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Passive Q-switch laser operation of circular, buried depressed-cladding waveguides realized by direct fs-laser beam writing in Nd:YAG/Cr^{4+}:YAG composite media

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Abstract: Circular, buried depressed-cladding waveguides were inscribed by direct fs-laser beam writing in diffusion-bonded Nd:YAG/Cr^{4+}:YAG composite media. Passive Q-switch operation was achieved using the pump at 807 nm with a fiber-coupled diode laser. Laser pulses at 1.06 µm with energy of 15.7 µJ and 3.9-ns duration (corresponding to a peak power of 4.0 kW) were obtained from a waveguide of 150-µm diameter that was realized in a 10.3-mm long, 1.0-at.% Nd:YAG/Cr^{4+}:YAG composite medium. The length of Nd:YAG crystal was 7.0 mm and initial transmission of Cr^{4+}:YAG saturable absorber crystal was 0.70. The average output power reached 1.13 W.

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1. Introduction

A large variety of photonic systems can now be built in many configurations, being designed to include various compact or miniature laser sources, such as waveguide lasers [1,2]. In the past decade a lot of research has been done based on the ability of a femtosecond- (fs-) laser beam to induce controllable changes of the refractive index in an amorphous or crystalline material. Thus, an fs-laser beam was used, for the first time by Davis et al. to inscribe tracks in some glasses [3]. In the case of such a material, melting and re-solidification of the

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irradiated zone provides a line (or a track) with an increased index of refraction compared with that of the medium; consequently, the track itself is used for light propagation.

In another writing technique that is mainly adequate for laser crystals, the fs-laser beam modifies (it can even damage) the crystal inside the irradiated region. Still, an increase of the refractive index is obtained in the adjacent zones by stress field [4]. In this case guiding can be realized between two tracks; such a waveguide is suitable for single transverse mode operation, although the narrow distance (of few tens of μm) between the walls imposes limits on the device power scalability. Channel waveguides consisting of two walls have been realized in many laser materials, including Nd:$Y_3Al_5O_{12}$ (Nd:YAG) [5] and Yb:YAG [6], or Nd:$GdVO_4$ [7]. Efficient laser emission was achieved from such channel waveguides employing as pump source continuous-wave (cw) tunable Ti:sapphire laser.

The buried depressed-cladding waveguide is nowadays recognized as the main configuration that allows power scaling of a waveguide that is directly written by the fs-laser beam technique. In this scheme, many parallel tracks are written around a defined contour [8,9], and a tubular waveguide is obtained by propagating the light inside this structure. Buried depressed-cladding waveguides (of different shapes) were inscribed in Nd:YAG [10] and Nd:YVO_4 [11], Tm:YAG [12] or Pr:$YLiF_4$ [13] (just to name few of them), from which laser emission performances were evaluated using, mainly, Ti:sapphire laser for the optical pump. Some reviews on the results obtained on various waveguides inscribed by direct writing with fs-laser beam could be found in Ref [2,14,15]. Our group have also inscribed circular, buried-depressed cladding waveguide in Nd:YAG and Nd-vanadates, from which watt-level power at 1.06 μm as well as 1.3 μm was obtained in cw regime under the pump with fiber-coupled diode laser [16–18].

