RAPORT STIINTIFIC

privind implementarea proiectului in perioada ianuarie - decembrie 2015

1. Emisie de mare putere in laseri de tip ghid de unda realizati in Nd:YAG de tip policristalin (ceramic) prin tehnica scrierii cu pulsuri laser cu durata de ordinul femtosecundelor (fs)

In experimente anterioare am utilizat pompajul cu dioda laser, in regim quasi-continuu, pentru a obtine emisie laser eficienta la lungimile de unda (λ_{em}) de 1.06 μm si 1.3 μm de la ghiduri de unda scrise cu fascicul laser cu durata de ordinul femtosecundelor in Nd:YAG si Nd:YVO$_4$. Totusi, in cazul emisiei in regim continuu (cw), la λ_{em}= 1.06 μm, puterea laser a fost limitata la 0.5 W (cu eficienta optica η_{oa}= 0.13, pompaj la λ_p= 807 nm) in Nd:YAG si la 1.5 W (cu eficienta optica η_{oa}= 0.27, pompaj la λ_p= 880 nm) in Nd:YVO$_4$; mai mult, pentru λ_{em}= 1.3 μm puterea laser a avut valori mici (de 0.15 W in Nd:YAG si 0.2 W in Nd:YVO$_4$). In prezenta faza de contract au fost imbunatatite performantele emisiei laser in regim cw (atat la 1.06 μm cat si la 1.3 μm) obtinute de la ghiduri scrise in Nd:YAG.

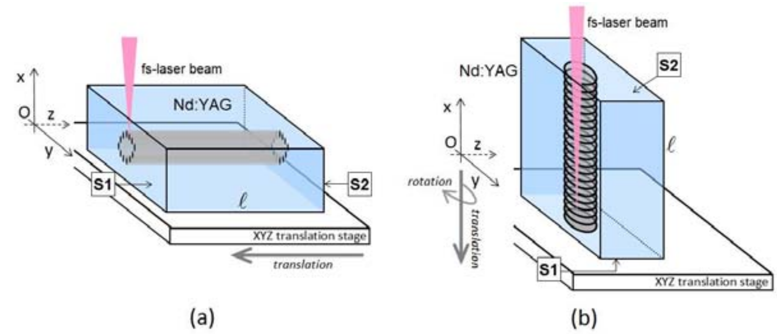

Fig. 1.1 Montajele experimentale utilizate pentru scrierea ghidurilor de unda in Nd:YAG: (a) tehnica clasica, de translatie pas cu pas a mediului laser; (b) tehnica de miscare pe o traiectorie helicoidala a mediului laser (tehnica dezvoltata in cadrul acestui contract).

Au fost realizate ghiduri de unda cu diametrul de 100 μm in diferite medii Nd:YAG, astfel: DWG-1 in 0.7-at.% Nd:YAG cu lungimea de 4.8 mm; DWG-2, in 0.7-at.% Nd:YAG, 7.8 mm; DWG-3, in 1.1-at.% Nd:YAG, 7.7 mm si DWG-4, in 1.1-at.% Nd:YAG, 4.5 mm; aceste ghiduri au fost obtinute prin tehnica clasica de incriptionare (Fig. 1.1a). In plus, am folosit metoda de miscare pe o tractorie helicoidala a mediului (Fig. 1.1b) pentru a realiza un ghid de unda cu acelasi diametru (ϕ= 100 μm) in 1.1-at.% Nd:YAG, lungime de 4.5 mm. Dupa inscriptionare, suprafetele de intrare si iesire in ghiduri (S1 si S2 in Fig. 1.1) au fost prelucrate optic (paralelism 10''; planeitate λ/10 la 633 nm) si au fost depuse cu straturi dielectrice. Astfel, S1 a fost depusa AR (R< 0.5%) la λ_{em}= 1.06 si 1.3 μm si HT (R< 2.5%) la λ_p= 807 nm; S2 a fost depusa AR la λ_{em}.

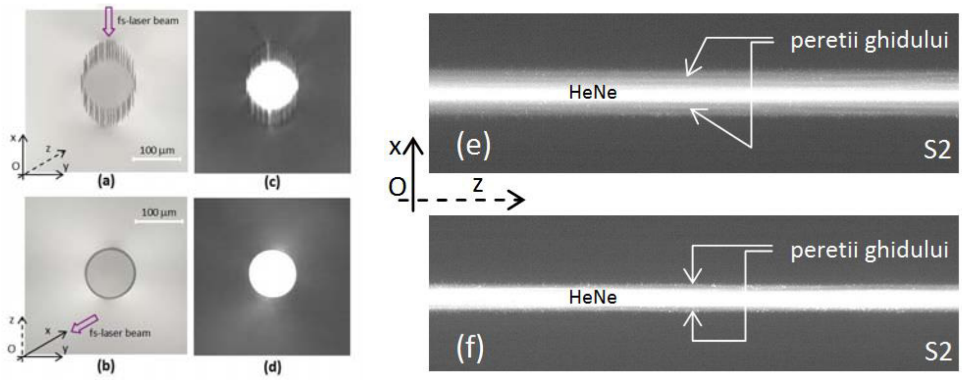

Fig. 1.2 Fotografii la microscop ale suprafetei S2 pentru ghidurior de unda (a) DWG-4 si (b) DWG-5. Imagini ale suprafetei S2 luate cu camera CMOS, in timpul pompajului optic, pentru ghidurile (c) DWG-4 si (d) DWG-5. Este aratata propagarea unui fascicul laser HeNe pe o lungime de 2.5 mm in ghidurile (e) DWG-4 si (f) DWG-5.

Figura 1.2a arata o imagine la microscop a suprafetei S2 a ghidului DWG-4. Se observa ca in cazul scrierii cu metoda clasica peretii ghidului sunt formati din suma urmelor lasate in Nd:YAG de laserul cu fs; zonele care au indicele de refractie neschimbat vor introduce pierderi, atat pentru radiatia de pompaj cat si pentru ghidarea emisiei laser. In cazul ghidului inscriptionat prin metoda helicoidala (Fig. 1.2b) peretele este continuu si uniform. Imagini ale suprafetei S2 in cazul pompajului, aratate in Fig. 1.2c pentru ghidul DWG-4 si in Fig. 1.2d pentru ghidul DWG-5, ilustreaza clar diferentele dintre ghidurile obtinute prin cele doua metode de realizare. Pierderile au fost obtinute prin cuplarea unui laser HeNe in fiecare ghid si prin masurarea puterii fasciculului laser la intrarea in si la iesirea din fiecare ghid. Astfel, pierderile calculate au fost de 1.7 dB/cm pentru ghidul DWG-1, de 1.5 dB/cm pentru ghidul DWG-2, de 1.2 dB/cm pentru ghidul DWG-3, de 1.5 dB/cm pentru ghidul DWG-4 si de 0.6 dB/cm pentru ghidul DWG-5. In Fig. 1.2e am aratat propagarea fasciculului laser HeNe in ghidul DWG-4 iar in Fig. 1.2f pentru ghidul DWG-5, pe o lungime de 2.5 mm (aproape de suprafata S2).

Emisia laser a fost obtinuta in rezonator de tip plan-plan, oglinda de pompaj (HRM) cat si oglinda de extractie (OCM) fiind plasate foarte aproape de suprafetele S1, respectiv S2 ale fiecarui mediu Nd:YAG. In plus, mediile au fost invelite in Indium si apoi plasate intr-o placa de cupru a carei temperatura a fost mentinuta la 20°C. Pompajul optic a fost realizat la λ_p= 807 nm cu dioda laser (Limo Co., Germania; fibra cu diametrul ϕ=100 µm si NA=0.22). Fasciculul de pompaj a fost focalizat in mediul laser folosind o lentila de colimare cu distanta focala de 40 mm si o lentila de focalizare cu distanta focala de 30 mm.

