RAPORT STIINTIFIC

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Sistem Laser pentru Aprinderea Motoarelor de Automobile (LASSPARK)

Etapa V / 2016: Motor de Automobil Echipat cu Bujii Laser

1. Studiu Experimental privind Aprinderea Amestecurilor Omogene cu Continut Scăzut de Combustibil (Amestecuri Sarace)

Au fost efectuate experimente privind consumul de combustibil si stabilitatea in funcționare a unui motor pe benzina cu injecție indirecta MPI, motorul fiind echipat cu un sistem de aprindere format numai din dispozitive laser de tip 'bujie', funcționând in puncte stabilizate de turație si sarcina la diferite concentratii ale amestecului aer-combustibil. Experimentele s-au efectuat in colaborare cu Renault Technologie Roumanie si Uzinele Dacia din Mioveni, Arges. Un dispozitiv laser de tip 'bujie' realizat in Laboratorul de Electronica Cuantica a Solidului din Institutul National de Cercetare-Dezvoltare pentru Fizica Laserilor, Plasmei si Radiatiei (INFLPR), Magurele, este prezentat in Fig. 1a. Laserul contine un mediu compozit Nd:YAG/Cr^{4+}:YAG de tip ceramic si emite pulsuri la lungimea de unda de 1.06 μm, avand energia de pana la 4 mJ cu durata de ~0.8 ns, puterea de varf fiind de ~5 MW. Frecventa maxima de operare este de 60 Hz. In plus, prin schimbarea conditiilor de pompaj, se poate obtine emisia in trenuri de pulsuri. Detalii privind proiectarea, testarea si caracteristicile unui astfel de laser au fost publicate in Ref. [1]. In Fig. 1b sunt aratate cele patru dispozitive laser de tip 'bujie', inainte de montarea pe motor.

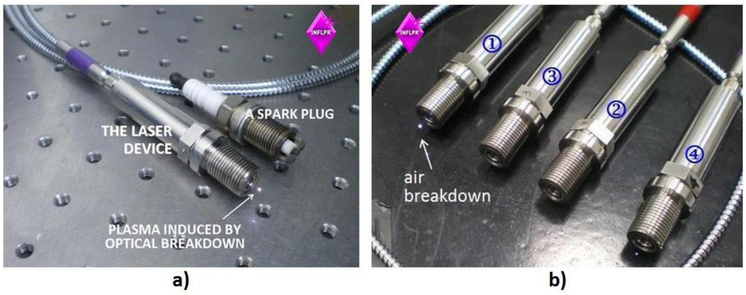

Fig. 1 a) Dispozitiv laser de tip 'bujie' laser utilizat in experimente. **b)** Sunt aratate cele patru dispozitive laser, inainte de montarea lor pe motor.

Motorul cu care s-au efectuat testele este un motor Renault tip K7M 812 alimentat cu benzina, injecția este de tip indirecta in poarta supapei de admisie, dispune de 4 cilindrii in linie având o capacitate cilindrica de 1.598 cm^3, un raport de compresie de 9.5, dezvoltând puterea nominala de 62 kW si un cuplu maxim de 135 N·m. Presiunea in cilindru a fost masurata cu un traductor de presiune piezoelectric AVL GU-21D, montat pe cilindrul 4 cu care au fost înregistrate 500 de cicluri consecutive pentru analiza detaliata a parametrilor arderii din motor.

