RAPORT STIINTIFIC

Contractul de Finantare nr. 58/02.07.2012

Sistem Laser pentru Aprinderea Motoarelor de Automobile (LASSPARK)

Etapa III / 2014: A. Motor de automobil aprins cu bujie laser.

Principalele rezultate obtinute in cadrul acestei etape sunt prezentate in continuare.

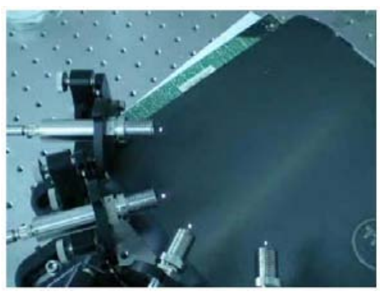
1. Sistem integrat dioda laser-fibra optica-bujie laser pentru aprinderea motorului.

A fost realizat un sistem din 4 (patru) dispozitive laser de tip bujie, acestea fiind controlate in temperatura si alimentate de la o singura sursa electrica, prin intermediul unui program de calculator (program dezvoltat in laborator). Sistemul a fost operat in conditii de laborator.

Acest sistem este prezentat in Fig. 1 [a) vedere generala; b) sursa electrica si calculatorul] si in Fig. 1c in timpul functionarii in conditii de laborator.

a)

b)



c)

Fig. 1 **a)** Sistemul cu 4-dispozitive laser si **b**) elementele de comanda; **c)** functionarea sistemului in conditii de laborator.

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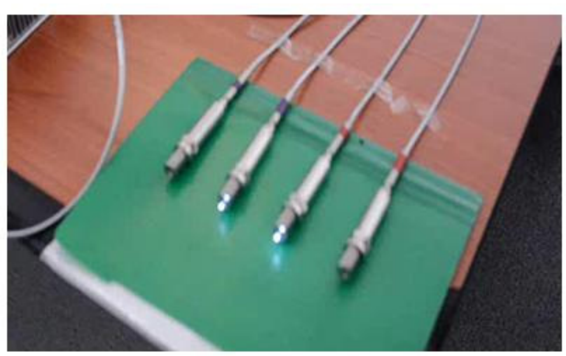

Fig. 2 Sistemul laser in timpul testelor efectuate la RTR - Centrul Pipera.

Sistemul a fost testat in cadrul unor experimente comune efectuate la Renault Technologie Roumanie (RTR) - Centrul Pipera, comanda acestuia facandu-se de aceasta data printr-un ECU (Electronic Control Unit) al unei masini Renault (Fig. 2).

2. Motor aprins cu bujie laser

Au fost efectuate experimente la RTR - Centru Tehnic Titu, unde sistemul laser a fost montat pe un motor Renault, motorul functionand (Fig. 3). Mentionam ca in urma experimentelor au fost observate deteriorari ale unor lentile sau chiar ale mediilor active (in principal arderea unor acoperiri dielectrice).

a) b)

Fig. 3 Sistemul laser in timpul testelor efectuate la RTR - Centrul Pipera: **a)** inainte de montare pe motor; **b)** in timpul functionarii motorului.

3. Masuratori privind noxele emise de motor

Testele au fost realizate pe un motor tip K7M 812 k echipat cu un calculator tip Valeo [redacted]

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4. Laser de tip Nd:YAG pompat lateral printr-o prisma YAG (laserul Nd:YAG-YAG prism). Operare in regim de generare libera si in regim de comutare pasiva cu Cr^{4+}:YAG

In aceasta etapa au fost imbunatatite performantele laserului Nd:YAG pompat lateral printr-o prisma de YAG si a fost realizat primul laser comutat pasiv Nd:YAG/Cr^{4+}:YAG compozit, pompat lateral printr-o prisma de YAG. In Fig. 5 este descris montajul experimental. O astfel de schema contine mai putine elemente optice si este mult mai usor de aliniat decat celelalte tipuri de geometrii: pompaj longitudinal sau lateral, pompaj prin mai multe treceri intr-un mediu tip disc subtire. Mediul activ laser este un cristal de Nd:YAG cu sectiune transversala de forma patrata ($t \times t$). Prisma utilizata este o prisma triunghiulara realizata din YAG.

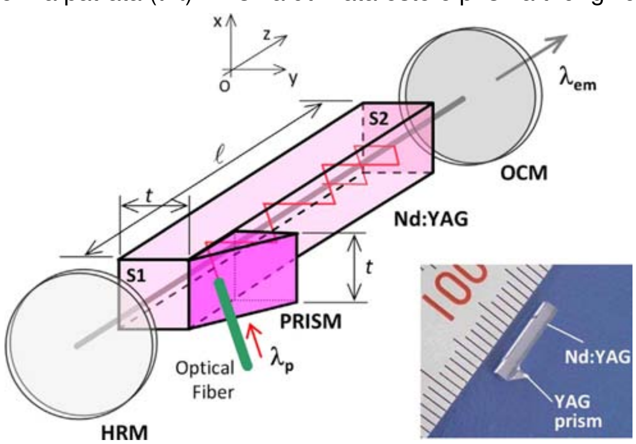

Fig. 5 Schema de principiu a unui laser Nd:YAG pompat lateral cu dioda laser printr-o prisma.

Eficienta cu care fasciculul de pompaj este absorbit (η_a) a fost determinata folosind un program realizat in Optica (Mathematica). Lungimea de unda a pompajului a fost λ_p=807 nm; diametrul fibrei ϕ=600 µm si NA=0.22. Intensitatea fiecarui fascicul a fost aleasa in functie de pozitia sa la capatul fibrei, considerand o distributi super-Gaussian de ordinul 6 pentru fasciculul de pompaj. Acesta se propaga in mediul laser datorita fenomenului de reflexie totala interna. In Fig. 6 sunt prezentate rezultatele acestei simulari. Se poate observa ca fasciculul de pompaj este absorbit in mod eficient atunci cand coeficientul de absorbtie (α_a) al mediului are valoare ridicata. De exemplu, η_a>0.99 pentru un cristal de Nd:YAG de lungime 4 mm si α_a=0.4 mm^{-1}. In acest caz, pompajul este in mare parte absorbit la prima trecere prin mediu. Pentru situatia in care coeficientul de absorbtie este mai mic, eficienta de absorbtie a pompajului scade. Adica, pentru un mediu de aceeasi lungime cu coeficientul α_a=0.1 mm^{-1}, eficienta de absorbtie este η_a=0.78. Daca lungimea cristalului creste, atunci si absorbtia pompajului la prima trecere prin cristal creste. In acest caz, un procent mai mic din fasciculul de pompaj este reflectat pe suprafata S_2, iar pierderile prin prisma triunghiulara scad.

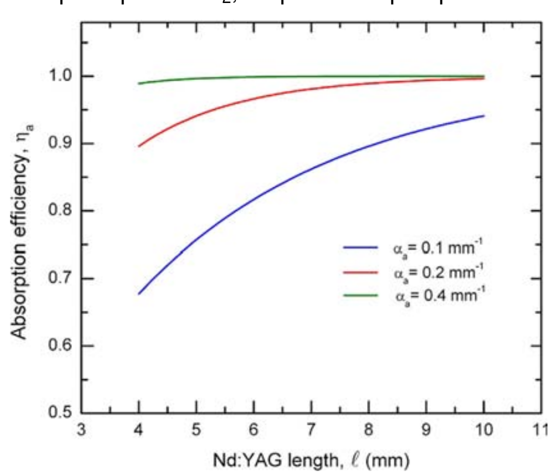

Fig. 6 Eficienta cu care este absorbit fasciculul de pompaj in functie de lungimea cristalului de Nd:YAG.

Au fost realizate experimente pentru caracterizarea emisiei laser la 1.06 µm. Pompajul a fost facut cu o dioda laser (JOLD 540 QAFN-6A, Jenoptik, Germania) ce functioneaza in regim pulsat (durata pulsului de pompaj 250 µs, rata de repetitie a fost variata pana la 100 Hz). Radiatia emisa de dioda la 807 nm a fost cuplata intr-o fibra optica cu diametru ϕ=600 µm si NA=0.22.