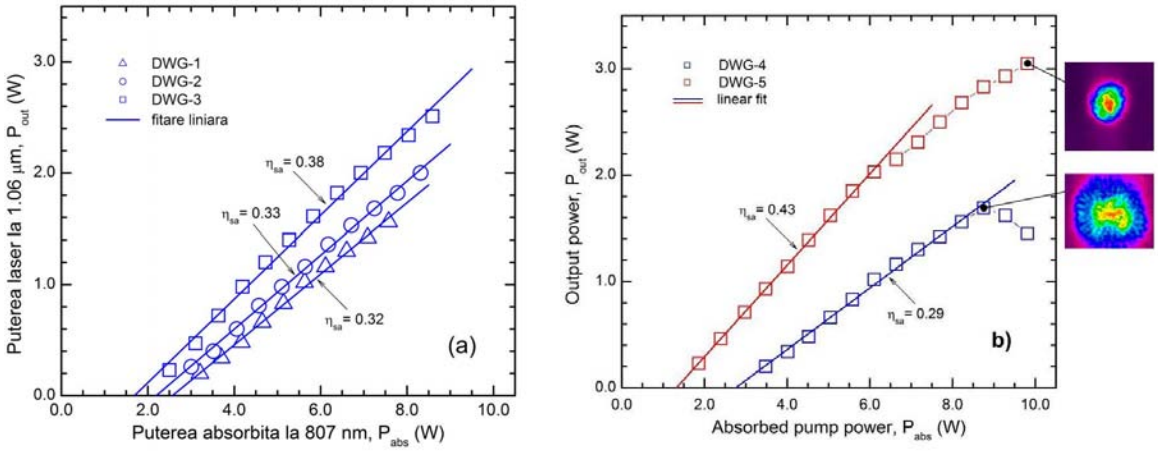

Fig. 1.3 Puterea laser la 1.06 µm in functie de puterea absorbita pentru (a) ghidurile DWG-1, DWG-2 si DWG-3 si (b) ghidurile DWG-4 si DWG-5. Oglinda OCM a avut transmisia T= 0.05 la λ_{em}= 1.06 µm. In Fig. 1.3b sunt aratate si distributiile fasciculelor laser in camp apropiat la puterile maxime.

In Fig. 1.3 este aratata variatia puterii laser la λ_{em}= 1.06 µm in functie de puterea absorbita la λ_p= 807 nm pentru ghidurile investigate. Ghidul DWG-1 a emis puterea P_{out}= 1.6 W pentru puterea absorbita P_{abs}= 7.6 W, cu eficienta optica η_{oa}= 0.21; panta eficientei laser a fost η_{sa}= 0.32 (Fig. 1.3a). Puterea obtinuta de la ghidul DWG-3 a fost P_{out}= 2.5 W, avand eficienta η_{oa}= 0.29; panta eficientei laser a fost η_{sa}= 0.38. Cele mai bune rezultate au fost obtinute de la ghidul DWG-5 (Fig. 1.3b). Astfel, s-a masurat puterea P_{out}= 3.1 W la 1.06 µm pentru o putere absorbita la 807 nm de P_{abs}= 9.8 W (cu eficienta η_{oa}= 0.31), panta emisiei laser fiind η_{sa}= 0.43. Pentru a explica diferentele observate in emisia laser au fost determinate pierderile L_i ale rezonatorului pentru fiecare ghid. Astfel, pierderile L_i au fost evaluate ca fiind 0.05 pentru ghidul DWG-3, de 0.07 la 0.08 pentru ghidurile DWG-1, DWG-2 si DWG-4 si de 0.03 pentru ghidul DWG-5.

Emisia laser la λ_{em}= 1.3 µm a fost obtinuta numai in ghidul DWG-5. Astfel, puterea laser a fost P_{out}= 1.6 W pentru P_{abs}= 9.3 W la λ_p= 807 nm, eficienta optica fiind η_{oa}= 0.17; panta emisiei laser a fost η_{sa}= 0.19 (Fig. 1.4). Rezultatele principale obtinute in aceste experimente, de la toate ghidurile de unda, sunt sistematizate in Tabelul 1.1.

Faptul ca emisia laser la 1.3 µm a fost eficienta numai in DWG-5 poate fi explicata prin pierderile L_i mai mici ale acestui ghid, dar si prin generarea de caldura mai ridicata in cazul emisiei la aceasta lungime de unda (in comparatie cu emisia la λ_{em}= 1.06 µm). Pentru a masura temperatura suprafetei S2 am utilizat o camera FLIR T620 (cu eroare de ±2°C in domeniul -40°C - 150°C) si am pompat mediul 1.1-at.% Nd:YAG (4.5 mm) in ’bulk’, adica nu direct in ghidul DWG-5. Mentionam ca pentru a vizualiza direct S2 (si pentru a masura temperatura) a fost nevoie sa crestem lungimea rezonatorului laser (la 40 mm), iar pentru aceasta dimensiune nu s-a mai obtinut emisie laser in ghid.

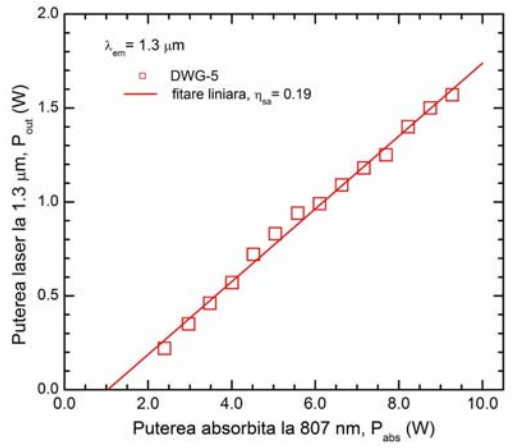

Fig. 1.4 Puterea laser la 1.3 µm in functie de puterea absorbita la 807 nm pentru ghidul DWG-5, OCM cu transmisia T= 0.03 la λ_{em}= 1.3 µm.

Tabel 1.1 Performantele emisiei laser la 1.06 µm and 1.3 µm obtinute in ghidurile realizate in Nd:YAG.

<table>
<tr><th>Metoda de scriere</th><th>Ghidul de unda</th><th>Nd:YAG</th><th>λ_{em} (µm)</th><th>Puterea laser, P_{out} (W)</th><th>Eficienta optica, η_{oa}</th><th>Panta eficientei, η_{sa}</th><th>Eficienta de absorbtie la λ_p, η_a</th></tr>
<tr><td rowspan="4">Translatie pas-cu-pas a mediului</td><td>DWG-1</td><td>0.7-at.% Nd, 4.8 mm</td><td rowspan="5">1.06</td><td>1.6</td><td>0.21</td><td>0.32</td><td>0.82</td></tr>
<tr><td>DWG-2</td><td>0.7-at.% Nd, 7.8 mm</td><td>2.0</td><td>0.24</td><td>0.33</td><td>0.90</td></tr>
<tr><td>DWG-3</td><td>1.1-at.% Nd, 7.7 mm</td><td>2.5</td><td>0.29</td><td>0.38</td><td>0.93</td></tr>
<tr><td>DWG-4</td><td rowspan="3">1.1-at.% Nd, 4.5 mm</td><td>1.7</td><td>0.19</td><td>0.29</td><td rowspan="3">0.89</td></tr>
<tr><td rowspan="2">Miscare helicoidala a mediului</td><td rowspan="2">DWG-5</td><td>3.1</td><td>0.32</td><td>0.43</td></tr>
<tr><td>1.3</td><td>1.6</td><td>0.17</td><td>0.19</td></tr>
</table>

Acest mediu (1.1-at.% Nd:YAG, 4.5 mm) a emis puterea P_{out}= 4.7 W la 1.06 µm pentru P_{abs}= 8.8 W (Fig. 1.5a). Temperatura suprafetei S2 (la aceasta putere de pompaj) fost de 49.6^{o}C in timpul emisiei laser si a crescut pana la 64.8^{o}C atunci cand emisia laser a fost oprita (Fig. 1.5b). Pe de alta parte, acelasi mediu Nd:YAG a emis P_{out}= 2.2 W la 1.3 µm pentru P_{abs}= 8.2 W (Fig. 1.5a). In cazul in care nu am avut emisie laser la aceasta lungime de unda temperatura maxima a suprafetei S2 a fost de 64.1^{o}C. In timpul emisiei laser temperatura a scazut, insa numai la 61.6^{o}C. Astfel, desi este generata mai putina caldura in cazul emisei laser la 1.3 µm in comparatie cu cazul in care nu avem emisie, cantitatea de caldura este mai mare decat cea generata pentru emisia la 1.06 µm. Anticipam ca un mediu laser cu continut de Nd mai ridicat (decat 1.1-at.% Nd) poate fi util pentru a creste performantele emisiei laser la 1.3 µm, insa pierderile acestui mediu trebuie sa fie scazute.