Cladding waveguides realized by direct writing with an fs-laser beam can be used in other integrated components, such as for beam manipulation [19] or for generation of visible light [20]. Very attractive is the possibility to obtain laser pulses with high-peak power by passive Q-switch and to integrate such a laser device for nonlinear conversion applications. For the first time, a circular buried depressed-cladding waveguide (with diameter of 110 μm) was inscribed by Okhrimchuk in a 5.4-mm long diffusion-bonded Nd:YAG/Cr^{4+}:YAG composite medium with 57% initial transmission (T_0) of Cr^{4+}:YAG saturable absorber (SA) [21]. The Q-switch operation was investigated in pump-pulse mode with a fiber-coupled diode laser emitting at 808 nm. Laser pulses at 1.06 μm with energy (E_p) of 10 μJ and 1.0-ns duration (t_p) were obtained at 1.0-kHz repetition rate (f_p). Calmano et al. have realized a two-wall channel waveguide in a 1.1-at.% Nd:YAG/Cr^{4+}:YAG (T_0~30%) composite medium with total length of 9.5 mm [22]. The pump with a Ti:sapphire laser enabled Q-switch operation with 300-mW average power (P_{ave}); the laser pulse energy was E_p = 1 μJ at f_p = 300 kHz and the shortest pulse duration was t_p = 1.0 ns. The same group has realized a similar channel waveguide in Yb:YAG/Cr^{4+}:YAG composite medium [23]. Passively Q-switch operation with few-ns pulse durations at f_p = 600 kHz (P_{ave} = 0.61 W) and E_p = 2.7 μJ (peak power, P_p around 1 kW) was achieved under the pump at 940 nm with a Ti:sapphire laser.

Other papers reported on laser emission in various waveguides that were inscribed by fs-laser beam and that were operated in Q-switch regime with SA media positioned nearby the laser medium. Thus, Q-switch operation of buried depressed double-cladding waveguides that were inscribed in Nd:YAG ceramics was obtained with external semiconductor saturable-absorber mirror (SESAM) [24]. Laser pulses with E_p~14 μJ and duration t_p = 21 ns at the repetition rate f_p = 3.65 MHz were obtained. A channel waveguide that was inscribed in an Yb:YAG crystal was Q-switched by an SA mirror that was made of single-walled carbon nanotubes [25]. The laser operated at f_p = 1.59 MHz (P_{ave} = 60 mW) with pulses of energy E_p = 37.7 nJ and duration t_p = 88 ns. A graphene SA mirror was used to passively Q-switch 3D structures that were inscribed in Nd:YAG [19]. Average power P_{ave} = 243 mW with pulses at high (above 4 MHz) repetition rate, energy E_p~55 nJ and duration t_p = 70 ns was obtained. A graphene thin film was employed to obtain 1064-nm Q-switch operation from a channel waveguide that was written in $Nd:YVO_4$ [26]. The pulse energy and duration was 8.1 nJ and 25.0 ns, respectively, with an average output power P_{ave} = 129 mW. A single-layer graphene was used to obtain mode-locking in an elliptical buried depressed-cladding waveguide that was inscribed in Nd:YAG; the laser delivered pulses with t_p = 16 ps and repetition rate up to f_p = 11.3 GHz (average power P_{ave} = 12 mW) [27].

Molybdenum disulfide (MoS_2) SA film was used for Q-switch operation of a depressed-cladding waveguide realized in Nd:YAG crystal [28]. Circular depressed-cladding waveguides inscribed in Nd:YAG were operated in Q-switch regime with tungsten disulfide (WS_2) and black phosphorous films [29] or WS_2 and molybdenum diselenide membranes that were coated on silica wafers by chemical vapour deposition [30]. A monolithic Q-switch waveguide laser was obtained by a monolayer graphene that was transferred onto one end surface of a two-line channel waveguide inscribed in Yb:YAG crystal [31]. Apart from other waveguides lasers, in this case the pump was made at 940 nm with a single-mode diode laser. The device delivered laser pulses (at 1029 nm) with energy E_p = 64 nJ and duration t_p = 96 ns at repetition rate f_p = 1.33 MHz (P_{ave} = 85 mW). Recently, high-average power P_{ave} = 5.6 W was reported from an Yb:YAG channel waveguide that was passively Q-switched with an SESAM mirror [32]. The laser operated at f_p = 5.4 MHz yielding pulses with duration t_p = 11 ns and energy E_p~1 μJ. A VO_2 SA crystal was used to Q-switch superficial cladding waveguides that were inscribed in $Nd:YVO_4$ [33]. Laser pulses with t_p = 690 ps were obtained at f_p = 2.9 MHz; the average power was P_{ave} = 66.7 mW, indicating that energy E_p was around 23 nJ. The depressed-cladding waveguide can be also inscribed in Cr^{4+}:YAG SA and then used for passive Q-switching of various configuration, like an Yb-fiber laser [34].