In cazul emisiei laser in regim relaxat au fost realizate trei configuratii pentru rezonatorul laser. Mediul activ a fost ales un cristal de Nd:YAG (1.0-at.% Nd) cu sectiune transversala 1.5$\times$1.5 mm^2 si lungime 10 mm. Suprafata S_1 a fost depusa cu reflectivitate ridicata (R>0.998) la lungimea de unda 1.06 µm (λ_{em}) si transmisie ridicata (T~0.95) la 807 nm (λ_p). Suprafata S_2 a fost depusa antireflex (T>0.99) pentru λ_{em}. Rezonatorul laser a fost realizat intre suprafata S_1 a cristalului si o oglinda de extractie plana cu diferite transmisii la λ_{em}. Prima configuratie este o configuratie clasica (notata cu simbolul ”A”) in care se folosesc doua lentile (raport 1:1) pentru focalizarea fasciculului de pompaj in cristalul de Nd:YAG. Pentru a doua configuratie, fibra a fost pozitionata aproape de oglinda cu reflectivitate ridicata (configuratia ”B”). In cazul celei de-a treia configuratii (configuratia ”C”), prisma triunghiulara de YAG a fost lipita de mediul de Nd:YAG in zona laterala suprafetei S_1 iar pompajul a fost realizat direct de la fibra. Adezivul folosit pentru acest proces a avut transmisia T>0.97 la λ_p; in plus, suprafata prismei de YAG pe care se pompeaza a fost depusa cu transmisie ridicata (T>0.99) la λ_p.

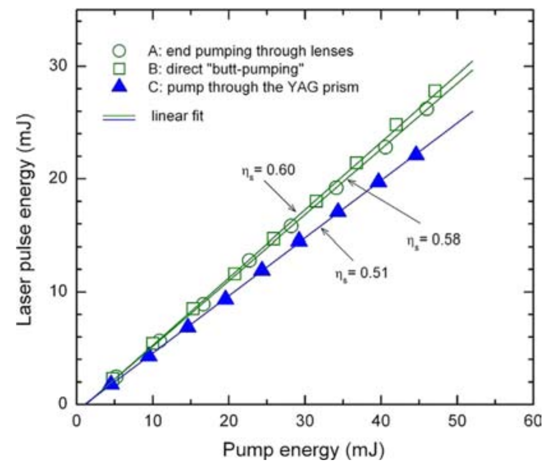

Fig. 7 Energia laser de iesire in functie de energia de pompaj; Oglinda de pompaj este depusa pe suprafata S_1 a cristalului de Nd:YAG.

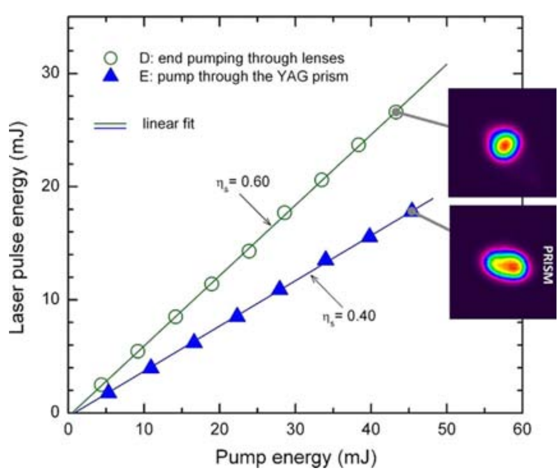

Fig. 8 Energia laser in functie de energia de pompaj pentru cristalul de Nd:YAG nedopat.

In Fig. 7 sunt prezentate rezultatele privind performantele laser pentru cele trei configuratii. Dupa cum se poate observa, in cazul configuratiei ”C”, a fost masurata o valoare maxima a energiei laser de E_p=22.1 mJ pentru o energie de pompaj E_{pump}= 44.5 mJ (eficienta optica η_o~0.50) cu panta eficientei η_s= 0.51. Absorbtia fasciculului de pompaj in cristal a fost de ~0.95. Calitatea fasciculului laser a fost determinata folosind tehnica knife-edge, astfel M^2(x,y) a fost 11.8x11.9. Forma distributiei fasciculului laser a fost eliptica. In concluzie, pentru configuratia ”C”, performantele laser sunt putin mai mici si calitatea fasciculului laser mai slaba. In schimb, aceasta schema este mai simpla decat configuratia in care pompajul este realizat longitudinal cu ajutorul liniei de focalizare compusa din cele doua lentile. De asemenea, sistemul este foarte compact, usor de aliniat si ofera posibilitatea pozitionarii unui element optic (element neliniar sau absorbant saturabil) intre oglinda de pompaj si cristalul de Nd:YAG.

Pentru comparatie, au fost investigate performantele pentru doua configuratii. Prima configuratie ”D”) a fost una clasica, in care pompajul este realizat folosind o linie de focalizare (iar cea de-a doua consta intr-un rezonator format din cele doua oglinzi (de pompaj si de extractie) si un cristal de Nd:YAG (1.0-at.% Nd) nedepus de care s-a lipit prisma triunghiulara (configuratie ”E”). Pompajul este realizat ca in Fig. 5.

Pentru sistemul laser din configuratia ”D” a fost masurata o energie E_p= 26.6 mJ pentru o energie de pompaj E_{pump}= 43.3 mJ (eficienta optica η_0= 0.61); panta eficientei a fost determinata ca fiind η_s= 0.60 (fig. 8). In cazul configuratiei ”E” a fost masurata o energie E_p= 17.8 mJ pentru E_{pump}= 45.4 mJ cu η_s= 0.40.

In final, au fost realizate experimente pentru generarea de pulsuri laser comutate. In acest scop au fost utilizat un mediu compozit Nd:YAG/Cr^{4+}:YAG ceramic (1.0-at.% Nd) de lungime 10 mm, fara depuneri. Transmisia initiala a comutatorului pasiv Cr^{4+}:YAG fost T_{01}= 0.85. Mediul a fost plasat intr-un rezonator plan-plan si pompat in trei configuratii diferite (Fig. 9). In prima configuratie, pompajul a fost realizat longitudinal folosind doua lentile iar mediul a fost pozitionat in rezonator astfel incat pompajul sa fie focalizat in mediul de Nd:YAG nu in cel de Cr^{4+}:YAG. In a doua configuratie, mediului i s-a atasat o prisma de YAG iar pompajul a fost realizat prin aceasta prisma. In ultima configuratie, prisma de YAG a fost lipita de mediu imediat dupa zona Cr^{4+}:YAG, iar pompajul realizat prin prisma.

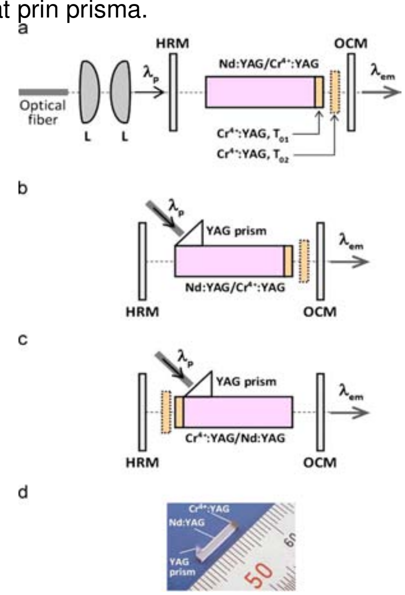

Fig. 9 Configuratiile utlizate in experimentele de Q-switch.

In Fig. 10 este reprezentata energia pulsurilor laser obtinute prin comutare pasiva si energia de pompaj la prag in functie de valoarea transmisiei oglinzii de extractie. In cazul configuratiei ”b” se obtine o energie a pulsului mai mare, adica E_p= 0.18 mJ fata de E_p= 0.12 (configuratia ”a”), transmisia oglinzii de iesire fiind 0.10 in ambele cazuri. In plus, atunci cand valoarea transmisiei T creste, energia pulsului laser creste dar si pragul energiei de pompaj creste.

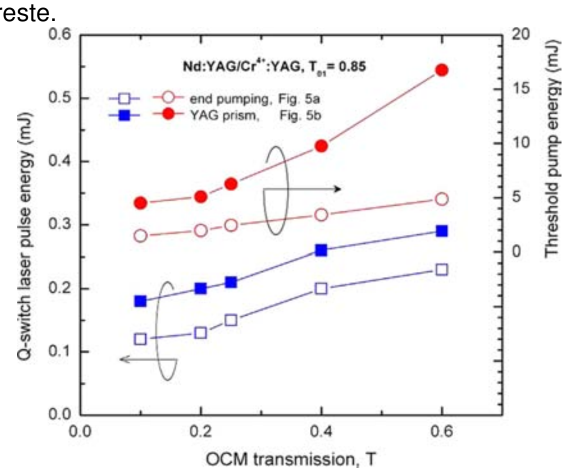

Fig. 10 Configuratiile utlizate in experimentele de Q-switch.