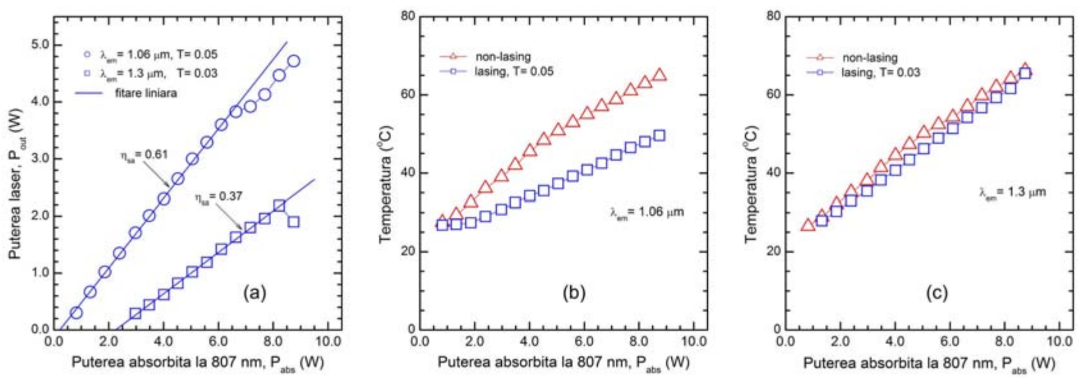

Fig. 1.5 (a) Puterea laser la 1.06 µm si la 1.3 µm in functie de puterea absorbita la 807 nm in mediul 1.1-at.% Nd:YAG (4.5 mm). Temperatura maxima a suprafetei S2 pentru emisia la (b) 1.06 µm si (c) 1.3 µm.

Emisia laser (la λ_{em}= 1.06 µm) in regim comutat s-a obtinut cu un cristal Cr^{4+}:YAG cu absorbtie saturabila, avand transmisia initiala T_i= 0.90. Mediul Cr^{4+}:YAG a fost plasat intre ghidul DWG-3 (1.1-at.% Nd:YAG, 7.7 mm) si oglinda de extractie OCM cu transmisia T= 0.05. Puterea medie masurata a fost de 680 mW pentru P_{abs}= 9.2 W. Rata de repetitie a pulsurilor laser a fost de 34.4 kHz, de aici rezultand o energie a pulsurilor laser de 19.7 μJ. Durata pulsurilor a fost de 2.8 ns, astfel incat puterea de varf a pulsurilor laser a atins 7 kW.

2. Incriptionarea de ghiduri de unda in medii compozite Nd:YAG/Cr^{4+}:YAG

Au fost inscriptionate ghiduri de unda de tip II (sau tip doi ”pereti”) cu distanta intre pereti de 50 μm precum si ghiduri de unda circulare cu diametrul de ϕ= 100 μm si ϕ= 150 μm in medii laser compozite Nd:YAG/Cr^{4+}:YAG (Fig. 2.1). Mediul activ 1.0-at.% Nd:YAG a avut lungimea de 7 mm, fiind lipit optic la diferite cristale Cr^{4+}:YAG, acestea avand transmisia initiala de 0.95, 0.85, 0.80 si 0.70. In experimentele urmatoare va fi investigata emisia laser la 1.06 μm, urmarindu-se obtinerea de pulsuri laser in regim comutat cu energie mare (zeci de μJ) si putere de varf ridicata (de ordinul kW).

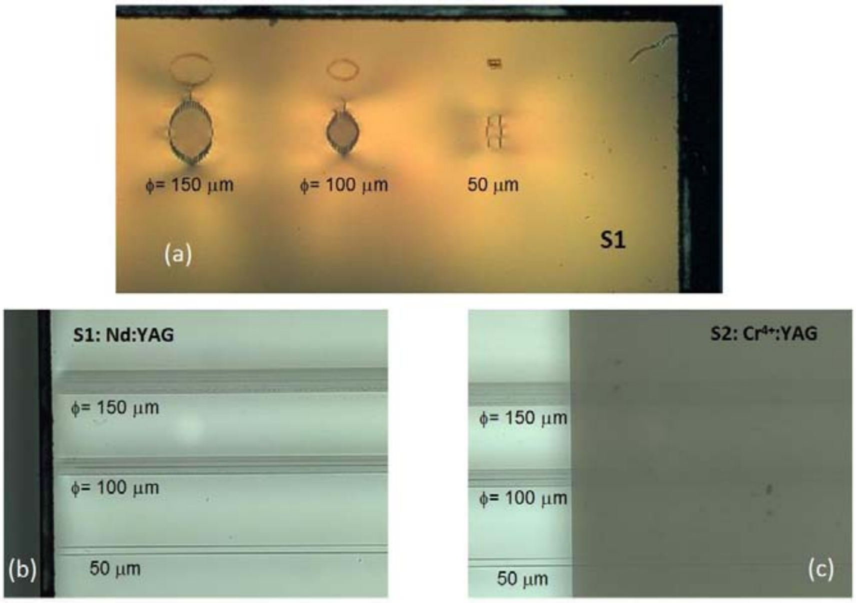

Fig. 2.1 (a) Fotografii ale suprafetei S1 pentru medii compozite Nd:YAG/Cr^{4+}:YAG care arata ghidurile incriptionate in aceasta structura hibrida. Vedere dinspre laserul de incriptionare: (a) Nd:YAG, capatul S1 si (b) Cr^{4+}:YAG, partea S2.

REZUMAT

- Folosind pompajul optic cu dioda laser la 807 nm, au fost obtinute puteri laser (record) de 3.1 W la 1.06 μm si de 1.6 W la 1.3 μm de la ghiduri cu diametrul de 100 μm care au fost realizate prin scriere cu pulsuri laser cu durata de ordinul femtosecundelor in medii Nd:YAG ceramic; eficienta optica a fost de 0.32 la 1.06 μm si de 0.17 la 1.3 μm. A fost realizata operarea in regim comutat a unui astfel de ghid, cu pulsuri laser avand energia de 19.7 μJ si putere de varf de 7 kW.
- Au fost inscriptionate ghiduri de unda in medii compozite Nd:YAG/Cr^{4+}:YAG (lipite optic), pentru a se obtine pulsuri laser direct in regim comutat de la o astfel de structura hibrida.

DISEMINARE

- A fost trimis un manuscris pentru publicare intr-o revista indexata ISI.

1. G. Salamu, F. Jipa, M. Zamfirescu, and N. Pavel, "Watt-Level Output Power Operation from Diode-Laser Pumped Circular Buried Depressed-Cladding Waveguides Inscribed in Nd:YAG by Direct Femtosecond-Laser Writing," trimis pentru publicare in IEEE Photonics Journal.
   Factor de impact pe anul 2014: 2.209

- Au fost prezentate comunicari la doua conferinte cu participare internationala si o comunicare la o scoala de vara, internationala.

1. N. Pavel, G. Salamu, F. Voicu, O. Grigore, T. Dascalu, F. Jipa, and M. Zamfirescu, "Depressed-cladding waveguides inscribed in Nd:YAG and Nd:YVO_4 by femtosecond-laser writing technique. Realization and laser emission," ROMOPTO 2015, 11th International Conference on Optics "Micro- to Nano-Photonics IV", September 1-4, 2015, Bucharest, Romania; presentation I.I.7 (invited presentation).
2. G. Salamu, N. Pavel, T. Dascalu, F. Jipa, and M. Zamfirescu, "Diode-Pumped Laser Emission from Depressed Cladding Waveguides Inscribed in Nd-doped Media by Femtosecond Laser Writing Technique," CLEO Europe - EQEC 2015 Conference, 21-25 June 2015, Münich, Germany, presentation CA-P.29 (poster presentation).
3. G. Salamu, F. Voicu, F. Jipa, M. Zamfirescu, T. Dascalu, N. Pavel, ”Efficient Laser Emission from Waveguides Inscribed in Nd-doped Media by Femtosecond-Laser Writing Technique," "Siegman International School on Lasers: 2015", 02-07 August 2015, Amberg, Germania (poster presentation).