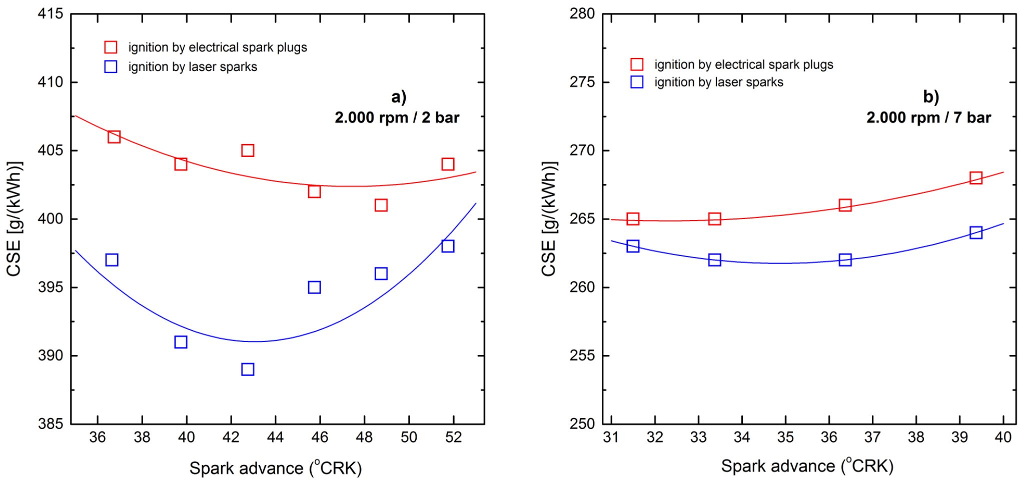

Fig. 2 Consumul specific efectiv in funcție de avansul la scanteie pentru un amestec stoichiometric aer-combustibil (λ~1), turație 2.000 rpm si PME: **a)** 2 bar; **b)** 7 bar.

Turatia motorului a fost ținuta constanta la 2.000 rpm de frâna electromagnetica cu curenți turbionari de tip AVL la toate sarcinile investigate, intre 2 si 8 bari presiune medie efectiva (PME). Pentru fiecare turatie si sarcina s-au achizitionat date pentru mai multe avansuri, stabilindu-se astfel avansul optim al motorului din punct de vedere al performantelor ambelor tipuri de aprinderi. S-au facut masuratori la diferite amestecuri (concentrații) de aer-combustibil (λ), limita amestecurilor sărace fiind determinata de atingerea punctului de funcționare instabila a motorului.

Consumul specific efectiv (CSE) este calculat ca raportul intre consumul efectiv de carburant măsurat gravimetric cu balanța AVL 733S împreuna cu regulatorul de presiune AVL753C si puterea efectiva dezvoltata de motor măsurata cu frâna electromagnetica AVL. In Fig. 2 este prezentata variația CSE in funcție de diferite valori ale avansului la scânteie, pentru un amestec aer-combustibil stoichiometric (λ~1) aer-combustibil si presiuni medii efective de 2 bar [Fig. 2a] si 7 bar [Fig. 2b]. Pentru fiecare sarcina a motorului investigata (măsurata in PME), după trasarea curbelor de avans optim la scânteie, a fost aleasa valoarea optima a CSE pentru fiecare tip de aprindere (clasica si laser) trasând-se astfel, in Fig. 3, cele 2 curbe ale consumului specific efectiv in funcție de PME. Se observa o îmbunătățire a randamentului motorului (tradus printr-o scădere a CSE) in cazul aprinderii cu dispozitivele laser, in special la sarcini mai scazute (PME< 5 bar in cazul nostru), unde se știe ca funcționarea motorului este mai instabila, deci cu o variabilitatea ciclica a motorului mai accentuata decât in cazul sarcinilor ridicate.

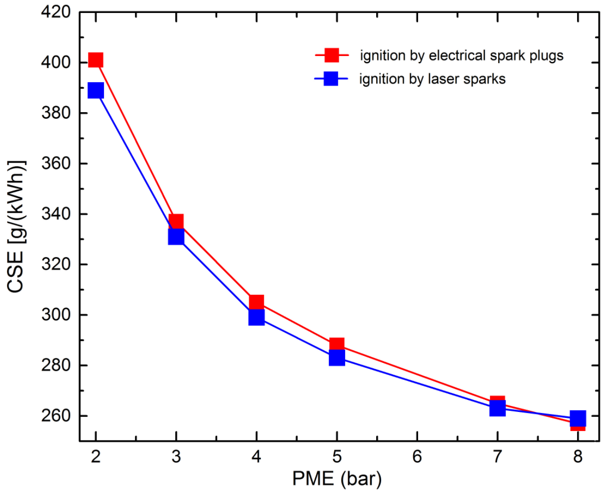

Fig. 3 Valori optime ale CSE la diferite sarcini (PME), pentru un amestec aer-combustibil stoichiometric (λ~1) si turatie de 2.000 rpm.

