. The optical pumping was made at 807 nm with a fiber-coupled diode laser. Concerning the writing method, we used firstly the classical technique in which the laser medium is moved transversally to the fs-laser beam. Further, we have applied for the first time to the best of our knowledge, a new writing scheme, employing a helical translation of the laser medium during the fs-laser writing, the direction of translation and that of the fs-laser beam being parallel.

2. WAVEGUIDE FABRICATION. LASER EMISSION RESULTS AND DISCUSSION

Figure 1 presents the experimental set-up used for writing waveguides by a classical translation method. The fs-laser pulses with wavelength at 775 nm were delivered by a chirped amplified system (Clark CPA-2101); the pulse duration was ~ 200 fs, the repetition rate was 2 kHz and the pulse energy was up to 0.6 mJ. The beam distribution had an M^2 factor of 1.5. A combination of half-wave plate (λ/2), a polarizer (P) and a calibrated neutral filter (F) was used to vary the fs-laser pulse energy. The fs-laser beam was then focused inside a laser medium with an optical system, which was either a microscope objective or an achromatic lens.

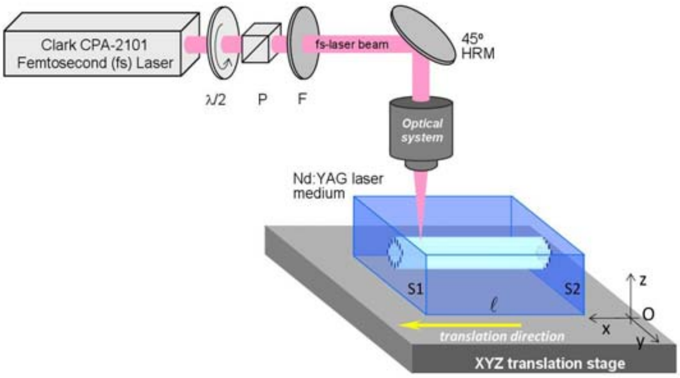

Fig. 1 – A sketch of the experimental set-up used for realizing waveguides in Nd:YAG by fs-laser direct writing is shown. P: polarizer; F: neutral filter; λ/2: half-wave plate. (The Nd:YAG medium and the XYZ translation stage were enlarged, for better understanding).

In the first experiments we used a 0.7at.% Nd:YAG single crystal with an initial length l = 5.4 mm. The medium was placed on a 3-axis motorized translation stage with controllable displacement on all directions. The fs-laser beam was focused in Nd:YAG with a 20× microscope objective (numerical aperture

NA = 0.40); the diameter (in air) of the beam waist was ~7.0 μm. By observing the shapes of the inscribed tracks, the pulse energy was set ~ 4.0 μJ. The tracks were inscribed on O*x* direction (starting from side S1 of Nd:YAG to side S2) at 50 μm/s speed of the translation stage. The end faces of the Nd:YAG were polished after writing and therefore the laser crystal final length was ~ 5.0 mm.

Figure 2 presents photos of the cladding waveguides that were obtained in these writing experiments. The first one (denoted by CWG-a, Fig. 2a) had an elliptical shape (120 μm on O*y* axis and 165 μm on O*z* axis). The second one (CWG-b, Fig. 2b) was circular with a diameter ϕ= 80 μm, and the third one (CWG-3, Fig. 2c) had a rectangular (30 μm length on Oy and 80 μm length on Oz) cross section. The distance between each track was ~10 μm in the case of structures CWG-a and CWG-b and ~5 μm for the CWG-c waveguide. All the waveguides were centered 250 μm below the Nd:YAG side that faced the microscope objective.

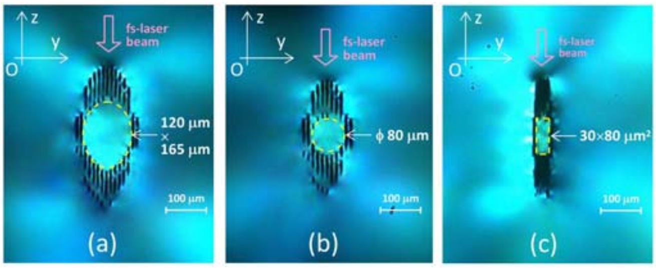

Fig. 2 – Photos of the tubular cladding waveguides inscribed in a 0.7at.% Nd:YAG single crystal: a) CWG-a – elliptical shape, 120 μm × 165 μm; b) CWG-b – circular shape with diameter ϕ= 80 μm; c) CWG-c – rectangular geometry, 30×80 μm^2. The yellow line outlines the waveguide core.