One could observe that most of the works mentioned above have employed as Q-switches SA media that were positioned separately, nearby the waveguide laser. Moreover, very few [21,31] have considered the pump with a diode laser. In addition, the Q-switch with graphene, MOS_2, WS_2 and black phosphoros films or even SESAM delivered laser pulses with low (few-tens of nJ) energy and limited average output power. Recently, we have reported passive Q-switching with Cr^{4+}:YAG SA of a circular buried depressed-cladding waveguide that was inscribed in Nd:YAG ceramics; the pump was done with a fiber-coupled diode laser, but still the SA crystal was positioned nearby the waveguide [17]. The laser pulse energy and duration was 19.7 μJ and 2.8 ns, corresponding to a laser peak power of 7 kW. These results show that Cr^{4+}:YAG SA is a good choice for obtaining laser pulses at 1.06 μm with both high energy and high peak power, whereas integration as well as the pump with a fiber-coupled diode laser could further increase the interest for such miniature devices.

In this work we report on laser performances obtained from circular, buried depressed-cladding waveguides inscribed by fs-laser beam in diffusion-bonded Nd:YAG/Cr^{4+}:YAG composite media and that were pumped by a fiber-coupled diode laser. Laser pulses at 1.06 μm with energy E_p = 15.7 μJ and duration t_p = 3.9 ns at f_p = 71.9-kHz repetition rate were obtained from an waveguide with 150-μm diameter that was realized in a Nd:YAG/Cr^{4+}:YAG composite medium that consisted of a 7.0-mm long, 1.0-at.% Nd:YAG crystal and a Cr^{4+}:YAG SA crystal with initial transmission T_0 = 0.70. The average output power was P_{ave} = 1.13 W. This seems to be the first demonstration of a circular, buried depressed-cladding waveguide that was inscribed by fs-laser beam in a Nd:YAG/Cr^{4+}:YAG composite medium and that was pumped with fiber-coupled diode laser to deliver watt-level average power at 1.06 μm in passive Q-switch regime.

2. Waveguides fabrication and characterization

In the experiments we used three diffusion-bonded Nd:YAG/Cr^{4+}:YAG composite media (Atom Optics Co. Ltd, China). The active side was (in the case of each composite medium) a Nd:YAG crystal with doping level of 1.0-at.% Nd and length of 7.0 mm. The Cr^{4+}:YAG SA was also a crystal, with initial transmission (as requested by us and then as specified by the supplier) of T_0 = 0.85 for the first composite medium (denoted by NYAG-1), T_0 = 0.80 for the

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second composite medium (NYAG-2) and T_0 = 0.70 for the third composite medium (denoted by NYAG-3). The total length of each Nd:YAG/Cr^{4+}:YAG composite medium was 8.5 mm for NYAG-1, 9.0 mm for NYAG-2 and 10.3 mm for NYAG-3.

A chirped pulsed amplified system (Clark CPA-2101) that delivered laser pulses at 775 nm with 200-fs duration and energy up to 0.6 mJ, at 2-kHz repetition rate, was used for inscribing the waveguides [16–18]. A combination of a half-wave plate, a polarizer and calibrated neutral filters was built to control the fs-laser pulse energy (and thus to choose the energy for obtaining tracks in the Nd:YAG/Cr^{4+}:YAG composite media). The fs-laser beam was focused with an aspheric lens of 7.5-mm focal length and numerical aperture NA = 0.30; the beam diameter at the focus position was ~5 µm (in air). The waveguides were realized by the step-by-step writing technique [8,9]. Thus, each composite medium was positioned on a motorized XYZ stage that was moved at 100-µm/s speed on Oz direction. Through experiments it was observed that a track can be obtained with fs-laser pulses of 3-µJ energy (measured after the focusing lens). After completing a track, the stage was moved to a different position in the Oxy plane and a new track was inscribed; the distance between two consecutive tracks was set at 5 µm. In this way many parallel tracks were realized around circular contours with defined diameters. The cores with unmodified refractive index are the circular, buried depressed-cladding waveguides; all waveguides were centered 500-µm below the surface of a Nd:YAG/Cr^{4+}:YAG composite medium. After inscribing the tracks, the surfaces of each Nd:YAG/Cr^{4+}:YAG were polished at laser grade (this reduced the length of both Nd:YAG and Cr^{4+}:YAG, but only with few tens of µm). In addition, these sides were coated as antireflection (reflectivity R< 0.25%) at the lasing wavelength λ_{em} = 1.06 µm and with high transmission (transmission T> 0.99) at the pump wavelength λ_p = 807 nm.