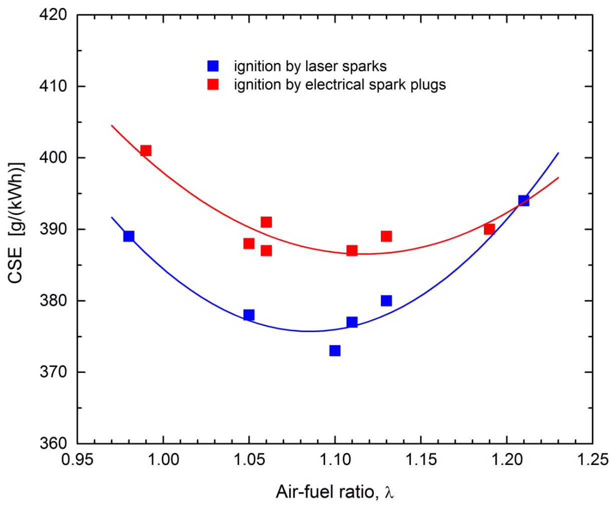

Fig. 4 Variatia CSE in funcție de raportul aer-combustibil la turatia de 2.000 rpm si sarcina PME= 2 bar.

In continuare, a fost evaluat randamentul motorului pe baza CSE in cazul funcționarii cu amestecuri sărace, in diferite proporții aer-combustibil λ, si pentru diferite sarcini exprimate in PME. Spre exemplu, in Fig. 4 este prezentat CSE in functie de λ pentru PME= 2 bar. Se observa ca diferenta intre cele doua sisteme de aprindere, cu dispozitive laser si cu bujiile clasice, este mica pentru amestecul aer-combustibil sărăcit (λ cu valori intre 1.15 si 1.21) Aceasta micșorare a diferenței de consum, neașteptata in cazul utilizării acestui nou tip de aprindere, este pusa pe seama lipsei unor curbe de avans la scânteie pentru fiecare amestec aer-combustibil. Avansul optim se modifica odată cu modificarea amestecului aer-combustibil λ de aceea este nevoie de realizarea unor curbe de avans. Pe de alta parte, pentru amestecuri cu concentratie in domeniul λ= 0.98-1.14 s-a obtinut o scadere a consumului de combustibil pentru aprinderea cu dispozitive laser, aceasta reducere fiind de ~3.4% fata de consumul masurat in cazul aprinderii cu bujiile clasice.

Stabilitatea motorului a fost evaluata prin parametrul COV_{IMEP}, definit ca raportul dintre deviatia standard a presiunii medii indicate IMEP si media presiunilor medii indicate. Dupa cum se observa in Fig. 5, in cazul functionarii motorului cu combustibil in raport stoichiometric (λ~1), diferentele intre COV_{IMEP} au fost mici intre cele 2 tipuri de aprindere. Diferente mai semnificative intre bujia clasica si cea laser au fost obtinute in special in zona amestecurilor mai sarace unde este binecunoscuta funcționarea instabila a motorului. Astfel, pentru λ>1.08 si aprinderea cu dispozitive laser s-a observat o imbunatatire a COV_{IMEP}, cu valori in domeniul 4% la 11% fata de COV_{IMEP} masurat pentru aprinderea cu bujii clasice. In plus, in cazul in care s-au facut mai multe determinari la aceeasi valoare a parametrului λ, s-a obtinut o mai buna repetabilitate a rezultatelor pentru aprinderea cu dispozitivele laser; un astfel de caz este aratat in Fig. 5, pentru λ= 1.08.