In order to characterize the guiding properties of the inscribed structures a HeNe laser beam was coupled into each waveguide and the power of the transmitted beam was measured. The laser beam was polarized along the O*z* axis, and the coupling efficiency was evaluated to unity. The propagation losses at 632.8 nm were 1.3 dB/cm for the CWG-a waveguide, 1.6 dB/cm for the CWG-b waveguide, and higher, about 2.2 dB/cm, for the CWG-c waveguide. These results compares with those obtained in similar work [13].

For the laser emission experiments we used a linear resonator with the mirrors placed very close of the Nd:YAG crystal. The medium was positioned on a metallic plate without any cooling. The flat high-reflectivity coated mirror had a reflectivity, R > 0.998, at the laser wavelength (λ_{em}) of 1.06 or 1.3 μm and had a high transmission, T > 0.98, at the pump wavelength (λ_p) of 807 nm. The out-coupling mirror (OCM) was also flat, with various transmissions T at λ_{em}. Furthermore, for the emission at 1.3 μm the OCM was high-transmission coated (T ~ 0.995) at 1.06 μm in order to suppress lasing at this high-gain line. The optical pumping was made at λ_p employing a fiber-coupled diode laser (LIMO Co., Germany) with 100 μm diameter of the fiber and NA = 0.22. Two lenses were used to focus the pump beam into Nd:YAG to a diameter of about 60 μm. The diode was operated in quasi-cw mode (pump pulse duration of 1 ms at 5 Hz repetition rate), as well as in cw regime.

The best laser performances obtained under quasi-cw pumping are summarized in Fig. 3. Laser pulses at λ_{em}= 1.06 μm (Fig. 3a) with maximum energy E_p= 1.85 mJ were measured from the CWG-a waveguide when the resonator was equipped with an OCM of T = 0.10; the pump pulse energy was E_{pump}= 9.0 mJ and therefore the overall optical-to-optical efficiency reached η_o= 0.20. The slope efficiency was η_s= 0.25. In the case of emission at 1.3 μm (Fig. 3b, OCM with T = 0.02 at this wavelength) the CWG-a waveguide yielded laser pulses with E_p = 0.35 mJ (at η_o~ 0.04), while the slope efficiency was η_s= 0.08.

Based on these results and the gathered experience, in the next step we have realized waveguides in Nd:YAG ceramic media. The laser materials were two Nd:YAG samples (Baikowski Co. Ltd., Japan) with 0.7 and 1.1 at.% Nd doping and a length of 5.0 mm. This time the fs-laser pulse (with energy of ~1 μJ) was focused into each Nd:YAG through an achromatic lens of 7.5 mm focal length; the diameter (in air) of the focused beam was ~5.0 μm. The distance between the inscribed tracks was 5 to 6 μm; the tracks were written at certain depths on circular perimeters, each waveguide being centered 500 μm below the Nd:YAG surface that was perpendicular to the incident fs-laser beam.