Watt-Level Output Power Operation from Diode-Laser Pumped Circular Buried Depressed-Cladding Waveguides Inscribed in Nd:YAG by Direct Femtosecond-Laser Writing

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Watt-Level Output Power Operation from Diode-Laser Pumped Circular Buried Depressed-Cladding Waveguides Inscribed in Nd:YAG by Direct Femtosecond-Laser Writing

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Abstract: Circular, buried depressed-cladding waveguides have been inscribed in Nd:YAG ceramic media by direct writing with a femtosecond- (fs-) laser beam. A classical step-by-step translation of the medium method as well as a newly developed helical-moving technique was employed to fabricate waveguides with 100-μm diameter. Laser emission has been obtained under the pump with a fiber-coupled diode laser. Continuous-wave output power of 3.1 W at 1.06 μm and 1.6 W at 1.3 μm were achieved from an waveguide inscribed by helical movement in a 4.5-mm long, 1.1-at.% Nd:YAG; the overall optical-to-optical efficiency with respect to the absorbed pump power was 0.31 at 1.06 μm and 0.17 at 1.3 μm. Q-switch operation has been realized with Cr^{4+}:YAG saturable absorber (SA) crystal. Using Cr^{4+}:YAG SA with initial transmission of 0.90, an average output power of 680 mW has been measured from an waveguide that was written by classical method in a 7.7-mm long, 1.1-at.% Nd:YAG ceramic. The laser pulse energy was 19.7 μJ and the pulse peak power reached 7 kW.

Index Terms: Solid state lasers, novel photon sources, Q-switched lasers.

1. Introduction

The realization of various miniature components for integrated optical devices is now possible also due to the ability of a fs-laser beam to induce localized modifications (at micrometer scale) of a material refractive index. The first demonstration of this process was made, in glasses, by Davis *et al.* in 1996 [1]. An increase of the refractive index was observed in the region where the fs-laser beam was focused, this increase being large enough to sustain waveguiding inside the written track. Such a waveguide has been classified as “type I” waveguide [2, 3].

On the other hand, in the case of many laser crystals a decrease of the refractive index is obtained in the close vicinity of the irradiated region. In addition, the modified region expands and the stress induced to the surrounding material increases its refractive index. Consequently, waveguiding is possible in the vicinity of a single track. Moreover, guiding of linearly-polarized beams can be realized between two such tracks that, however, have to be written at short (few tens of microns apart) distance from each other. This scheme is called “type II’ waveguide. Very attractive for building a compact laser device is the tubular-shape waveguide, the so-called "type III" waveguide. This structure (also named 'buried depressed-cladding waveguide') consists of an unmodified region of the material that is surrounded by a large number of tracks inscribed by a fs-laser beam [4]. Such waveguide can be realized in many shapes and sizes thus enabling power scaling; usually such waveguide laser delivers randomly-polarized beams.

In the case of Nd:$Y_3Al_5O_{12}$ (Nd:YAG), a fs-laser beam was employed to inscribe, for the first time in 2007, type II waveguides that were situated near the medium surface [5]. The same two-line confinement approach was used to realize the first buried waveguide in Nd:YAG ceramic, from which continuous-wave (cw) laser emission at 1064 nm was achieved under the pump at 748 nm with a Ti:sapphire laser [6]. Record cw output power of 1.3 W at 1064 nm was reported from a Nd:YAG two-line waveguide using the pump with Ti:sapphire laser [7]. Type II waveguides were inscribed in various other laser media, like Yb:YAG [8, 9], Nd-vanadates [10, 11], Pr:$SrAl_{12}O_{19}$ [12] or Nd:$KGd(WO_4)_2$ [13].

The first buried depressed-cladding waveguide (type III) was realized in a Nd:YAG single crystal and had a rectangular shape; the waveguide was pumped with an array-diode laser and delivered nearly 180 mW power at 1064 nm at an overall optical-to-optical efficiency with respect to the absorbed pump power (η_{oa}) of 0.11 [4]. An ellipse-shape buried depressed-cladding waveguide that was fabricated by the same research group in Nd:YAG yielded similar output power under the pump with a fiber-coupled diode laser [14]. Lately, buried depressed-cladding waveguides with circular, hexagonal and trapezoidal cross section were incribed in Nd:YAG [15], as well as in other laser media, such as Tm:YAG [16], Pr:$YLiF_4$ [17], or Nd:$YCa_4O(BO_3)_3$ [18]. A review on these works could be found in Refs. [2, 3].

Most of the previous waveguides that were written in Nd:YAG were operated at the emitting wavelength (λ_{em}) of 1.06 μm, using the pump with tunable Ti:sapphire lasers. Such an excitation source can not be integrated in and would not assure compactness of optical device; the pump with diode lasers is desirable. Recently, we have inscribed circular, buried depressed-cladding waveguides in Nd:YAG from which laser emission at 1.06 μm as well at 1.3 μm was achieved under the pump with a fiber-coupled diode laser [19-21]. Pulses with 3.4 mJ and 1.2 mJ at 1.06 μm and 1.3 μm, respectively were demonstrated from a 100-μm diameter waveguide that was written in a 5.0-mm long, 1.1-at.% Nd:YAG ceramic. The pump was made at 807 nm in quasi-cw regime; the laser device overall optical-to-optical efficiency was 0.26 for λ_{em}= 1.06 μm and 0.09 at λ_{em}= 1.3 μm. On the other hand, in cw operation the output power (P_{out}) reached only 0.5 W at 1.06 μm, whereas the emission at 1.3 μm was modest (with P_{out} below 150 mW) for the pump (in both cases) with nearly 3.7 W at 807 nm.

In this work we are reporting efficient, watt-level cw operation in 100-μm diameter buried depressed-cladding waveguides that were inscribed with a fs laser in several Nd:YAG ceramics. The classical step-by-step writing technique [4] and a helical-moving technique that was developed in our group [20] were used to write the waveguides. Output power of 3.1 W at 1.06 μm for 9.8 W absorbed pump power (P_{abs}) at 807 nm and emission at 1.3 μm with P_{out}= 1.6 W for P_{abs}= 9.3 W have been obtained from a 4.5-mm long waveguide that was written in 1.1-at.% Nd:YAG. The waveguides' realization and characterization will be discussed in section 2. Cw laser emission performances are described in section 3. Moreover, passive Q-switching with a Cr^{4+}:YAG SA of 0.90 initial transmission yielded pulses with 19.7-μJ energy and 2.8-ns duration at 34.5-kHz repetition rate. Section 4 concludes this work.

2. Waveguides Writing and Characterization

As described in our previous works [19-21], the fs-laser system used for inscribing waveguides was a chirped pulsed amplified laser (Clark CPA-2101) that yielded pulses at 775 nm with duration of 200 fs, repetition rate of 2.0 kHz and energy up to 0.6 mJ. A half-wave plate, a polarizer and several calibrated neutral filters were used to vary the fs-laser beam energy.