Sistemul laser Nd:YAG/Cr^{4+}:YAG poate fi pompat printr-o prisma triunghiulara de YAG, iar aceasta configuratie permite ca mediul de absorbant saturabil sa fie pozitionat oriunde in rezonator; in acelasi timp, sunt generate pulsuri laser cu energie mai mare decat in cazul pompajului longitudinal. Dar, pentru acest tip de configuratie, pragul energie de pompaj necesara pentru a genera emisie laser este mai ridicat, deci este nevoie de un set de investigatii mai amanuntite pentru a optimiza parametrii pulsurilor laser Q-switch.

In **concluzie**, in cadrul acestei etape:

- A fost realizat un sistem din 4 dispozitive laser de tip bujie. In prima etapa, sistemul a fost operat in conditii de laborator. In continuare, sistemul a fost comandat printr-un ECU (Electronic Control Unit) al unei masini Renault;
- Sistemul laser a fost montat pe un motor Renault, iar motorul a functionat;

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- Au fost efectuate experimente prin care s-a obtinut scalarea performantelor laserului Nd:YAG - prisma YAG (laser Nd:YAG pompat printr-o prisma de YAG) in regim de functionare relaxat. A fost demonstrat primul laser comutat pasiv Nd:YAG/Cr^{4+}:YAG compozit, pompat printr-o prisma YAG. Performantele unui astfel de laser trebuie imbunatatite, pentru a se obtine efectul de ’spargere a aerului’;
- Rezultatele au fost diseminate printr-un articol publicat intr-o revista indexata ISI - Web of Knowledge, o prezentare orala la o conferinta internationala desfasurata in strainatate, doua prezentari (una poster si una invitata) la o conferinta internationala desfasurata in tara, o participare la Expozitia Internationala Renault destinata Cercetarii, 10-13 iunie, Versailles-Satory, Paris, Franta si o participare la Salonul Cercetarii Romanesti, octombrie 2014, Bucuresti.

DISEMINARE REZULTATE

ARTICOLE ISI

1. T. Dascalu, G. Salamu, O. Sandu, M. Dinca, and N. Pavel, “Scaling and passively Q-switch operation of a Nd:YAG laser pumped laterally through a YAG prism,” Opt. & Laser Techn. **67**, 164-168 (2015). http://dx.doi.org/10.1016/j.optlastec.2014.10.017 [2013 Impact Factor: 1.649]

CONFERINTE

1. N. Pavel, G. Salamu, and T. Dascalu, “Passively Q-switched, composite Nd:YAG/Cr^{4+}:YAG laser pumped laterally through a prism,” The 2nd Laser Ignition Conference, 22 - 25 April 2014, Pacifico Yokohama, Yokohama, Japan, presentation LIC5-2 (oral presentation).
2. F. Voicu, C. Gheorghe, S. Hau, L. Esposito, and J. Hostasa, “Preliminary results on Sm^{3+}:YSAG transparent ceramic,” 5th International Student Conference on Photonics, Orastie, Romania, 23-26 September 2014; presentation P.09 (poster presentation).
3. N. Pavel, M. Dinca, and T. Dascalu, “Passively Q-switched Nd:YAG/Cr^{4+}:YAG Lasers for Automobile-Engine Ignition,” 5th International Student Conference on Photonics, Orastie, Romania, 23-26 September 2014; presentation I.07 (invited presentation).
4. "Dispozitiv laser destinat aprinderii motoarelor de autoturisme". Prezentare la Salonul Cercetarii Romanesti, 15-18 octombrie 2014, Bucuresti, Romania.
5. Participare cu montaj experimental si poster la Expozitia Internationala Renault destinata Cercetarii, 10-13 iunie, Versailles-Satory, Paris, Franta.

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Scaling and passively Q-switch operation of a Nd:YAG laser pumped laterally through a YAG prism

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ABSTRACT

We report on scaling of a laser configuration in which a YAG prism is used to couple the pump beam from a fiber-coupled diode laser directly into a Nd:YAG medium. Several resonator geometries have been investigated. In free generation regime laser pulses at 1.06 μm with energy of 22.1 mJ for the pump energy of 44.6 mJ were obtained from a 10.0 mm long, 1.0-at% Nd:YAG single crystal that had the high-reflectivity mirror coated directly on one of the laser crystal surface. The slope efficiency was 0.51. A similar uncoated Nd:YAG crystal placed in a plane–plane resonator delivered laser pulses with 17.8 mJ energy under the pump with 45.4 mJ energy, at 0.40 slope efficiency. Further, a passively Q-switched Nd:YAG/Cr^{4+}:YAG composite ceramic laser pumped through a YAG prism has been built. Using a Cr^{4+}:YAG saturable absorber of 0.85 initial transmission the device delivered laser pulses with 0.29 mJ energy and 11 ns duration. The output performances are compared to those obtained in a classical end-pumping scheme.

1. Introduction

A main objective of the investigations that considered the laser-induced ignition of engines with internal combustion was to build a laser with a size comparable to that of an electrical spark plug. First experiments on laser ignition were performed with commercial lasers that delivered pulses with energy in the range of tens to a few hundreds of mJ and several-ns pulse duration [1,2]; however, these lasers had large dimensions. Later, the experiments concluded that a suitable device for engine ignition can be realized by employing a Nd:YAG laser that is passively Q-switched by Cr^{4+}:YAG saturable absorber (SA) [3–5]. An end- (or longitudinally-) pumped scheme with fiber-coupled diode lasers [3,4], or side-pumping with array diode lasers [5] were the solutions used to build novel laser devices; still, these lasers had larger sizes than those of a classical (electrical) spark plug.

A Nd:YAG-Cr^{4+}:YAG laser with dimensions comparable to those of an electrical spark plug was first realized by Tsunekane et al. [6]. The laser pulse features, suitable for ignition, were achieved by shortening the resonator length, and by maximizing the laser pulse energy following optimization of the pump conditions through right choice of the Nd:YAG parameters and of the Cr^{4+}:YAG SA crystal initial transmission [7]. Furthermore, such a scheme was employed for efficient generation of laser radiation into visible and ultraviolet spectra by single-pass nonlinear conversion of the fundamental wavelength [8–10]. An Yb:YAG-Cr^{4+}:YAG laser was developed recently by the same research group [11]. The passively Q-switched lasers mentioned above were realized with discrete Nd:YAG or Yb:YAG and Cr^{4+}:YAG SA single-crystal media. On the other hand, the ceramic techniques allow obtaining of laser media with very good optical quality, featuring easy manufacturability at competitive prices. Consequently, optically-bonded, composite Nd:YAG/Cr^{4+}:YAG all-poly-crystalline (or ceramic) media were used to build compact lasers with sizes comparable to that of a classical spark plug [12–14]. Such lasers outputted multiple beams and had maneuverability in varying distance between the ignition points as well as the depth of the focusing point.

These lasers have been realized using longitudinal pumping [3,4,6,11–14]. In general, in this arrangement the pump beam is delivered by a fiber-coupled diode laser and then it is transferred into the laser medium through one end of the laser rod. Typical coupling optics contains two lenses, and therefore the pump beam and the laser beam are collinear. Recently we have proposed a configuration that improves the compactness of a diode-pumped Nd:YAG laser [15]. This geometry employs a rectangular laser medium in which the pump beam is coupled directly from a fiber end through a single optical element, a prism. In the first experiments a diode-pumped YAG prism-Nd:YAG laser that in free-generation regime outputted pulses at 1.06 μm with energy

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E_p=2.1 mJ under the pump with pulses at 807 nm of energy E_{pump}=9.9 mJ was demonstrated; the overall optical-to-optical efficiency (η_o) was 0.21. The laser slope efficiency (η_s) amounted to 0.22. Also, a passively Q-switched YAG prism-Nd:YAG-Cr^{4+}:YAG laser that delivered laser pulses with low energy E_p=90 μJ and long duration t_p=26 ns was built [15].