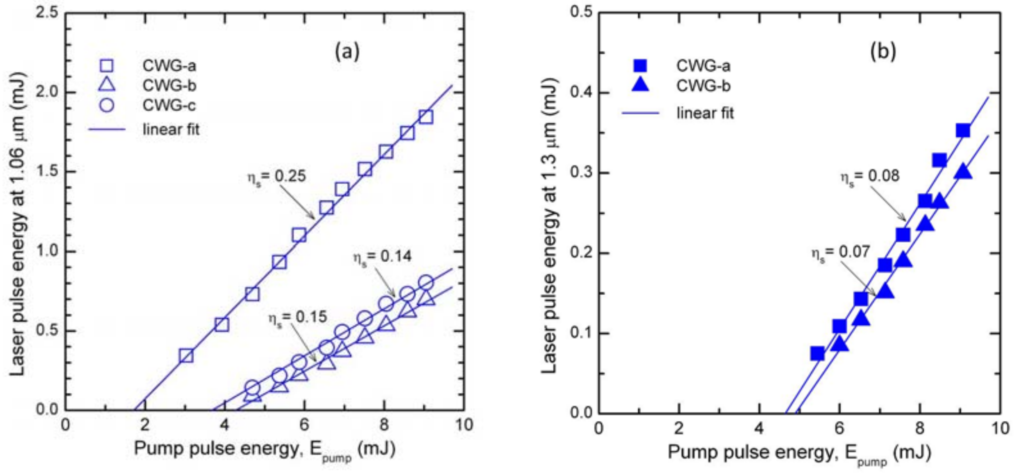

Fig. 3 – Energy of the laser pulses yielded by the cladding waveguides inscribed in the Nd:YAG single crystal, for emission at: a) 1.06 μm (OCM with $T = 0.10$); b) 1.3 μm (OCM with T= 0.02).

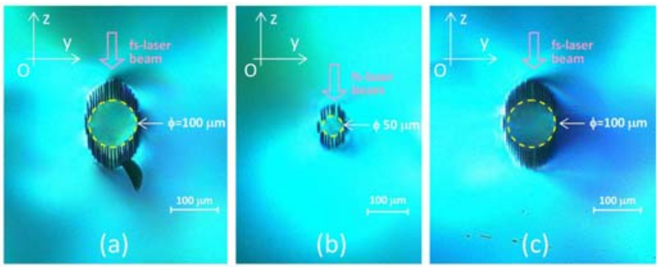

Fig. 4 – Photos of the circular waveguides inscribed in the Nd:YAG ceramic media doped with 0.7 at.% Nd; a) CWG-d – circular, ϕ= 100 μm; b) CWG-e – circular ϕ= 50 μm and with 1.1 at.% Nd; c) CWG-f – circular ϕ= 100 μm. Again, each yellow line delimits a waveguide core.

Photos of the circular cladding waveguides are shown in Fig. 4. In the case of the 0.7 at.% Nd:YAG ceramic, a structure with diameter of 100 μm is presented in Fig. 4a (CWG-d), while Fig. 4b displays a waveguide with ϕ = 50 μm (CWG-e). Furthermore, a waveguide with ϕ = 100 μm (CWG-f) that was realized in the 1.1 at.% Nd:YAG ceramic medium is given in Fig. 4c. The propagation losses at 632.8 nm were measured to be 1.4 and 1.2 dB/cm for waveguides CWG-d and CWG-e, respectively, and losses of the CWG-f waveguide were 1.3 dB/cm.

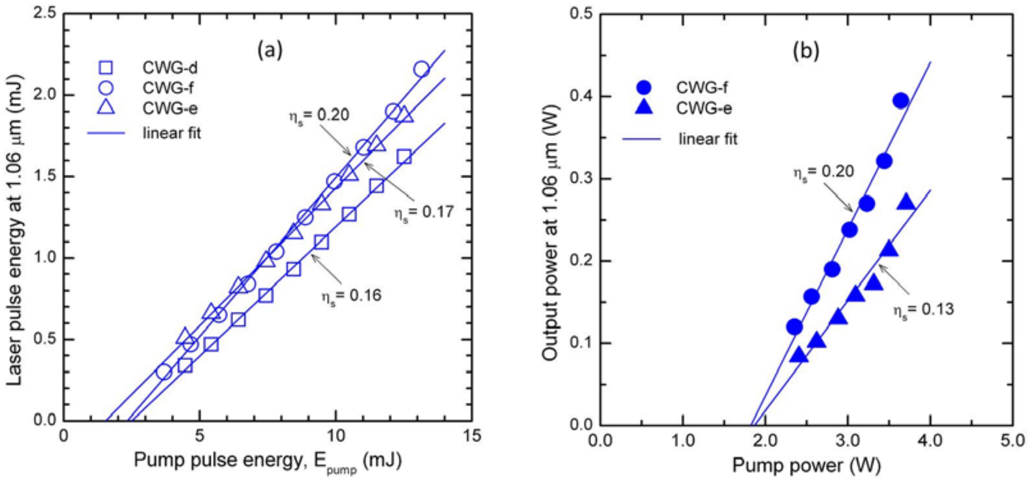

Fig. 5 – Performances of laser emission at 1.06 μm obtained from the circular waveguides inscribed in the Nd:YAG ceramic media, for operation in: a) quasi-cw regime; b) cw mode; OCM with $T = 0.05$.