Functionarea mai uniforma a motorului in cazul utilizarii aprinderi laser, duce la posibilitatea micsorarii turatiei motorului la regimul de relanti (mers in gol), la posibilitatea de deplasare a arderii in zona amestecurilor sarace cat si diluarea mai puternica a amestecului cu gaze inerte (EGR intern sau extern) prin respectarea caietului de sarcini din punct de vedere al variabilitatii ciclice (COV_{IMEP} si σ_{IMEP}), precum si la reducerea zgomotelor, vibratiilor si a solicitarilor mecanice.

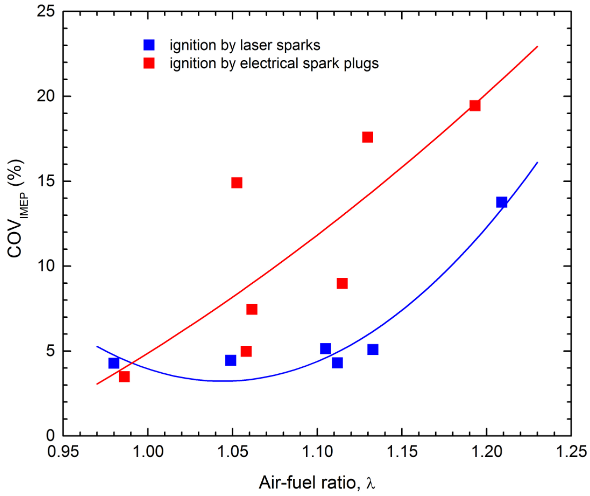

Fig. 5 Variatia parametrului de stabilitate COV_{IIMEP} in functie de raportul aer-combustibil la turatie de 2.000 rpm si sarcina PME= 2 bar.

Variabilitatea ciclica mai mare care s-a observat pentru aprinderea cu bujii clasice a motorului la sarcini mici si in cazul amestecurilor sarace in combustibil conduce la arderi partiale sau aprinderi ratate a combustibilului, având ca rezultat emisia de hidrocarburi si un randament scăzut al motorului [2]. Este posibil ca aprinderea cu dispozitive laser sa fie o solutie pentru astfel de probleme. Astfel, in comparatie cu aprinderea cu bujii clasice, modul de concentrare al energiei pulsului laser conduce la o mai buna formare si dezvoltare a nucleului de ardere si la o mai buna stabilitate a arderii de la ciclu la ciclu.

Rezultatele au fost prezentate intr-o comunicare orala, la conferinta The 4th Laser Ignition Conference, 17-20 May 2016, Pacifico Yokohama, Yokohama, Japan.

Un rezumat al activitatii desfasurate in cadrul acestui proiect si rezultate obtinute au fost prezentate la "Workshop 1: History, Status and Future of Laser Ignited Combustion Engines," care s-a desfasurat in perioada 29-30 septembrie 2016 la INFLPR, Magurele, in cadrul proiectului European "691688 LASIG-TWIN: Laser Ignition - A Twinning Collaboration for Frontier Research in Eco-Friendly Fuel-Saving Combustion". Titlul prezentarii a fost "Development of a Laser Spark Plug for Internal Combustion Engines", sesiunea Automotive Applications - II -, in ziua de 30 septembrie.

Rezultatele au fost popularizate in cadrul Renault Technologie Roumanie, intr-o nota interna din data de 30 octombrie 2016.