In this work we report on further investigations of this pumping geometry and obtain good improvements of the output performances. Laser pulses with E_p=22.1 mJ at optical efficiency η_o~0.49 were measured from a 10.0 mm long, 1.0-at.% Nd:YAG crystal of 1.5 × 1.5 mm² cross section that was pumped through a YAG prism (i.e. the YAG prism-Nd:YAG laser). The slope efficiency was η_s=0.51. The emission characteristics delivered from various pumping arrangements are discussed. Furthermore, a passively Q-switched Nd:YAG/Cr^{4+}:YAG laser that consisted of an optically-bonded, composite, ceramic structure was build for the first time (i.e. the YAG prism-Nd:YAG/Cr^{4+}:YAG laser). Laser pulses with energy E_p=0.29 mJ and duration t_p=12 ns were obtained by pumping this device through a YAG prism. Two geometries of such a Q-switched laser are presented and the corresponding experimental results are given.

2. The Nd:YAG laser pumped laterally through a YAG prism

2.1. The laser concept

Fig. 1 shows the laser configuration that will be discussed in this work. The Nd:YAG medium has square ($t \times t$) transversal section, and a YAG prism is positioned near one of Nd:YAG ends. The prism is an isosceles triangle having a 90°-angle section, being in contact with Nd:YAG through one of the right angled surfaces; a glue of suitable refractive index is used to attach the prism to the laser medium. The pump beam is delivered from the fiber (which is placed close to the prism hypotenuses) and propagates in Nd:YAG by total internal reflections. Inset of Fig. 1 is a photo of the YAG prism-Nd:YAG laser. It is observed that such a scheme contains fewer optical elements and it is simpler and easier to align than other well known geometries, such as end [3,4,6,11–14] or side pumping [5], or like a thin-disc medium that is multi-pass pumped [16] or pumped through edges [17–19].

The pump-beam absorption efficiency (η_a) was evaluated by a ray-tracing program that was realized in the Optica (Mathematica) software. The pump wavelength was λ_p=807 nm; the optical fiber had a diameter (ϕ) of 600 μm and numerical aperture NA=0.22.

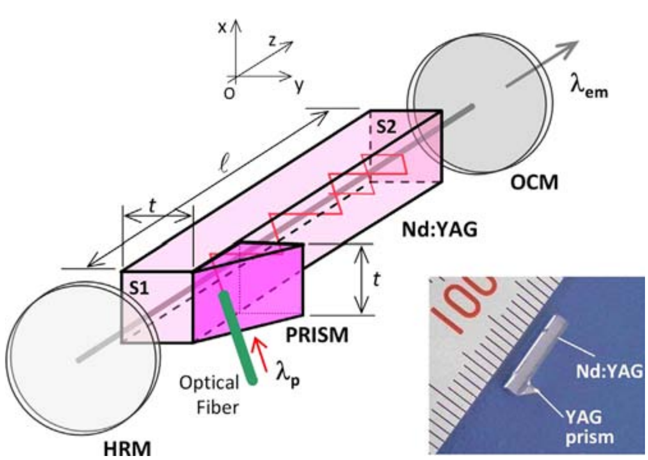

Fig. 1. Schematic of the Nd:YAG laser that is pumped laterally, through a YAG prism, with a fiber-coupled diode laser. HRM: high-reflectivity mirror; OCM: out-coupling mirror. Inset is a photo of a Nd:YAG crystal with the YAG prism attached to it.

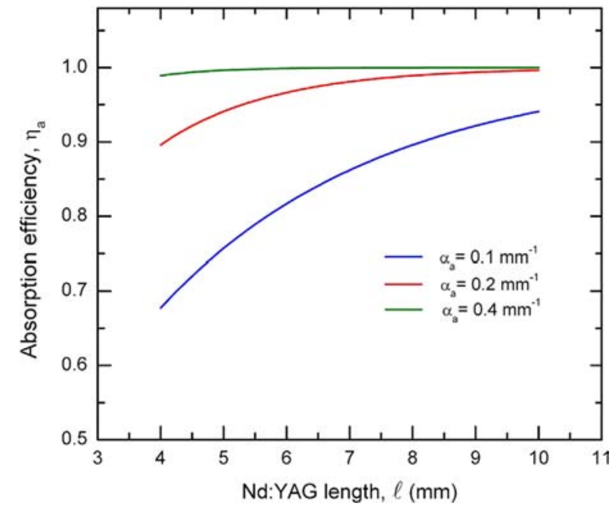

Fig. 2. The pump beam absorption efficiency versus the Nd:YAG crystal length.

The intensity of each ray was initially set accordingly to its position at the fiber tip and considering a super-Gaussian distribution of the 6th order (i.e. very close to a top-hat like distribution) for the pump beam. The beam propagates inside the laser medium by total internal reflection.

Results of these simulations are shown in Fig. 2. The pump beam is absorbed efficiently when a Nd:YAG medium with high effective absorption coefficient (α_a) is used. For example, η_a is higher than 0.99 for a 4 mm long Nd:YAG with α_a=0.4 mm^{-1}. Furthermore, in this case η_a is little influenced by the Nd:YAG length, because most of the beam is absorbed in the first-pass transition of the medium and less fraction is lost (during the second-pass transition) through the YAG prism surface that is attached to Nd:YAG. On the other hand, a decrease of α_a will lower η_a. Thus, a short, low-doped Nd:YAG will absorb less pump beam during the first pass, and after reflection on surface S2 of Nd:YAG losses through the YAG prism are not negligible. For example, a 4 mm thick Nd:YAG with α_a=0.1 mm^{-1} has η_a=0.78, while increasing α_a at 0.2 mm^{-1} improves η_a to 0.89. Increasing the Nd:YAG length will improve the first-pass absorption; in this case less pump beam is reflected on side S2 and thus losses through the YAG prism decrease. A 10 mm thick Nd:YAG will have absorption η_a=0.94 for α_a=0.1 mm^{-1}, and a little higher η_a=0.99 for α_a=0.2 mm^{-1}. Besides, efficiency η_a is not influenced by the Nd:YAG cross-section. This parameter had to be chosen such to have a proper gain distribution in the Nd:YAG, a good overlap between the pump beam and the laser mode (depending of the resonator configuration), but also taking into account technical limitations imposed by manufacturing of the Nd:YAG medium.

2.2. Operation in free-generation regime

The pump was made with a diode laser (JOLD 540 QAFN-6A, JENOPTIK, Germany) that was operated in quasi-continuous wave mode; the pump radiation at 807 nm was delivered through an optical fiber of ϕ=600 μm and NA=0.22. The pump pulse duration was fixed at 250 μs while the repetition rate could be increased up to 100 Hz. For the emission in free-generation regime we used several configurations. A first Nd:YAG medium (1.0-at% Nd; 1.5 × 1.5 mm² cross section, 10 mm length) has side S1 coated with high reflection HR (reflectivity, R > 0.998) at 1.06 μm (λ_{em}) and with high transmission HT (transmission, T~0.95) at 807 nm (λ_p). Side S2 was anti-reflection coated (AR, T > 0.99) at λ_{em}. The optical resonator was realized between side S1 of Nd:YAG (that acted as the high-reflectivity mirror, HRM) and a plane out-coupling mirror (OCM) of defined transmission T at λ_{em}. For comparison three configurations were realized. One of these employed two lenses for the transfer (with a 1:1 ratio) of the pump beam from the fiber into Nd:YAG. This is a classical end-pumping arrangement that will be denoted by scheme "A". In the second arrangement the fiber was positioned close to the HRM; known as 'butt-coupling' this setup will be denoted by scheme "B". For the last setup (scheme "C", the YAG prism-Nd:YAG medium) a YAG prism was attached near side S1 of Nd:YAG (inset of Fig. 1) and the pump was made directly from the fiber. The glue between the YAG prism and Nd:YAG had $T > 0.97$ at λ_p; besides, the side of the YAG prism used for the pump was coated HT ($T > 0.99$) at λ_p.