The laser emission characteristics at 1.06 μm that were obtained with an OCM of $T = 0.05$ are given in Fig. 5. The CWG-d waveguide yielded laser pulses with $E_p = 1.6$ mJ at optical efficiency $\eta_o = 0.13$; the slope efficiency was $\eta_s = 0.16$ (Fig. 5a). Better results, i.e. pulses with $E_p = 2.15$ mJ (at $\eta_o = 0.16$) and slope $\eta_s = 0.20$ were measured from waveguide CWG-f. An increased absorption efficiency of the pump pulse energy in the 1.1 at.% Nd:YAG compared with that of the 0.7 at.% Nd:YAG could be a reason for this behavior. On the other hand, the CWG-d waveguide has a small crack (it can be observed in Fig. 4a) that could be responsible for additional losses of the waveguide and that could influence the laser emission. Indeed, the CWG-d waveguide operated with low performances in cw regime; furthermore, the output power fluctuated in time and eventually vanished. On the other hand, the CWG-f waveguide outputted ~0.4 W cw power at 1.06 μm (Fig. 5b), at optical efficiency $\eta_o = 0.11$ and with slope efficiency $\eta_s = 0.20$. It is also worthwhile to mention that in the case of the 0.7 at.% Nd:YAG single crystal the highest cw output power at 1.06 μm of 0.39 W ($\eta_o = 0.10$) was delivered by the elliptical CWG-a waveguide; the slope efficiency was $\eta_s = 0.13$.

As it was mentioned, these cladding waveguides were obtained using a translation technique in which the fs-laser beam and the laser medium direction on which lasing occurs are perpendicular to each other [10]. The Nd:YAG is translated and once the writing is made along its entire length the fs-laser focusing position is moved to a new location. Many parallel tracks that simulate the waveguide shape are obtained in this way. However, there is always a space of unmodified refraction index left between each track, and all these zones with unchanged refraction index can increase the waveguide propagation losses.

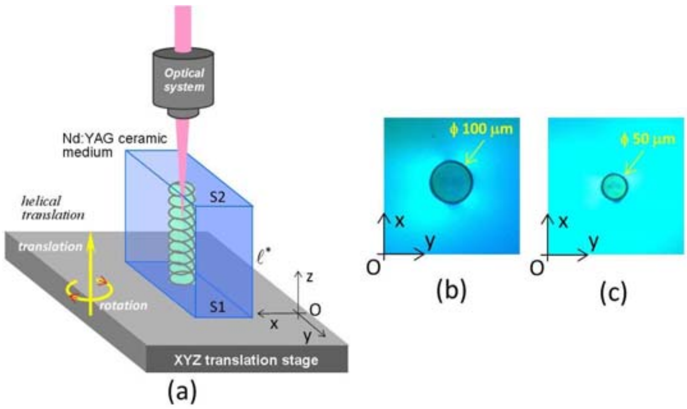

Fig. 6 – a) The set-up used for inscribing circular waveguides in a Nd:YAG ceramic medium by helical translation is shown. Photos of the waveguides with diameter; b) CWG-g – $\phi = 100$ μm and; c) CWG-h – $\phi = 50$ μm that were obtained by this technique are presented.

An alternative solution that can eliminate these regions is to move the Nd:YAG medium on a helical trajectory during the writing process. This new arrangement is shown in Fig. 6a. Thus, the laser medium is positioned with surface S1 on the motorized stage, it is moved circularly in the O*xy* plane and translation is performed on direction O*z*. In the new writing experiments we used a 10 × microscope objective that focused the fs-laser beam to a diameter (in air) of ~12 μm. The fs-laser pulse energy was set to 15 μJ. Waveguides with diameters $\phi = 100$ μm (CWG-g) and $\phi = 50$ μm (CWG-h) that were obtained by this inscribing technique in a 5 mm long, 1.1 at.% Nd:YAG ceramic medium are shown in Fig. 6b and Fig. 6c, respectively. It is observed that the circular walls are well defined, without discontinuities. Consequently, the propagation losses were reduced to 1.1 dB/cm for the DWG-g waveguide and to 1.2 dB/cm for waveguide DWG-h. Furthermore, the writing time was very much decreased, from ~1 hour in the case of a structure like CWG-f (Fig. 4c) to less than 2 min. for the 100-μm diameter CWG-g waveguide (Fig. 6b). On the other hand, this method requires a carefully choice of the focusing optics in order to obtain tracks in a medium of sufficient length for efficient absorption of the pump beam. We mention that recently this writing technique was used to obtain waveguides in an As_2S_3 glass sample [19]; the radius of an inscribed track was below 10 μm, its length was 25 mm and, specific to a glass, this track of increased refraction index was used itself for light guiding. Therefore, it is for the first time to the best of our knowledge when helical translation is applied to inscribe waveguides in a laser medium.