Two inscribing techniques were employed. The first one was the classical method [4], or the so called ‘step-by-step translation’ technique, shown in Fig. 1a. In this scheme the Nd:YAG is moved transversally (along axis Oz) to the fs-laser beam, starting from one of its side (S1). Once the opposite surface (S2) is reached the fs-laser beam focus is positioned to a different position (in the Oxy plan) that is situated on a circular shape. The process was repeated until many tracks have been inscribed around a circular shape of 100-μm diameter (ϕ). In addition, the starting point and position of each next track were chosen such to avoid overlapping between the fs-laser beam and any of an already inscribed track. Following several writing tests and process optimization, the fs-laser beam was focused to a 5.0-μm in diameter spot, the translation along Oz was made at a speed of 50 μm/sec and the distance between two-consecutive tracks (along Oy) was 5 μm; the fs-laser pulse energy was about 2.0 μJ. Figure 1b illustrates the ‘helical-moving of the medium technique’ [20]. In this configuration the fs-laser beam and the waveguide axis (along which laser emission will be obtained) are parallel. The Nd:YAG medium is translated on axis Ox and in the same time it is rotated in the Ozy plane. Typically, rotation on a circle with ϕ= 100 μm was made in less than 1 sec and the speed translation was chosen such to obtain a helical trajectory with ~50-μm pitch. The fs-laser beam was focused to a spot of 10-μm diameter and the pulse energy was set at 15 μJ.

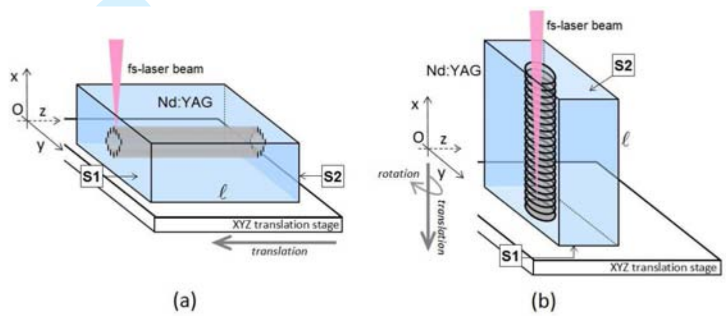

Fig. 1. Techniques used to realize circular, buried depressed-cladding waveguides by direct writing with a fs-laser beam: (a) classical method, in which the medium is translated perpendicularly to the fs-laser beam, with a step-by-step movement along a circular perimeter; (b) continuous writing using helical movement of the medium, parallel to the fs-laser beam.

Both of these methods have advantages and presents disadvantages. The classical method allows fabrication of waveguides in long media. On the other hand, the inscribing process takes time, as many tracks have to be realized. For example, the writing with this technique an waveguide with ϕ= 100 μm in a 5.0-mm long Nd:YAG was done in ~1 hour. The helical-moving technique allowed writing of a similar (ϕ= 100 μm) waveguide, in the same Nd:YAG, in less than 2 min. For the lasing experiments, the classical method was used to incribe waveguides (all with ϕ= 100 μm) in 0.7-at.% Nd:YAG ceramics of 5-mm and 8.0-mm length and in a 8.0-mm long, 1.1-at.% Nd:YAG ceramic. After inscribing, sides S1 and S2 were polished at laser grade (each Nd:YAG length was reduced by ~0.2 mm by polishing) and coated with antireflection layer AR (reflection, R< 0.5%) at λ_{em} of 1.06 μm and 1.32 μm; also, S1 was coated high transmission, HT (R<2.5%) at the pump wavelength (λ_p) of 807 nm. These waveguides are denoted by DWG-1 (0.7-at.% Nd:YAG, 4.8 mm), DWG-2 (0.7-at.% Nd:YAG, 7.8 mm) and DWG-3 (1.1-at.% Nd:YAG, 7.7 mm). The helical moving method was used to realize a circular waveguide (denoted by DWG-5) in a 4.5-mm thick, 1.1-at.% Nd:YAG ceramic; for comparison, an waveguide (DWG-4) was fabricated in this Nd:YAG by the classical method.

A microscope photo of DWG-4 (side S2) is shown in Fig. 2a. The waveguide wall is the sum of the written tracks, with some unmodified material left between each track. On the other hand, waveguide DWG-5 (realized by the helical-moving method) presents a circular, well delimited wall (Fig. 2b). Images of side S2 taken with a CMOS camera during optical pumping are given in

Fig. 1c for DWG-4 and in Fig. 1d for DWG-5. A better confinement of the pump beam is obvious in the case of waveguide DWG-5. In addition, fluorescence images of S2 were recorded with a Spiricon camera (model SP620U, 190-1100 nm spectral range) are shown in Fig. 1e for DWG-4 and in Fig. 1f for DWG-5. Better symmetry of the gain distribution is observed for DWG-5.

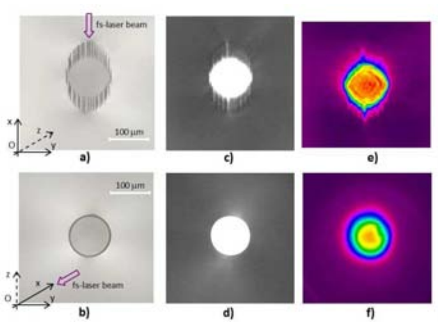

Fig. 2. Microscope photos of two buried depressed-cladding waveguides with ϕ= 100 μm: (a) DWG-4, inscribed by classical method, and (b) DWG-5, written by the helical-movement technique. Camera view of surface S2 under low-pump level at 807 nm: (c) DWG-4 and (d) DWG-5 and fluorescence image of surface S2 for (e) DWG-4 and (f) DFWG-5.

In order to evaluate the propagation losses, a HeNe laser beam (632.8 nm wavelength) was coupled (with unit efficiency) into each waveguide and the power of the incident and transmitted light was measured. Calculus concluded that propagation losses were 1.7 dB/cm for DWG-1, nearly 1.5 dB/cm for DWG-2 and about 1.2 dB/cm for DWG-3. The waveguide DWG-5 (realized by the helical-moving method) had the lower losses of 0.6 dB/cm, whereas losses of DWG-4 were ~1.5 dB/cm. Figure 3 shows propagation of the HeNe beam in bulk Nd:YAG (Fig. 3a) and in waveguides DWG-4 (Fig. 3b) and DWG-5 (Fig. 3c). Comparison between Fig. 3b and Fig. 3c shows that the Nd:YAG with unchanged refractive index left between the inscribed tracks is a reason for increased losses of the waveguides fabricated by the classical writing method.

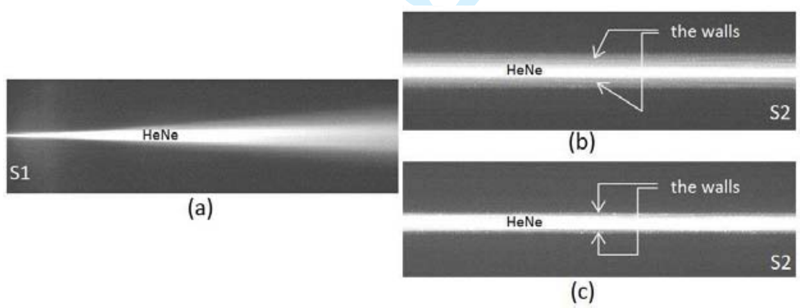

Fig. 3. HeNe laser beam propagation is shown in (a) bulk Nd:YAG, right after surface S1 and after coupling, near the exit surface S2 in waveguides (b) DWG-4 and (c) DWG-5 (2-mm length propagation in all figures). Differences between the waveguide' walls can be observed clearly.

3. Laser Emission Performances

The laser emission characteristics were investigated in plane-plane resonators. The rear mirror was coated high reflectivity (R> 0.998) at 1.06 μm and 1.3 μm and with HT (transmission, T>0.98) at 807 nm (λ_p). Various out-coupling mirrors (OCM), with T between 0.01 and 0.10 for λ_{em}= 1.06 μm and between 0.01 and 0.07 for λ_{em}= 1.3 μm were used; in addition each OCM for λ_{em}= 1.3 μm was coated HT (T> 0.995) at 1.06 μm, to suppress lasing at this high-gain transition. The pump mirror and the output mirror were positioned close of surfaces S1 and S2, respectively, of Nd:YAG. Each Nd:YAG medium was wrapped in Indium foil and clamped in a copper holder whose temperature was controlled at 20^{o}C by Peltier element. The pump was made at 807 nm (λ_p) with a fiber-coupled diode laser (LIMO Co., Germany); the fiber end (100-µm diameter, numerical aperture NA= 0.22) was imaged into a waveguide with a collimating lens of 40-mm focal length and a focusing lens of 30-mm focal length.