The laser pulse energy at 1.06 μm versus the pump energy at 807 nm is shown in Fig. 3 for an OCM with $T = 0.05$; the repetition rate was kept at 100 Hz. The laser "A" delivered pulses at 1.06 μm with maximum energy $E_p = 27.8$ mJ for the pump energy $E_{pump} = 47.1$ mJ, corresponding to an efficiency $\eta_o = 0.59$. The slope efficiency was $\eta_s = 0.60$. This result was expected, because the setup offers possibility to adjust the pump-beam focusing point inside Nd:YAG for output optimization. Laser pulses with $E_p = 26.2$ mJ for $E_{pump} = 46$ mJ (i.e. $\eta_o \sim 0.57$) and slope $\eta_s = 0.58$ were obtained from the butt-coupling scheme "B". Measurements concluded that for end pumping nearly 92% of the pump beam was absorbed in Nd:YAG. On the other hand, the YAG prism-Nd:YAG laser (scheme "C") yielded laser pulses with maximum $E_p = 22.1$ mJ for $E_{pump} = 44.5$ mJ (i.e. $\eta_o \sim 0.50$); the slope was $\eta_s = 0.51$. In this case the absorption efficiency was $\eta_a \sim 0.95$. The laser beam M^2 factor was measured by the knife-edge method (10–90% cut-level output). The YAG prism-Nd:YAG laser outputted a multimode, slightly elliptical beam with $M_x^2 \times M_y^2$of 11.8×11.9. In addition, the beams yielded by the "A" and "B" lasers had symmetrical transverse distributions with $M^2 = 10.5$ and $M^2 = 8.5$, respectively. Thus, a little bit lower performances were obtained from the YAG prism-Nd:YAG laser; nevertheless, this device is simpler than a laser end-pumped through the lenses. Furthermore, in comparison with the butt-coupling geometry, which is also neat and easy to align, a YAG prism-Nd:YAG laser offers possibility to set optical elements (like a nonlinear crystal for wavelength conversion or a SA medium for passive Q-switching) not only between Nd:YAG and the OCM of the resonator like in classical arrangements, but also between the resonator HRM and the Nd:YAG medium.

The performances of a laser built with discrete mirrors were also investigated. Based on availability, an uncoated 1.0-at% Nd:YAG laser crystal (1.5×1.5 mm^2 cross section, length of 10 mm) was used to build two additional setups. The Nd:YAG was positioned at the center of a linear resonator that consisted of a plane HRM and a plane OCM placed 30 mm apart. For the first laser the pump was made through lenses (as described previously); this setup will be denoted by scheme "D". In the second arrangement (scheme "E") a YAG prism was glued to Nd:YAG; the YAG prism-Nd:YAG element was placed in the same resonator and the pump was made from the fiber through the YAG prism (as shown in Fig. 1).

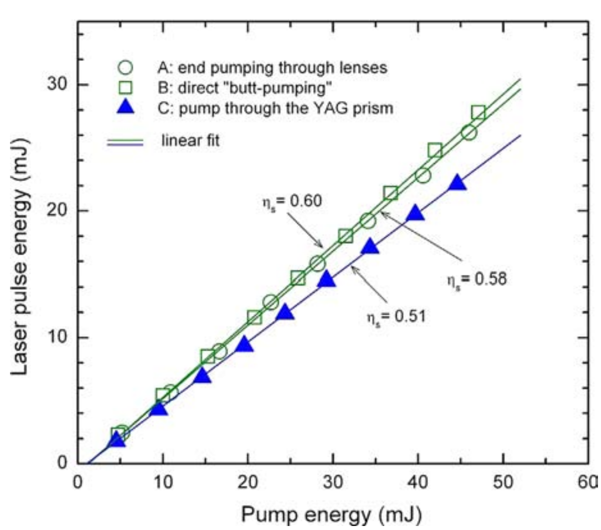

Fig. 3. Laser pulse energy versus pump energy yielded by the Nd:YAG crystal with the HRM coated directly on surface S1.

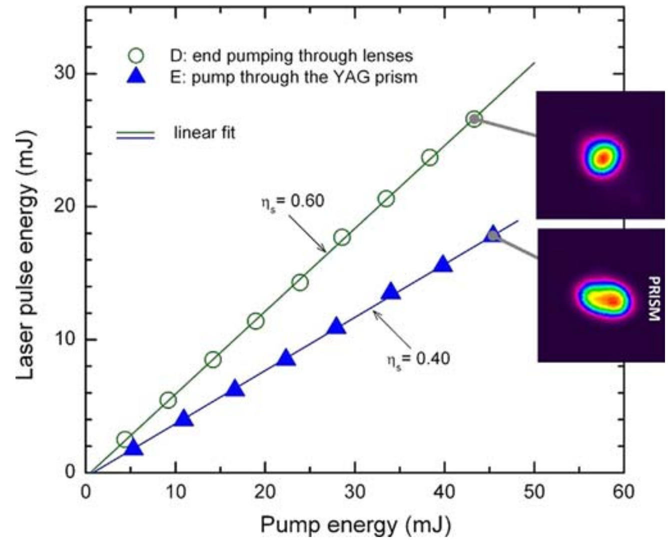

Fig. 4. Laser pulse energy versus pump energy obtained from the uncoated Nd:YAG crystal. Insets are 2D maps of the laser beam near-field distributions at the indicated points; the Nd:YAG side in contact with the YAG prism was indicated.

Fig. 4 compares the energy E_p yielded by these two lasers with an OCM of $T = 0.10$. The end-pumped laser ("D") outputted pulses with maximum energy $E_p = 26.6$ mJ for $E_{pump} = 43.3$ mJ (at optical efficiency $\eta_o = 0.61$); the slope efficiency amounted to $\eta_s = 0.60$. The near-field distribution (which was recorded with a Spiricon camera, model SP620U, 190–1100 nm spectral range) is shown in Fig. 4. The beam had an M^2 factor of 4.2. On the other hand, the YAG prism-Nd:YAG laser delivered pulses with energy $E_p = 17.8$ mJ ($E_{pump} = 45.4$ mJ, $\eta_o \sim 0.39$), while slope η_s was 0.40. The laser beam distribution (shown in Fig. 4) was elliptical with $M_x^2 \times M_y^2$ of 4.5×10.2. It is also worthwhile to mention that the pulse-to-pulse variation of the maximum energy E_p was less than 2%.

2.3. The passively Q-switched Nd:YAG/Cr^{4+}YAG laser with YAG prism

For the Q-switch experiments we used an uncoated, composite Nd:YAG/Cr^{4+}:YAG ceramic medium (Baikowski Co., Japan) with 1.5×1.5 mm^2 cross section. It consisted of a 10 mm long, 1.0-at.% Nd:YAG ceramic that was optically bonded to a 0.6 mm thick Cr^{4+}:YAG SA ceramic. The initial transmission of Cr^{4+}:YAG was $T_{01} = 0.85$. This medium was placed at the middle of a plane HRM – plane OCM resonator and it was pumped in three ways.

For the first setup the pump was made longitudinally through two identical lenses (as shown in Fig. 5a). In this case the Nd:YAG/Cr^{4+}:YAG medium has to be positioned with Cr^{4+}:YAG facing the OCM resonator in order to avoid a change of the Cr^{4+}:YAG initial transmission due to direct interaction with the pump beam [20]. For the second scheme a YAG prism was attached to Nd:YAG and the YAG prism-Nd:YAG/Cr^{4+}:YAG optical element was placed in the same resonator (Fig. 5b). For the last layout a YAG prism was glued to the Nd:YAG side that was optically

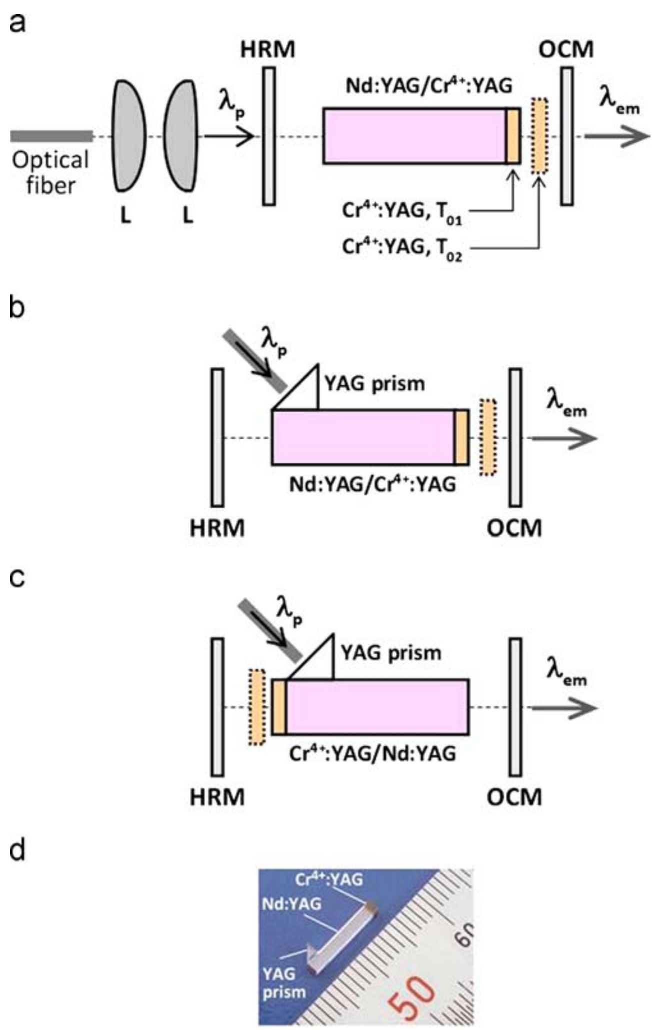

Fig. 5. Geometries of the passively Q-switched Nd:YAG/Cr^{4+}:YAG laser used in the experiments: (a) end pumping through lenses; the pump through YAG prism, with the Cr^{4+}:YAG SA crystal positioned (b) between Nd:YAG and OCM (classical arrangement) or (c) between HRM and Nd:YAG. (d) A photo of the YAG prism-Nd:YAG/Cr^{4+}:YAG laser is shown.