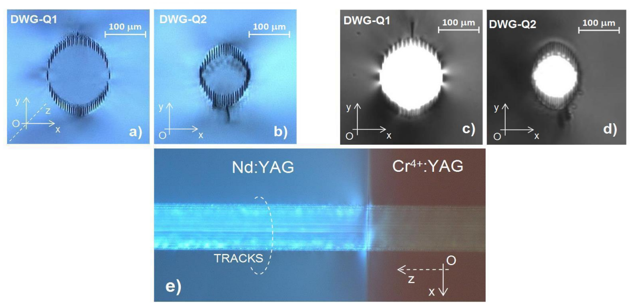

Fig. 1. Photos of two circular buried depressed-cladding waveguides inscribed in Nd:YAG/Cr^{4+}:YAG composite media are shown. Microscope view of (a) DWG-Q1 (ϕ = 150 µm) and (b) DWG-Q2 (ϕ = 100 µm). Photo taken during the optical pump of (c) DWG-Q1 and (d) DWG-Q2. (e) Photo from top of DWG-Q1; the waveguide position is visible in both Nd:YAG active medium and in Cr^{4+}:YAG SA.

Circular cores with diameter (ϕ) of 100 µm and 150 µm were obtained in all the Nd:YAG/Cr^{4+}:YAG composite media. Results will be presented further for three selected structures. Cross-section views of two circular depressed-cladding waveguides are given in Fig. 1. The waveguide shown in Fig. 1(a) has a diameter ϕ = 150 µm and it was realized in NYAG-1 (Cr^{4+}:YAG with T_0 = 0.85); this waveguide will be denoted by DWG-Q1. A similar waveguide (ϕ = 150 µm) that was written in the NYAG-3 composite medium (Cr^{4+}:YAG with T_0 = 0.70) will be named by DWG-Q3. A microscope view of a circular waveguide with ϕ = 100 µm (denoted by DWG-Q2) that was obtained in NYAG-2 (Cr^{4+}:YAG with T_0 = 0.80) is shown in Fig. 1(b). Guiding in these waveguides is illustrated in Fig. 1(c) and Fig. 1(d) that present views of Cr^{4+}:YAG side for DWG-Q1 and DWG-Q2, respectively under the pump at 807 nm. Furthermore, Fig. 1(e) is a photo of the waveguide DWG-Q1 taken from top (in the Oxz plane); the waveguide position is clear and several inscribed tracks can be seen.

In order to evaluate the propagation losses, the light (red at 632.8 nm) of a HeNe laser was coupled (with a coupling efficiency equal to unit) in each waveguide and light power was measured before and after the waveguide. The calculus concluded that the propagation loss at 632.8 nm was 0.9 dB/cm for the waveguide DWG-Q1; also, loss for the waveguide DWG-Q2 and DWG-Q3 amounted to 0.7 dB/cm and 0.6 dB/cm, respectively. Although small, the differences between these losses suggest that improvements of the writing technique are still necessary. On the other hand, these values compares quite well with the losses of 0.8 to 1.4 dB/cm that were reported for various buried depressed-cladding waveguides that were inscribed in Nd:YAG ceramics by the same writing technique [10]. Furthermore, loss is decreased in comparison with the values (of up to 1.7 dB/cm) that were measured in our previous work for circular buried depressed-cladding waveguides that were written in Nd:YAG ceramics [17]. It should be noted that these losses include some absorption of each Cr^{4+}:YAG sample at the 632.8 nm wavelength of the HeNe laser probe.