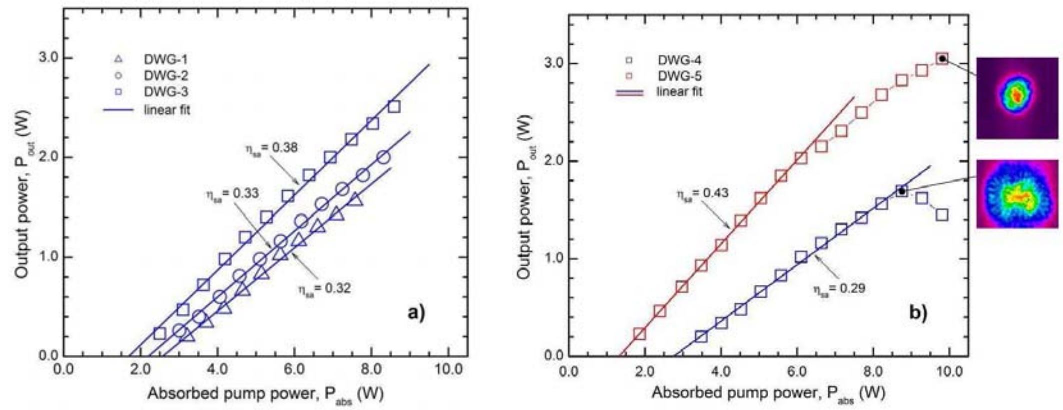

Fig. 4. (a) Cw output power, P_{out} at 1.06 μm versus absorbed pump power, P_{abs} for waveguides DWG-1, DWG-2 and DWG-3. (b) Comparison of laser performances at 1.06 μm yielded by waveguides DWG-4 and DWG-5 is made. The OCM had T= 0.05.

The output power (P_{out}) at 1.06 μm versus the absorbed pump power (P_{abs}) at 807 nm is shown in Fig. 4; the best results were obtained with an OCM of transmission T= 0.05 at this λ_{em}. The waveguide DWG-1 (0.7-at.% Nd:YAG, 4.8 mm) yielded maximum P_{out}= 1.6 W for P_{abs}= 7.6 W, corresponding to an optical-to-optical efficiency η_{oa}= 0.21; the slope efficiency (with respect to P_{abs}) was η_{sa}= 0.32. An increased P_{out}= 2.5 W was measured from waveguide DWG-3 (1.1-at.% Nd:YAG, 7.7 mm) with efficiency η_{oa}= 0.29; the slope amounted to η_{sa}= 0.38. On the other hand, the circular waveguide DWG-5 (1.1-at.% Nd:YAG, 4.5 mm) yielded P_{out}= 3.1 W for P_{abs}= 9.8 W (with η_{oa}= 0.31). The slope efficiency for absorbed power P_{abs} up to 6.6 W was around η_{sa}= 0.43; at this pump level the waveguide DWG-5 emitted P_{out}= 2.2 W with efficiency η_{oa}= 0.33. Saturation of P_{out} was observed for P_{abs} in excess of ~7 W, which can be attributed to the thermal effects induced by optical pumping in the waveguide. The waveguide DWG-4 yielded maximum P_{out}= 1.7 W for P_{abs}= 8.8 W; the slope efficiency was η_{sa}= 0.29. The output power decreased above this pump level. The near-field distribution of the laser beams recorded from waveguides DWG-4 and DWG-5 at corresponding maximum P_{out} are also shown in Fig. 4b.

Differences in the laser emission performances could be explained partially by losses of the waveguides. A Findlay-Clay analysis [22] of threshold pump powers function of OCM transmission was performed for each waveguide in order to evaluate the round-trip cavity residual loss (L_i). The lower loss (of L_i~0.03) were determined for waveguide DWG-5 that was fabricated by the helical moving method. Loss L_i were nearly 0.05 for waveguide DWG-3, whereas L_i increased up to 0.07-0.08 for waveguides DWG-1 and DWG-5.

Efficient emission at λ_{em}= 1.3 μm was achieved only from waveguide DWG-4. As shown in Fig. 5, when an OCM with transmission T= 0.03 at 1.3 μm was used, this waveguide emitted cw power P_{out}= 1.6 W for P_{abs}= 9.3 W; the optical efficiency was η_{oa}= 0.17. The slope efficiency η_{sa} amounted to 0.19. The output power measured from the waveguides fabricated by the classical step-by-step translation method was low, below 0.3 W for P_{abs} of nearly 5 W. The results were attributed to higher losses of these waveguides, but also to an increased heat generation in the medium for laser emission at 1.3 μm in comparison emission at 1.06 μm [23, 24].

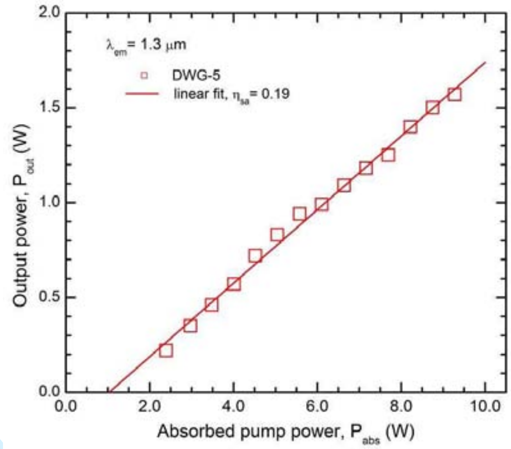

Fig. 5. Cw output power at 1.3 μm yielded by waveguide DWG-5, OCM with T= 0.03.

For the temperature measurement we used a FLIR T620 thermal camera (±2°C accuracy on the −40°C to +150°C range). Still, direct measurement of waveguide DWG-5 temperature was not possible because visualization of side S2 required a longer (about 40-mm length) resonator, for which laser emission ceased at both λ_{em} of 1.06 μm and 1.3 μm. Alternatively, the temperature was measured using the pump directly in Nd:YAG bulk. As shown in Fig. 6a, the 4.5-mm long, 1.1-at.% Nd:YAG ceramic yielded 4.7 W at 1.06 μm for P_{abs}= 8.8 W. Using Findlay-Clay analysis, the residual loss L_i were evaluated below 0.01. The temperature of side S2 reached 49.6^{o}C (Fig. 6b) for the maximum P_{abs}= 8.8 W. Under non-lasing condition (that was obtained by misalignment the resonator OCM) the temperature of side S2 increased up to 64.8^{o}C. Thus, less heat is generated in Nd:YAG under lasing at 1.06 μm in comparison with non-lasing regime. On the other hand, the Nd:YAG medium emitted 2.2-W power at 1.3 μm for P_{abs}= 8.2 W (Fig. 6a). Under non-lasing the S2 side temperature increased to 64.1^{o}C for P_{abs}= 8.2 W; as shown in Fig. 6c the temperature decreased to 61.6^{o}C for lasing. Although less heat is generated for lasing at 1.3 μm in comparison with non-lasing, the generated heat is higher for emission at this λ_{em} in comparison with laser emission at 1.06 μm. Improved output performances at 1.3 μm could be obtained by using a Nd:YAG medium with high-doping level [23, 24], but keeping the residual losses at low level is necessary. The main results reported in this work for cw lasing at 1.06 μm and 1.3 μm are summarized in TABLE I.