2. Laser Nd:YAG/Cr^{4+}:YAG cu Patru Fascicule de Mare Putere de Varf

Utilizarea unui sistem laser pentru aprinderea de combustibil ofera posibilitatea de a realiza aprinderea in mai multe puncte, rezultand un proces de combustie mai uniform in comparatie cu fenomenul de aprindere obtinut intr-un singur punct. In cazul aprinderii laser in doua puncte ale amestecurilor de CH_4/aer si H_2/aer, intr-o incinta statica, au fost observate o scadere a duratei arderii si o crestere a presiunii [3]. De asemenea, experimente realizate cu amestecuri de H_2/aer au dus la concluzia ca aprindere in doua puncte asigura o ardere mai rapida decat cea obtinuta in urma aprinderii intr-un punct [4]. In aceste conditii, un sistem laser cu mai multe puncte de aprindere este de real interes, iar pentru obtinerea unui astfel de sistem pana acum au fost propuse cateva solutii. Astfel, pompand longitudinal un mediu ceramic compozit de $Nd:YAG/Cr^{4+}:YAG$ comutat pasiv, a fost dezvoltat un sistem laser cu trei puncte de focalizare in pozitii fixe [5]. De asemenea, un modulator de lumina spatial a fost aplicat unui fascicului laser pentru a obtine puncte de focalizare cu pozitii arbitrare intr-un plan, sau la diferite distante pe axa propagare [6]. In plus, transferul radiatiei de pompaj de la dioda laser in mediul $Nd:YAG/Cr^{4+}:YAG$ s-a facut cu o matrice de lentile 2×2, laserul furnizand patru fascicule [7]; totusi, energia pe puls a fost redusa. Prezentam, in continuare, un sistem laser comutat pasiv $Nd:YAG/Cr^{4+}:YAG$ compozit, in configuratie monolitica, care livreaza patru fascicule laser, fiecare avand caracteristici astfel incat sa se obtina fenomenul de spargere a aerului.

Sistemul laser este prezentat in Fig. 6. Mediul laser este $Nd:YAG/Cr^{4+}:YAG$ compozit, cu diametrul de 10 mm, fiind compus dintr-un mediu 1.1-at.% Nd:YAG de lungime 8.5 mm care a fost pus in contact optic cu un mediu de $Cr^{4+}:YAG$ cu absorbtie saturabila, acesta avand transmisia initiala de 40% si lungimea de 2.5 mm. Suprafata S1 a mediului Nd:YAG a fost depusa cu straturi dielectrice avand reflectivitate ridicata (HRM, R>0.999) la lungimea de unda laser, λ_{em}=1.06 µm, iar suprafata S2 a $Cr^{4+}:YAG$ a fost depusa cu transmisie ridicata T_{OCM}=50% (±5%) la λ_{em}; astfel, rezonatorul laser monolitic s-a obtinut intre suprafetele S1-S2. De asemenea, S1 a fost depusa cu transmisie ridicata (T>0.98) la lungimea de unda de pompaj, λ_p=807 nm. Pompajul optic (la λ_p= 807 nm) a fost facut in regim cuasi-cw cu diode laser (JOLD-120-QPXP-2P, Jenoptik, Germania), avand fibre optice cu diametrul de 600 µm si NA= 0.22; durata pulsului de pompaj a fost de 250 µs. Radiatia provenita de la fiecare dioda laser a fost livrata de fibra optica (F) si focalizata intr-un mediu Nd:YAG cu o singura lentila (L). O prisma de dimensiuni mici (P) a fost utilizata pentru a directiona fiecare linie de pompaj, astfel obtinandu-se plasarea celor patru fibre in jurul mediului activ laser Nd:YAG.