Characteristics of the laser emission at 1.06 μm recorded from these two waveguides under quasi-cw pumping are shown in Fig. 7a (the best performances were obtained with an OCM of transmission $T = 0.05$). Pulses with energy $E_p = 2.65$ mJ (for $E_{pump} = 13.1$ mJ, then with $\eta_o = 0.20$) and slope $\eta_s = 0.23$ were obtained from waveguide CWG-g. The CWG-h waveguide improved the pulse energy to $E_p = 3.45$ mJ and slope η_s increased to 0.29. On the other hand, when the pump was made in cw mode the CWG-g waveguide yielded 0.48 W power at 1.06 μm with slope $\eta_s = 0.24$; the maximum pump power was 3.7 W. The CWG-h waveguide increased the cw power at 0.51 W, with slope $\eta_s = 0.25$. An explanation of these improvements could be the fact that although less pump light is coupled into CWG-h (ϕ= 50 μm) than in CWG-g (ϕ= 100 μm) a better overlap between the pumped volume and the laser beam is obtained in the CWG-h waveguide.

Figure 7b compares the performances of laser emission at 1.3 μm recorded from the 100-μm diameter CWG-f waveguide that was inscribed by the classical translation technique and the CWG-g waveguide (of the same dimension) that was obtained by the helical movement of the 1.1 at.% Nd:YAG ceramic medium. Laser pulses with energy $E_p = 1.15$ mJ at slope $\eta_s = 0.12$ were obtained from CWG-g; these results were better than the laser pulses of energy $E_p = 1.05$ mJ and slope $\eta_s = 0.11$ that were yielded by the CWG-f waveguide. Finally, Table 1 summarizes the energy of laser pulses emitted at 1.06 and 1.3 μm by the various waveguides that were characterized in this work.

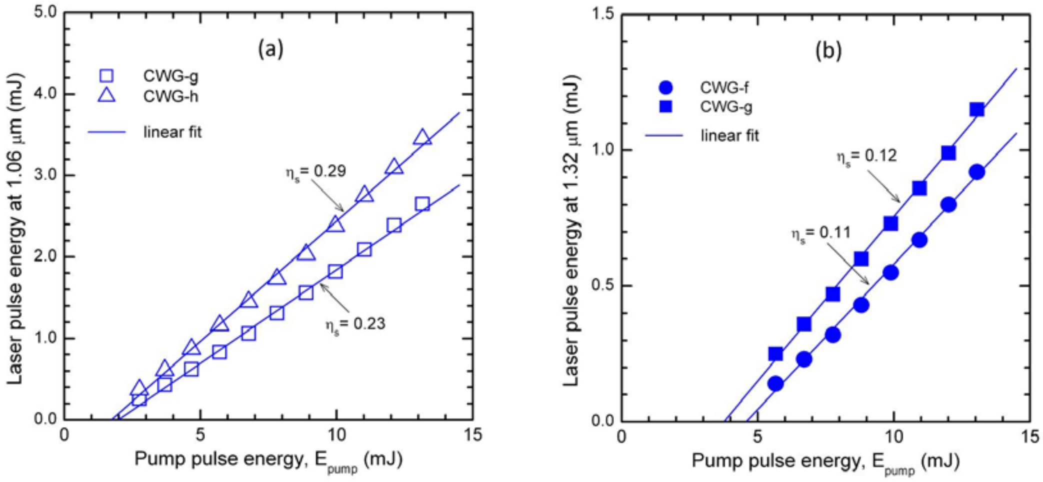

Fig. 7 – a) Laser pulse energy at 1.06 μm obtained from the waveguides inscribed by helical movement of the 1.1 t.% Nd:YAG ceramic (OCM with $T = 0.05$); b) comparison of E_p at 1.3 μm delivered by the waveguides with ϕ = 100 μm that were written by the two techniques in 1.1 at.% Nd:YAG ceramics (OCM with $T = 0.03$).