3. Laser emission experiments. Results and discussion

The optical pump was made at λ_p = 807 nm with a fiber-coupled diode laser (LIMO Co., Germany) that was operated in cw mode. The fiber diameter was 100 μm with numerical aperture NA = 0.22. For collimating the pump beam we used an aspheric lens with focal lens of 50 mm. The focusing was done with an aspheric lens of 40 mm for waveguide DWG-Q2 (ϕ = 100 μm) whereas in the case of the waveguides with ϕ = 150 μm a high coupling efficiency (equal to unit) of the pump beam was obtained with an aspheric focusing lens of 60-mm focal length.

Laser emission was achieved in a linear resonator with plane mirrors that were positioned very close of each Nd:YAG/Cr^{4+}:YAG composite medium. The resonator rear high-reflectivity mirror (HRM) was coated high reflectivity, HR (reflectivity, R> 0.998) at λ_{em} = 1.06 μm and with high transmission (transmission, T> 0.98) at λ_p = 807 nm. This mirror was positioned near the Nd:YAG side of a composite medium. The out-coupling mirror (OCM) was placed right after the Cr^{4+}:YAG SA; various mirrors with transmission T between 0.05 and 0.60 were used. Each Nd:YAG/Cr^{4+}:YAG composite medium was wrapped in Indium foil and fixed in a copper holder whose temperature was maintained at 20°C by a Peltier element. We mention that the pump beam absorption efficiency (η_a) was determined using a 7.0-mm long, 1.0-at.% Nd:YAG crystal (Atom Optics Co. Ltd, China). Measurements concluded that η_a~0.90; therefore, it is considered that the residual pump radiation after Nd:YAG does not affect the initial transmission T_0 of a Cr^{4+}:YAG SA crystal.

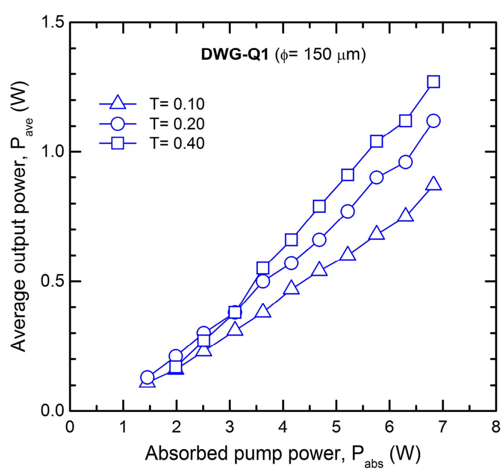

Fig. 2. Average output power, P_{ave} at 1.06 μm versus the absorbed pump power, P_{abs} at 807 nm yielded by the waveguide DWG-Q1 (NYAG-1 of T_0 = 0.85). T is the OCM transmission.

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Main parameters of laser emission, like average output power, P_{ave}, pulse repetition rate, f_p and pulse duration, t_p (FWHM definition) were determined for each waveguide. For example, Fig. 2 presents the dependence of P_{ave} yielded by waveguide DWG-Q1 versus the absorbed pump power, P_{abs} at λ_p = 807 nm. One can see that with an OCM of T = 0.10 this waveguide delivered P_{ave} = 0.87 W at λ_{em} = 1.06 µm for P_{abs} = 6.8 W at 807 nm. The repetition rate was f_p = 116.9 kHz and therefore the laser pulse energy amounted to E_p = 7.4 µJ. The pulse duration was t_p = 4.2 ns, which indicates a pulse peak power of P_p = 1.76 kW. We mention that the laser pulse frequency and duration were measured with a fast UPD-35-IR2-D photodiode (Alphalas, Germany) with a short (<35 ps) rise time and recorded with a Tektronix DPO7254 digital oscilloscope (2.5-GHz bandwidth, 40-GS/s sample rate). On the other hand, when an OCM with T = 0.40 was used, the output power yielded by the waveguide DWG-Q1 increased to P_{ave} = 1.27 W. The ratio between P_{ave} and the absorbed pump power P_{abs} was η~0.19. The repetition rate was f_p = 138.8 kHz and therefore the pulse energy reached E_p = 9.15 µJ. The laser pulse peak power was P_p = 1.99 kW. The absorbed pump power at threshold was P_{abs}~1.0 W for the OCM with T = 0.10 and it increased to P_{abs}~1.5 W for the OCM with T = 0.40.