bonded to the Cr^{4+}:YAG SA and the composite Nd:YAG/Cr^{4+}:YAG ceramic was positioned with the Cr^{4+}:YAG facing the resonator HRM (Fig. 5c); thus the pump through the YAG prism eliminated any concern regarding the SA bleaching by the pump beam. A photo of the YAG prism-Nd:YAG/Cr^{4+}:YAG device is shown in Fig. 5d, for exemplification.

The Q-switch laser pulse energy versus OCM transmission is shown in Fig. 6. The end-pumped Nd:YAG/Cr^{4+}:YAG laser yielded Q-switch pulses with E_p=0.12 mJ when the OCM had T=0.10; E_p has improved to 0.23 mJ for T=0.60. The pump energy necessary for Q-switch operation (E_{th}) increased from 1.9 mJ for the OCM with T=0.10 to 4.9 mJ for the OCM with T=0.60. In the case of the YAG prism-Nd:YAG/Cr^{4+}:YAG laser (Fig. 5b), more energy E_p was obtained at the same T of the OCM. Thus, E_p increased from 0.18 mJ for T=0.10 to E_p=0.29 for an OCM with T=0.60. On the other hand, E_{th} rose from 4.5 mJ for the OCM with T=0.10 to 16.7 mJ for the OCM with T=0.60. These behaviors were related to the transverse mode distribution of the laser beam. The Q-switch pulse duration shortened for both configurations, from 15 ns to 11 ns when T varied from 0.10 to 0.60.

In order to obtain Q-switch laser pulses with higher energy (and thus to check each system scalability), another Cr^{4+}:YAG SA crystal was added in the laser resonator, being placed close to the Cr^{4+}:YAG SA ceramic with T_{01}=0.85 (as shown in Fig. 5a–c).

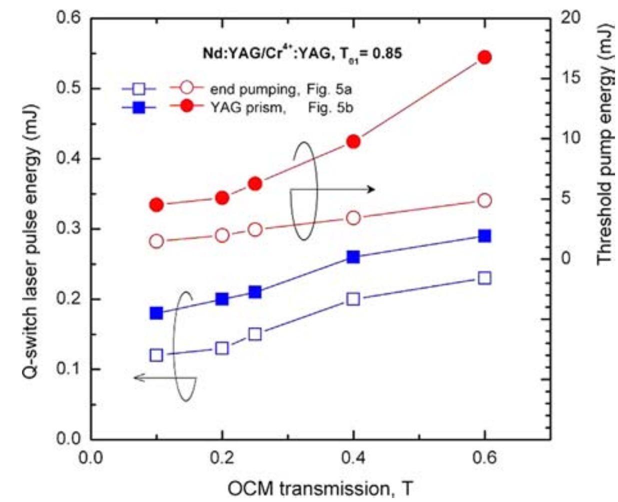

Fig. 6. Q-switch laser pulse energy and pump energy at threshold versus T for the composite Nd:YAG/Cr^{4+}:YAG (T_{01}=0.85) ceramic laser.

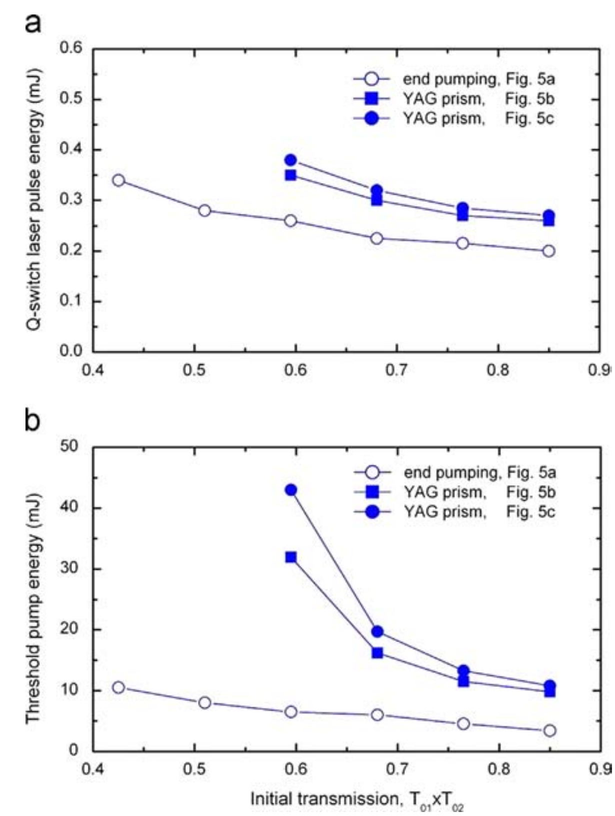

Fig. 7. (a) Q-switch laser pulse energy and (b) pump energy at threshold versus initial transmission $T_{01} \times T_{02}$ (T_{01}=0.85) of the Cr^{4+}:YAG SA media, OCM with T=0.40.

Several Cr^{4+}:YAG SA crystals with initial transmission T_{02} between 0.9 and 0.5 were used. The resonator OCM was fixed at T=0.40. As illustrated in Fig. 7a, the laser pulse energy E_p of the end-pumped laser raised from 0.2 mJ (T_{01}=0.85) to 0.34 mJ when an additional Cr^{4+}:YAG SA crystal with T_{02}=0.50 was added in the resonator. The corresponding E_{th} was 3.4 mJ and 10.5 mJ for T_{01}=0.85 and for (T_{01}=0.85, T_{02}=0.5), respectively (Fig. 7b).

The YAG prism-Nd:YAG/Cr^{4+}:YAG laser (Fig. 5b) yielded laser pulses with E_p=0.26 mJ and threshold E_{th}=9.8 mJ. Insertion of a Cr^{4+}:YAG SA crystal with T_{02}=0.70 (between the ceramic medium and the OCM) improved Q-switch laser pulses to E_p=0.35 mJ

(Fig. 7a), while E_{th} increased at 31 mJ (Fig. 7b). Laser operation beyond these conditions was not obtained. A similar behavior was observed for the arrangement shown in Fig. 5c. The YAG prism-Cr^{4+}:YAG/Nd:YAG laser outputted pulses with E_p=0.27 mJ for the pump with E_{th}=10.8 mJ; an extra Cr^{4+}:YAG SA crystal with T_{02}=0.70 that was added between HRM and Cr^{4+}:YAG/Nd:YAG increased E_p at 0.38 mJ, but raised E_{th} to 43.1 mJ. It is worthwhile to mention that the end-pumped Nd:YAG/Cr^{4+}:YAG laser (Fig. 5a) outputted pulses with E_p=0.26 mJ for the pump with E_{th}=6.5 mJ when the same Cr^{4+}:YAG SA crystal (T_{02}=0.70) was inserted in the resonator.

Based on these experiments we can say that a passively Q-switched Nd:YAG/Cr^{4+}:YAG laser that is pumped through a YAG prism shows flexibility in positioning the SA medium in the laser resonator and delivers Q-switch pulses with increased energy in comparison with a similar end-pumped laser. The laser pump energy required for operation was, however, much higher; therefore, additional investigations are necessary in order to optimize the Q-switch regime and to obtain laser pulses with parameters (energy and duration) suitable for ignition. Other experiments are driven by the possibility to build a compact, monolithic YAG prism-Nd:YAG/Cr^{4+}:YAG laser with two distinct beams [21] that could find application in the automotive industry.