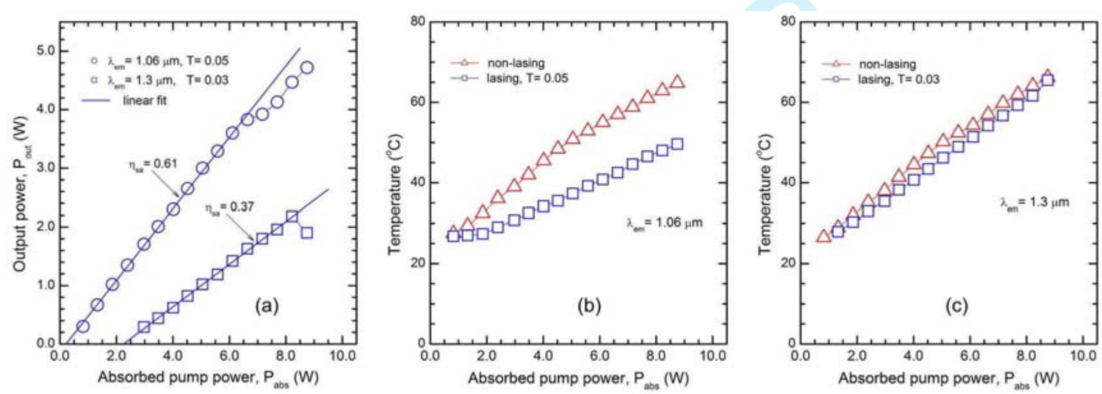

Fig. 6. (a) Cw laser emission at 1.06 μm and 1.32 μm obtained by the pump in bulk 1.1-at.% Nd:YAG (4.5-mm length); the resonator length was 40 mm. Maximum temperature of the output surface S2 for laser emission at (b) 1.06 μm and (c) 1.3 μm.

TABLE I
THE RESULTS OBTAINED FOR CW LASER EMISSION AT 1.06 μm and 1.3 μm

Writing method	Waveguide	Nd:YAG	λ_{em} (μm)	Output power, P_{out} (W)	Optical efficiency, η_{oa}	Slope efficiency, η_{sa}	Pump beam absorption efficiency, η_a
Classical step-by-step translation method	DWG-1	0.7-at.% Nd, 4.8 mm	1.06	1.6	0.21	0.32	0.82
	DWG-2	0.7-at.% Nd, 7.8 mm		2.0	0.24	0.33	0.90
	DWG-3	1.1-at.% Nd, 7.7 mm		2.5	0.29	0.38	0.93
	DWG-4	1.1-at.% Nd, 4.5 mm		1.7	0.19	0.29	0.89
Helical-moving technique	DWG-5			3.1	0.32	0.43	
			1.3	1.6	0.17	0.19	

Q-switch operation of such a waveguide laser is interesting for various applications as pulses with short duration and high-peak power could be obtained. Previously, a type II waveguide inscribed in Nd:YAG was passively Q-switched by Cr^{4+}:YAG SA, yielding 300 mW average power, 1-ns duration pulses at 300 kHz repetition rate [25]. Also, type II waveguides fabricated in Yb:YAG and Nd:YVO_4 were Q-switched by carbon nanotubes [26] and graphene [27], respectively. Laser pulses with nearly 40-nJ energy and 78-ns duration were obtained [26]. Mode-locking with single-layer graphene of a circular, buried depressed-cladding waveguide inscribed in Nd:YAG was reported recently [28].

In our experiments passive Q-switching at 1.06 μm was obtained with an uncoated Cr^{4+}:YAG SA crystal of 0.90 initial transmission. We used the waveguide DWG-3 (1.1-at.% Nd, 7.7 mm) because it assures high absorption of the pump beam; thus, the unabsorbed pump light will have little influence on the Cr^{4+}:YAG properties. The Cr^{4+}:YAG SA was positioned between side S2 of Nd:YAG and an OCM with T= 0.05; the resonator length was 10.5 mm. This Q-switch laser started to oscillate at P_{abs}= 4.5 W and delivered maximum average power of 680 mW for P_{abs}= 9.2 W. The highest repetition rate was 34.4 kHz and the pulse energy was estimated to be 19.7 μJ. The pulse duration was 2.8 ns and therefore the pulse peak power reached 7 kW.

4. Conclusions

In summary, we have obtained efficient laser emission using the pump with fiber-coupled diode laser of circular (100-μm diameter), buried depressed cladding waveguides that were inscribed in several Nd:YAG ceramics by fs-laser beam writing method. Output powers of 3.1 W at 1.06 μm and of 1.6 W at 1.3 μm were measured from a 4.5-mm long waveguide that was inscribed in a 1.1-at.% Nd:YAG using a novel, helical-moving of the medium writing technique. The optical-to-optical efficiency was 0.32 at 1.06 μm and 0.17 at 1.3 μm, whereas the slope efficiency was 0.43 and 0.19, respectively. Laser operation in Q-switch regime was obtained with Cr^{4+}:YAG SA, the waveguide laser delivering 680 mW average power, in pulses with 19.7-μJ energy at 7-kW pulse peak power. To the best of our knowledge the data reported in this work for both cw and Q-switch operation are the highest for such configurations; these results prove the potential of the waveguides inscribed by fs-laser beam technique to realize efficient integrated laser sources pumped by fiber-coupled diode lasers.

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strengths for selected transition. Competing processes describing the level population distribution include auto-ionization, Auger decay and collisional ionization of the outer –shell electrons by electrons generated during photo-ionization.

I.I.7. Depressed-cladding waveguides inscribed in Nd:YAG and $Nd:YVO_4$ by femtosecond-laser writing technique. Realization and laser emission

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The femtosecond-laser writing technique was used to inscribe circular (up to 100-μm diameter) depressed-cladding waveguides in Nd:YAG and $Nd:YVO_4$. Laser emission (of few mJ-energy per pulse) at 1.06 μm and 1.3 μm was achieved under quasi-continuous-wave pumping with a 0.81-μm emitting fiber-coupled diode laser. Continuous-wave 1.06-μm emission with wattpower level was recorded from such waveguides. While these first structures were fabricated by a step-by-step translation technique, we have proposed a novel helical-moving method to realize waveguides in Nd:YAG with decreased losses and improved output performances. Laser emission in $Nd:YVO_4$ waveguides was improved by employing the pump at 0.88 μm.

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— Keio University, Kanagawa, Japan

We achieved the first diode-pumped mode-lock Pr:YLF laser. The average output power reaches 68 mW at 640 nm with a pulse width of 15 ps and a repetition rate of 108 MHz.

CA-P.24 *(910)* Sun 12:30

Temperature Influence on Diode-pumped Tunable $Tm:BaF_2$ Laser — •J. SULC[1], M. NEMEC[1], M. FIBRICH[1], H. JELINKOVA[1], M.E. DOROSCHENKO[2], V.A. KONYUSHKIN[2], and V.V. OSIKO[2] — [1]Czech Technical University in Prague, Prague, Czech Republic — [2]AM Prokhorov General Physics Institute of RAS, Moscow, Russia

The performance and tunability of a newly developed $Tm:BaF_2$ laser was investigated. The temperature independent (80 – 280 K) laser tuning range extended from 1822 nm up to 1948 nm.

CA-P.25 *(679)* Sun 12:30

Room temperature, diode-side-pumped, passively Q-switched Yb:LuAG slab laser — •M. KASKOW[1], J.K. JABCZYNSKI[1], W. ZENDZIAN[1], J. SULC[2], M.

Lübeck, Lübeck, Germany

In order to increase the energy of a Q-switched Ho:YAG laser pulses with durations stretched to several hundred nanoseconds, a master oscillator power amplifier system pumped by a single source was designed for medical applications.

CA-P.29 *(253)* Sun 12:30

Diode-Pumped Laser Emission from Depressed Cladding Waveguides Inscribed in Nd-doped Media by Femtosecond Laser Writing Technique — •G. SALAMU[1], N. PAVEL[1], T. DASCALU[1], F. JIPA[2], and M. ZAMFIRESCU[2] — [1]National Institute for Laser, Plasma and Radiation Physics, Solid-State Quantum Electronics Laboratory, Bucharest 077125, Romania — [2]National Institute for Laser, Plasma and Radiation Physics, Solid-State Laser Laboratory, Bucharest 077125, Romania

Depressed cladding waveguides were inscribed in Nd:YAG and Nd:YVO4 laser media by direct optical writing with a femtosecond-laser beam. Continuous-wave laser emission at 1.06 microns was obtained under the pump with fiber-coupled diode lasers.