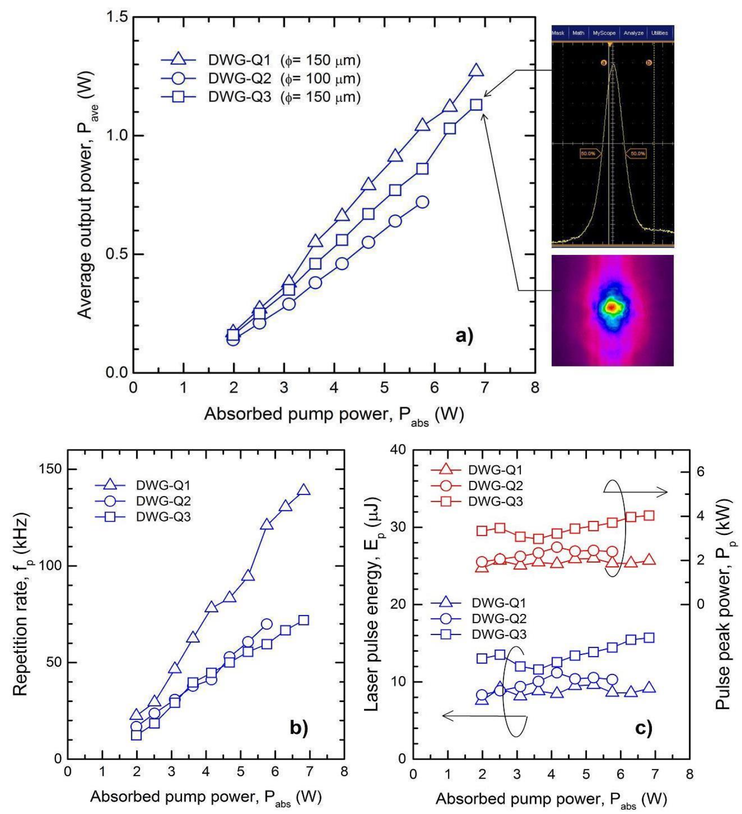

Fig. 3. Characteristics of Q-switch operation obtained from all circular, buried depressed-cladding waveguides, OCM with T = 0.40. (a) Average output power, P_{ave}. The laser pulse temporal shape and the laser beam near-field distribution are shown at the indicated point. (b) Laser pulse repetition rate. (c) Laser pulse energy, E_p and corresponding peak power, P_p.

The best performances obtained from all three waveguides are plotted in Fig. 3 for an OCM with transmission T = 0.40. The waveguide DWG-Q3 (that was written in NYAG-3, the composite medium with Cr^{4+}:YAG of T_0 = 0.70) yielded an average power P_{ave} = 1.13 W at P_{abs} = 6.8 W [Fig. 3(a)]. The repetition rate varied linearly with P_{abs} [as shown in Fig. 3(b)], increasing from f_p = 12.3 kHz at low levels (P_{ave} = 0.16 W, P_{abs}~2.0 W) up to f_p = 71.9 kHz