3. Conclusions

In summary, we have reported on scaling the output performances of a laser geometry in which the pump beam is coupled directly from the diode-laser fiber into the laser medium through a prism optical element. Laser pulses with 22.1 mJ energy at optical efficiency of nearly 0.50 and 0.51 slope efficiency were obtained in free-generation operation from such a compact, coated Nd:YAG-YAG prism laser. In addition, an uncoated Nd:YAG crystal delivered pulses with energy of 17.8 mJ at 0.39 optical efficiency, with slope efficiency of 0.40. For the first time, a passively Q-switched, composite Nd:YAG/Cr^{4+}:YAG laser was built in this configuration. Laser pulses with 0.29 mJ energy and 11 ns duration were obtained. These performances are compared with those obtained from several end-pumped lasers that were operated in free-generation mode as well as in the Q-switch regime.

Acknowledgments

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Passively Q-switched, composite Nd:YAG/Cr^{4+}:YAG laser pumped laterally through a prism

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Abstract: We report on power scaling of a compact Nd:YAG laser that is pumped laterally through a YAG prism. A 1.0-at.% Nd:YAG medium (10-mm long, 1.5×1.5 mm^2 square shape) operated in free generation regime with 0.51 slope efficiency, yielding laser pulses with 22.1-mJ energy for the pump with pulses of 44.5-mJ energy. For the integration of such a laser geometry we used a composite, diffusion-bonded Nd:YAG/Cr^{4+}:YAG ceramic; the device delivered Q-switched laser pulses with up to 0.29-mJ energy. This laser design can be used for realization of various integrated optoelectronics devices, or it could find applications in the automotive industry.

The diode-pumped solid-state lasers are nowadays common tools in many industrial applications, medical investigations and surgery or in communications. A very interesting field is the ignition of an automobile engine, for which the use of a laser device offers attractive advantages over a conventional spark-ignition system, like ignition of leaner mixtures, reduction of erosion effects, increases of engine efficiency, or shorter combustion time. Generally, the laser devices used for ignition were built in an end-pumping geometry [1-3], but side pumping was proven also to be effective [4]. Recently we have proposed a compact laser scheme that uses a single optical element, namely a prism, to transfer the pump-beam radiation directly into the laser medium. Based on this design a Nd:YAG laser that yielded pulses with 1.8-mJ energy (with overall optical-to-optical efficiency η_o= 0.18) was built for the first time [5]. In this work we report on power scaling of such a laser geometry, achieving in free-generation operation regime laser pulses of 22.1 mJ energy at optical efficiency η_o~0.50. Furthermore, a passively Q-switched, composite Nd:YAG/Cr^{4+}:YAG laser that was pumped laterally through a YAG prism was realized.

A general sketch of the laser configuration investigated in this work is shown in Fig. 1a. The Nd:YAG crystal has square transversal section and a YAG prism is positioned near one of the laser crystal ends. The diode-laser fiber end is placed close to the prism hypotenuses and the pump beam propagates in Nd:YAG by total internal reflections. The pump was performed at λ_p= 807 nm with a pulsed diode laser (JOLD 540 QAFN-6A, JENOPTIK, Germany) that was coupled to an optical fiber (600-μm diameter, NA= 0.22). The laser emission performances of various configurations were investigated in free-generation regime. Firstly, we built a Nd:YAG/YAG prism device in which the resonator high-reflectivity mirror (HRM) was coated directly on the medium (surface S1), whereas side S2 was coated for antireflection at the laser emission wavelength (λ_{em}) of 1.06 μm. This medium was end-pumped through a 1:1 optical system (scheme A), but also it was pumped directly through a YAG prism (scheme B, as shown in Fig. 1b). A second Nd:YAG/YAG medium that has both sides uncoated was placed at the center of a 35-mm-long resonator; it was pumped longitudinally (scheme C), as well as through the YAG prism (scheme D, as presented in Fig. 1c). The Nd:YAG (1.0-at.% Nd) media were square shaped (1.5×1.5 mm^2) with a length of 10 mm.

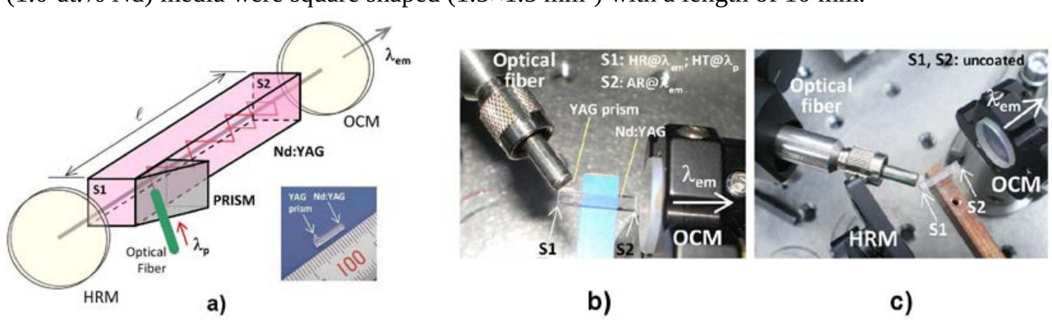

Fig. 1. **a)** A sketch of the Nd:YAG laser pumped laterally through a YAG prism is shown. Inset is a photo of such a laser device. Photos of the **b)** configuration "B" and **c)** scheme "D" used in the experiments are presented. OCM: out-coupling mirror.

Figure 2 shows the laser emission characteristics in free-generation regime. Laser pulses with maximum energy E_p of 27.8 mJ were obtained from "scheme A", for the pump with pulses of energy E_{pump}= 47.1 mJ (overall optical-to-optical efficiency η_o= 0.59). The slope efficiency (OCM with transmission T= 0.10) was η_s~ 0.60 (Fig. 2a).

The Nd:YAG/YAG prism laser (scheme B) yielded pulses with E_p= 22.1 mJ (for E_{pump}= 44.5 mJ, η_o~ 0.50) at slope η_s= 0.51. On the other hand, end-pumping of "scheme D" delivered laser pulses with E_p= 27.7 mJ (E_{pump}= 43.3 mJ, η_o~ 0.64) and slope η_s= 0.64 (Fig. 2b). The uncoated Nd:YAG/YAG prism laser (scheme D) has emission with slope η_s= 0.44 and outputted pulses with maximum energy E_p= 20 mJ (E_{pump}= 46.8 mJ, η_o~ 0.43). A discussion on the laser beam quality will be given. The performances of the Nd:YAG/YAG prism laser are a little lower than those obtained with the end-pumping schemes. However, this configuration is simply to align and it is more compact having less optical elements. Furthermore, it is interesting for passively Q-switched lasers as it provide flexibility to place the saturable absorber (SA) either between OCM and the Nd:YAG crystal or among the HRM and Nd:YAG [5].

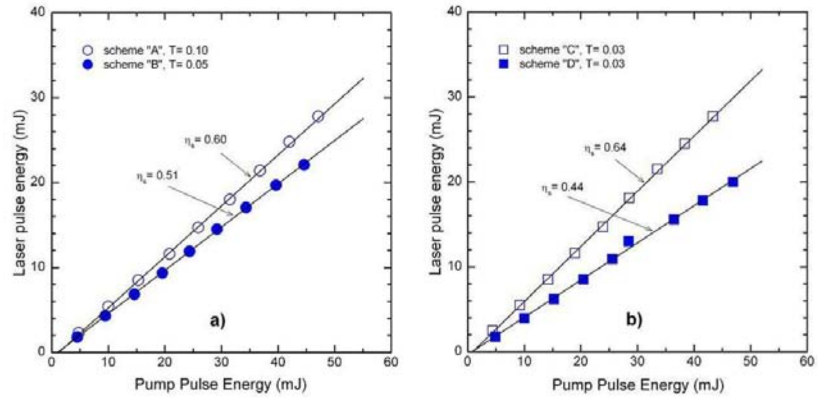

Fig. 2. Laser pulse energy versus pump pulse energy for the **a)** coated and **b)** uncoated Nd:YAG crystals used in the experiments. T is the OCM transmission.