Table 1

The main results reported in this work for laser emission at 1.06 and 1.3 μm from the cladding waveguides that were inscribed in Nd:YAG single crystal or ceramic media are given. CWG-a (elliptical, 120 μm × 165 μm); CWG-b (circular, ϕ = 80 μm); CWG-c (rectangular, 30×80 μm^2); CWG-d, CWG-f and CWG-g (circular, ϕ = 100 μm); CWG-e and CWG-h (circular, ϕ = 50 μm). The pump was made in quasi-cw regime with a fiber-coupled diode laser at 807 nm

Nd:YAG	The cladding waveguide	Propagation losses (dB/cm)	λ_{em}= 1.06 μm			λ_{em}= 1.3 μm		
			Laser pulse energy E_p (mJ)	Optical efficiency η_o	Slope efficiency η_s	Laser pulse energy E_p (mJ)	Optical efficiency η_o	Slope efficiency η_s
0.7 at.% Nd, single crystal	CWG-a CWG-b CWG-c	1.3 1.6 2.2	1.85 0.7 0.8	0.20 0.08 0.09	0.25 0.15 0.14	0.35 0.3 -	0.04 0.03 -	0.08 0.07 -
0.7 at.% Nd, ceramic	CWG-d CWG-e	1.4 1.2	1.6 1.8	0.13 0.15	0.16 0.17	- 1.2	- 0.09	- 0.12
1.1 at.% Nd, ceramic	CWG-f	1.3	2.15	0.16	0.20	0.9	0.07	0.11
1.1 at.% Nd, ceramic	CWG-g CWG-h	1.1 1.2	2.65 3.45	0.20 0.26	0.23 0.29	1.15 1.05	~0.09 0.08	0.12 0.11

We mention that laser emission at 1.3 μm was also observed under cw pumping. However, it was of low level (few tens of mW for the pump with 3.7 W at 807 nm) in the case of all waveguides that were inscribed by the classical translation technique and, furthermore, it was unstable, showing time fluctuations. The circular CWG-h waveguide increased the 1.3 μm cw power at 0.15 W (but still it is of low level). The heat generated in Nd:YAG that increases during lasing in comparison with non-lasing regime for laser media with doping below 1.14 at.% Nd could be a reason for this behavior [20, 21]. The use of more concentrated Nd:YAG media and controlled cooling could be ways of action for improving the laser emission at 1.3 μm.

3. CONCLUSIONS

In summary, we have realized buried cladding waveguides in Nd:YAG single crystal and ceramic media by direct writing with a fs-laser beam. Classical techniques in which the laser medium is translated perpendicular to the fs-laser beam and many tracks are written around a defined contour, as well as a new method that employs helical translation of the laser medium were used for waveguides writing. The propagation losses have been determined for each waveguide. Laser emission at 1.06 and 1.3 μm has been obtained employing the pump with a fiber-coupled diode laser at 807 nm. Laser pulses with energy E_p = 3.45 mJ and 0.51 W of cw output power at 1.06 μm were obtained from a 50-μm in diameter waveguide that was inscribed by the helical movement method in a 5-mm long, 1.1 at.% Nd:YAG ceramic medium. The same waveguide yielded pulses with E_p = 1.05 mJ at 1.3 μm. Further investigations will concentrate on improving the Nd:YAG waveguides laser emission performances in cw mode of operation. Furthermore, realization of cladding waveguides in Nd-vanadates laser crystals, in passively Q-switched composite Nd:YAG/Cr^{4+}:YAG media, or generation of visible light from waveguides inscribed in a hybrid laser medium/nonlinear crystal arrangement are aims of our future work in this area. This kind of waveguides shows good prospects for realizing compact and efficient diode-pumped laser sources with applications in optoelectronics.

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