(P_{out} = 1.13 W, P_{abs} = 6.8 W; η~0.17). In addition, the laser pulse energy was nearly constant on the entire pump level (as expected for a passively Q-switched laser system), with a value E_p = 15.7 µJ at the highest pump level of P_{abs} = 6.8 W [Fig. 3(c)]. The pulse duration was also constant, t_p = 3.9 ns, indicating a pulse peak power of P_p = 4.0 kW [Fig. 3(c)]. The temporal shape of the laser pulse (t_p = 3.9 ns) is presented in the inset of Fig. 3(a). It is worthwhile to mention that several acquisitions, each of 500 laser pulses, concluded that peak-to-peak fluctuation (standard deviation) was below 3% whereas changes in the pulse duration were less than 2%. A Spiricon camera (model SP620U, 190-1100 nm spectral range) was employed to record the laser-beam near-field distribution. As shown in the inset of Fig. 3(a), the beam is symmetric and of multimode transverse distribution. The laser beam M^2 factor (that was measured by the 10%-90% knife-edge method) was M^2 = 4.6 at low output power (P_{ave} = 0.4 W) and increased up to M^2 = 5.3 at the maximum power yielded by this waveguide.

In the case of waveguide DWG-Q2 (ϕ = 100 µm, the NYAG-2 with Cr^{4+}:YAG of T_0 = 0.80), the average power at 1.06 µm reached P_{ave} = 0.72 W for P_{abs} = 5.75 W at 807 nm [Fig. 3(a)]. At this point the repetition rate was f_p = 69.9 kHz [Fig. 3(b)] and thus the laser pulse energy was evaluated as E_p = 10.3 µJ. The pulse duration was t_p = 4.3 ns, indicating a pulse peak power of P_p~2.4 kW. Increasing the pump above this level resulted, unfortunately, in a fast decrease of the laser power; later observations concluded that the NYAG-2 medium was damaged along this waveguide. This behavior could be attributed to thermal effects during laser emission and to some induced stress while inscribing the waveguide, but further investigations are necessary for a better explanation of the phenomenon.

Table 1. Characteristics of laser pulses at 1.06 µm obtained from the circular, buried depressed-cladding waveguides investigated in this work, OCM with T = 0.40.

Nd:YAG/Cr^{4+}:YAG ceramic medium / T_0	Waveguide, ϕ (µm)	Average output power, P_{ave} (W)	Absorbed pump power, P_{abs} (W)	P_{ave} / P_{abs}, η	Pulse energy, E_p (µJ)	Pulse peak power, P_p (kW)
NYAG-1, T_0= 0.85	DWG-Q1, ϕ= 150 µm	1.27	6.80	~0.19	9.1	1.99
NYAG-2, T_0= 0.80	DWG-Q2, ϕ= 100 µm	0.72	5.75	~0.13	10.3	2.4
NYAG-3, T_0= 0.70	DWG-Q3, ϕ= 150 µm	1.13	6.80	~0.17	15.7	4.0

The characteristics of laser emission obtained in this work from the circular, buried depressed-cladding waveguides that were inscribed by the fs-laser beam writing technique in the Nd:YAG/Cr^{4+}:YAG composite media are summarized in Table 1. It can been seen that, as expected, laser pulses with increased energy and higher peak power were obtained by using Cr^{4+}:YAG SA with lower initial transmission.

4. Conclusions

In summary, circular, buried depressed-cladding waveguides were inscribed by fs-laser beam writing technique in Nd:YAG/Cr^{4+}:YAG composite media. Passive Q-switch operation was obtained under the pump with fiber-coupled diode laser. Laser pulses with energy of 9.1 µJ (peak power P_p = 1.99 kW) and 15.7 µJ (P_p = 4.0 kW) were measured from waveguides with 150-µm diameter that were realized in Nd:YAG/Cr^{4+}:YAG composite media with Cr^{4+}:YAG SA of initial transmission T_0 = 0.80 and T_0 = 0.70, respectively. The average output power reached watt-level. These results prove the possibility to build diode-pumped high-average power compact laser systems with high-peak power laser pulses based on waveguides realized by direct writing with an fs-laser beam.

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