Diode-Pumped Laser Emission from Depressed Cladding Waveguides Inscribed in Nd-doped Media by Femtosecond Laser Writing Technique

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Femtosecond- (fs-) laser pulses are recognized nowadays as an important tool for realizing optical devices in many materials. A change of the refractive index appears in the region were the laser pulse interacts with the material. Based on this effect, waveguides were inscribed in various laser media, like Nd:$Y_3Al_5O_{12}$ (Nd:YAG) and Yb:YAG, Nd:YVO_4 and Nd:$GdVO_4$, Pr:$YLiF_4$ and Pr:$SrAl_{12}O_{19}$, or mid-infrared emitting Tm and Cr:ZnS media [1,2]. Continuous-wave (cw) emission was obtained from these waveguides, using in principal the pump with Ti:sapphire lasers. In this work we report on realization of depressed cladding waveguides in Nd:YAG (single crystals and ceramics) and in Nd:YVO_4 by a classical (step-by-step translation) fs-laser writing method; furthermore, a new (helical moving of the medium) inscribing technique is proposed. Cw laser emission at 1.06 μm was achieved from these waveguides under the pump with a fiber-coupled diode laser.

The first waveguides were inscribed by the step-by-step translation method [3], using a chirped pulsed amplified Clark CPA-2101 (200-fs duration at 2-kHz repetition rate, 775-nm wavelength) laser. The fs-laser beam energy, the focusing conditions and the translation speed were carefully chosen for each medium through experiments [4,5]. Depressed cladding waveguides with a diameter between 50 and 100 μm were inscribed in 0.7-at.% Nd:YAG single crystals, in 0.7 and 1.1-at.% Nd:YAG ceramics and in Nd:YVO_4 crystals of 0.5, 0.7 and 1.0-at.% Nd, of various lengths; the media were polished after writing, but left uncoated. Laser emission at 1.06 μm was obtained in short, linear resonators, using the pump at 808 nm with a 100-μm fiber-coupled diode laser. The highest performances were measured, in general, with an output mirror with transmission T= 0.05.

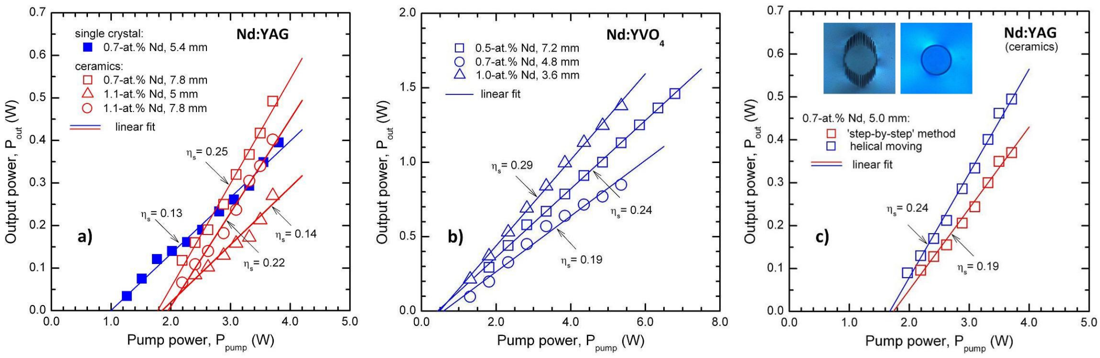

Fig. 1 Output power at 1.06 μm obtained from 100-μm diameter depressed cladding waveguides inscribed by classical 'step-by-step' translation method in **a)** Nd:YAG media and **b)** Nd:YVO_4 crystals, or realized in **c)** Nd:YAG ceramics by classical method as well as by a new helical moving technique. Each medium length is indicated on the figure. Inset of Fig. 1c shows typical images of a cladding waveguide inscribed by the classical method (left) and by the helical moving technique (right).

As shown in Fig. 1a, an output power (P_{out}) of 0.49 W for 3.7-W pump power (P_{pump}) was obtained from a 100-μm diameter waveguide that was realized in a 0.7-at.% Nd:YAG ceramic of 7.8-mm length. A similar waveguide inscribed in a 7.2-mm thick, 0.5-at.% Nd:YVO_4 yielded P_{out}= 1.46 W for P_{pump}= 6.8 W (Fig. 1b).

The walls of such depressed cladding waveguide consist of many parallel tracks [3]; therefore, each space of unmodified refractive index that is left between consecutive tracks can increases the waveguide propagation losses. In order to obtain waveguides with continuous walls we proposed a new technique, in which the laser medium is moved on a helical trajectory, with it axis parallel to the fs-laser beam [6]. For example, an 100-μm diameter waveguide inscribed in a 5.0-mm thick, 0.7-at.% Nd:YAG ceramic had 1.1-dB/cm propagation losses, lower than 1.6 dB/cm losses of a similar waveguide written by the classical method. Thus, higher P_{out} (0.5 W in comparison with 0.37 W at the same P_{pump}= 3.7 W) was obtained from this new circular waveguide (Fig. 1c).

In conclusion, we have obtained cladding waveguides in Nd:YAG and Nd:YVO_4 by direct writing with a fs-laser beam and show that such devices present potential for realizing diode-pumped integrated laser sources.

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of the SRS-spectrum of acetone and stable long-term operation over 45 min by taking an SRS image of PM-MA-beads.

EVELYN STRUNK

Coherent Revivals of Nonlinear Refractive Index Changes in Carbon Disulfide Vapors

Carbon Disulfide (CS2) has been studied in nonlinear optics (NLO) for many years but typically in liquid form. The experiments I am performing study CS2 in vapor form. I am utilizing the beam deflection technique which is an extremely sensitive technique shown to be sensitive to one 20 thousandth of a wavelength. This same experiment has been performed and revivals of the refractive index were observed in the components of air, nitrogen and oxygen, using femtosecond excitation. When the molecules are excited with the femtosecond excitation beam (essentially giving the impulse response function of the molecules), liquid molecules rotate but are restricted by the surrounding molecules; however, in vapor form, the molecules are able to make many complete revolutions. We are able to see the nonlinear refractive response of the carbon disulfide vapors for many 10's of picoseconds. I will present analyses of these results.

GABRIELA SALAMU

Efficient Laser Emission from Waveguides Inscribed in Nd-doped Media by Femtosecond-Laser Writing Technique

In this work we report on the realization of depressed cladding waveguides in Nd-doped laser media by direct writing with a fs-laser beam.The first waveguides were fabricated by a classical step-by-step translation technique. Using the pump at 808 nm with a fiber-coupled diode laser we have obtained efficient laser emission at 1.06 and 1.3 microns from circular waveguides inscribed in Nd:YAG. Further, we have developed a novel technique in which the laser medium is moved on a helical trajectory during the writing process. We applied this arrangement to inscribe, in Nd:YAG ceramics, cylindrical waveguides with improved laser performances than those of similar waveguides realized by the classical method. Circular depressed cladding waveguides were also inscribed in Nd:YVO4. These results show that depressed cladding waveguides inscribed by fs-laser writing techniques can be a solution for realizing of diode-pumped compact lasers.

STEPHEN WOLF

2um Degenerate OPO's for Dielectric Particle Accelerators

We present the work our group is doing in order to power scale 2um degenerate optical parametric oscillators (OPOs). Such devices are methods of taking a frequency locked pump (1um in our devices) and transferring the frequency comb properties to wavelengths deeper in the infrared. The current use of these devices will also be discussed, where we use the ultrafast 2um radiation (around 50fs) to drive a dielectric particle accelerator.

JOHNSTON K. KALWE

Exploiting Cellophane Birefringence to Generate Radially and Azimuthally Polarized Vector Beams

We exploit the birefringence of cellophane to convert a linearly polarised Gaussian beam into either a radially or azimuthally polarised beam. For that, we fabricated a low-cost polarisation mask consisting of four segments of cellophane. The fast axis of each segment is oriented appropriately in order to rotate the polarisation of the incident linearly polarised beam as desired. To ensure the correct operation of the polarisation mask, we tested the polarisation state of the generated beam by measuring the spatial distribution of the Stokes parameters. Such a device is very cost efficient and allows for the generation of cylindrical vector beams of high quality.