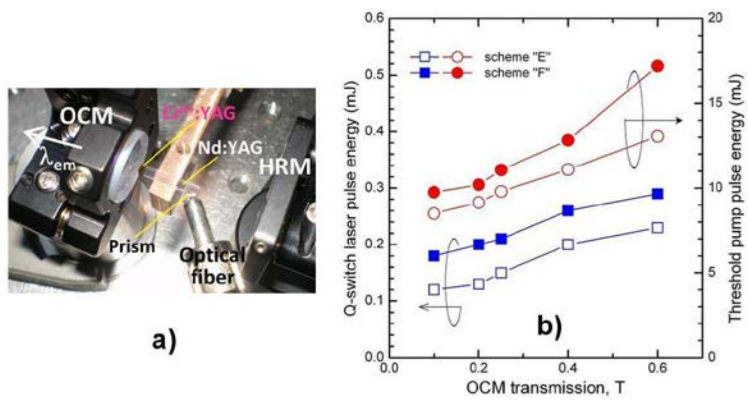

Fig. 3. **a)** The composite Nd:YAG/Cr^{4+}:YAG laser pumped through the YAG prism. **b)** Q-switch laser pulse energy and pump pulse energy at threshold for the two pumping schemes of the Nd:YAG/Cr^{4+}:YAG laser.

For the Q-switch experiments we used a composite Nd:YAG/Cr^{4+}YAG ceramic made of a 1.0-at.%, 10-mm long Nd:YAG that was diffusion-bonded to a Cr^{4+}YAG SA with initial transmission T_o= 0.85. The uncoated medium was placed in a 20-mm long resonator; it was end pumped using the 1:1 imaging optics (scheme E), but also it was pumped directly from the diode fiber through a YAG prism (scheme F, as shown in Fig. 3a). The laser delivered pulses with energy E_p= 0.23 mJ (for an OCM with T= 0.40) when it was pumped longitudinally, with a pump-pulse energy at threshold E_{th}= 13 mJ (Fig. 3b). The laser pulse energy increased at E_p= 0.29 mJ (with E_{th}= 17.2 mJ) when the Nd:YAG/Cr^{4+}:YAG medium was pumped in "scheme F". An analysis on the laser beam transverse distribution and its influence on the Q-switch laser pulse characteristics will be presented.

In conclusion we report improved emission characteristics from a Nd:YAG laser pumped laterally through a YAG prism, directly from a diode-laser fiber end. A passively Q-switched composite Nd:YAG/Cr^{4+}:YAG laser was build in this new geometry. Further experiments aiming increasing the emission performances in both regimes are in progress.

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I.07

Passively Q-switched Nd:YAG/Cr^{4+}:YAG Lasers for Automobile-Engine Ignition

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The ignition of engines with internal combustion using a laser has been extensively studied during last years. It was shown that in comparison with a conventional spark-ignition system the laser-induced ignition has some attractive advantages, such as higher probability to ignite leaner mixtures, reduction of erosion effects and increase of engine efficiency, or shorter combustion time. On the other hand, realization of a compact laser with size comparable to that of an electrical spark plug and that can withstand and operate in conditions of vibration and temperature similar to those encountered during the engine operation is a challenging task.

In this talk we will present our experience toward realization of a laser-spark device. We will discuss two-laser configurations, the end-pumping scheme and a novel design in which the laser medium is pump directly through a prism, which were investigated in order to miniaturize the laser and make it suitable for engine ignition. Laser-spark devices with dimensions close to a classical electrical spark plug were built employing passively Q-switched composite Nd:YAG/Cr^{4+}:YAG ceramic media.

Finally, a static engine automobile was fully run with its four cylinders being equipped with laser-spark devices.

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P.09

Preliminary results on Sm^{3+}:YSAG transparent ceramic

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Cubic $Y_3Sc_xAl_{3-x}O_{12}$ (YSAG) crystals are attractive laser-host materials due to their high thermal conductivity, broad spectral region, chemical stability, strong Stark splitting and relatively low phonon energies. However, it is very difficult to grow large-size single crystals with high quality because of the high melting point (~1950^{0}C). On the other hand, polycrystalline ceramics have lower sintering temperature, about 1750^{o}C. Moreover, because of the absence of segregation coefficient, ceramics can be doped with a higher fraction of active ions and can be fabricated in larger sizes compared to single crystals. In this work we present the results of our research on the production of samarium doped YSAG (Sm^{3+}:YSAG) transparent polycrystalline ceramics for visible laser emission [1, 2].

High purity α-Al_2O_3 (99.99+% purity, ~100-nm diameter), Y_2O_3 (99.99% purity, 20 to 40 nm diameter), Sc_2O_3 and Sm_2O_3 (99.99% purity) powders were used as starting materials. The selected composition is $Sm_{0.03}Y_{2.97}Sc_2Al_3O_{12}$. The powders were magnetically mixed in stoichiometric ratio in anhydrous ethylic alcohol for 24 h. As sintering additive, 0.5 wt.% of tetraethyl orthosilicate (TEOS) was used. The alcohol solvent was removed by drying the slurry at 80^{0}C. The dried powder was milled and pressed at low pressure (10 MPa) into pellet with half of inch diameter in a metal mold and then cold isostatically pressed at 240 MPa. Before sintering the sample was heated at 800^{0}C for removing organic substances used in preparation.

Fig. 1 Photo of the 1.0-at.% Sm:YSAG ceramic.

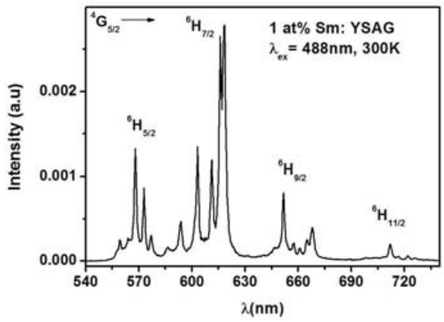

Fig. 2. Emission spectrum of the 1.0-at.% Sm:YSAG at 300 K under excitation at 488 nm.

Transparent Sm^{3+}:YSAG ceramic (Fig. 1) was obtained by sintering 4 h at 1700°C in high vacuum atmosphere. Emission and absorption spectra of the 1.0-at.% Sm^{3+}:YSAG at 300 K and 10 K were recorded (Fig. 2).

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DISPOZITIV LASER DESTINAT APRINDERII MOTOARELOR DE AUTOTURISME

INSTITUTUL NATIONAL DE CERCETARE-DEZVOLTARE PENTRU FIZICA LASERILOR, PLASMEI SI RADIATIEI - INCDFLPR DIN BUCURESTI, LABORATORUL DE ELECTRONICA CUANTICA A SOLIDULUI
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• AVANTAJE ale APRINDERII cu LASER :

- Reduce durata arderii;
- Elimina efectele de eroziune a electrodului;
- Poate aprinde amestecuri mai sarace, rezultand o scadere a consumului;
- Pozitia nucleului flacarii in camera de ardere poate fi controlata;
- Permite crearea mai multor nuclee de flacara simultan;
- Dispozitivul laser poate fi instalat fara adaptari suplimentare ale motorului;
- CRESTE RANDAMENTUL MOTORULUI.

• PROVOCARE:

• Realizarea unui laser cu dimensiuni apropiate de cele ale unei bujii clasice, avand caracteristici ale emisiei care sa permita aprinderea combustibilului.

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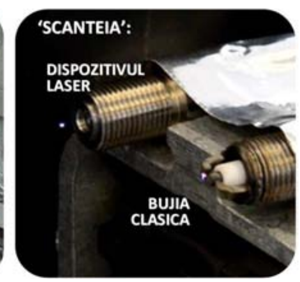

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2014:

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DOAR CU
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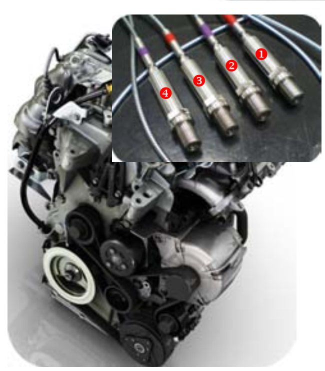

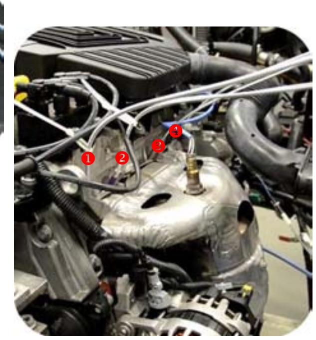

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