Linia de focalizare a fost aleasa in urma unor experimente in care mediul compozit $Nd:YAG/Cr^{4+}:YAG$ a fost pompat in centrul lui, direct de la fibra optica F si doar cu o singura lentila L. Sistemul laser cu patru fascicule laser este prezentat in Fig. 7. Patru prisme, P (Fig. 7a), au fost folosite pentru a redirectiona fiecare fascicul de pompaj provenit de la cate o fibra optica F catre mediul $Nd:YAG/Cr^{4+}:YAG$ (Fig. 7b). Pentru o rata de repetitie a pompajului de 5 Hz, energia pulsului laser a fost E_p= 3.25 mJ pentru fasciculul laser "1", E_p= 3.30 mJ pentru fasciculul "2", E_p= 3.60 mJ pentru fasciculul "3" și E_p= 3.20 mJ pentru fasciculul laser "4". Diferențele fata de valoarea așteptata de E_p= 3.4 mJ (obtinuta pentru pompajul in centrul mediului $Nd:YAG/Cr^{4+}:YAG$) au fost atribuite unor diferențe de lungime in fiecare linie de pompaj optic, precum și datorita faptului ca pompajul optic nu s-a facut în centrul mediului $Nd:YAG/Cr^{4+}:YAG$, dar pe circumferinta sa (iar in acest caz mici diferențe în concentrația de Nd sau Cr^{4+} sau chiar in acoperirile dielectrice ar putea afecta rezultatele). In plus, diferențele dintre lungimile de unda ale celor patru diode laser de pompaj pot influenta energia E_p. Energia pulsului de pompaj a fost E_{pump}= 30.5 mJ și 32 mJ pentru fasciculul laser "1" și "2", respectiv, E_{pump}= 33 mJ pentru fasciculul "3" și E_{pump}= 30 mJ pentru fasciculul laser "4". Astfel, eficiența optica globala (definita ca raportul E_p/E_{pump}) a fost intre 0.103 pentru fasciculul laser "2" si 0.109 pentru fasciculul laser "3". Durata pulsului laser a fost de ~0.9 ns pentru fiecare fascicul; astfel, puterea de varf a pulsului laser s-a situat intre 3.55 MW pentru fasciculul laser "4" si 4.0 MW pentru fasciculul laser "3".

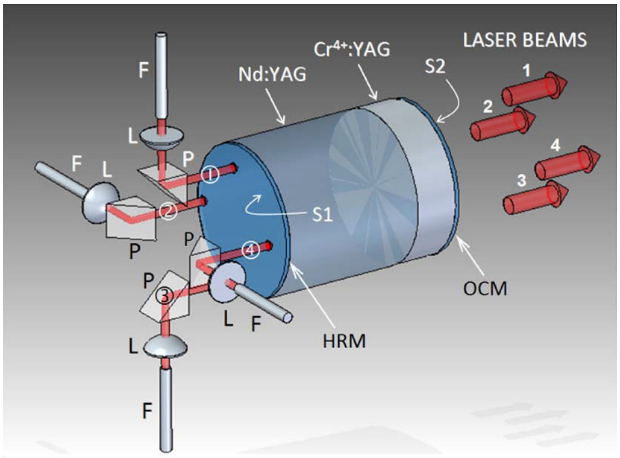

Fig. 6. Sistemul laser cu patru fascicule. Fiecare fascicul de pompaj este livrat de catre o fibra (F), este colimat cu cate o lentila (L) si apoi este directionat catre mediul laser $Nd:YAG/Cr^{4+}:YAG$ cu ajutorul unei prisme (P). In acest mod sunt generate patru fascicule laser: 1, 2, 3 si 4.

Un astfel de dispozitiv laser poate fi utilizat pentru aprinderea in mai multe puncte a amestecurilor aer-combustibil, in special pentru aprinderea amestecurilor diluate. Diferite scheme de focalizare, care sa permita accesul unui volum definit de combustibil, pot sa fie folosite. In Fig. 8a prezentam o schema in care toate fasciculele laser pot fi focalizate in același punct, cu o singura lentila. Intr-un alt aranjament, aratat in Fig. 8b, fiecare fascicul laser poate fi focalizat intr-un punct de pe axa sa de propagare, folosindu-se lentile identice. Un volum mai mare de combustibil poate fi aprins prin focalizarea fasciculelor laser la distanțe diferite fata de optica de focalizare, asa cum am aratat in Fig. 8c.

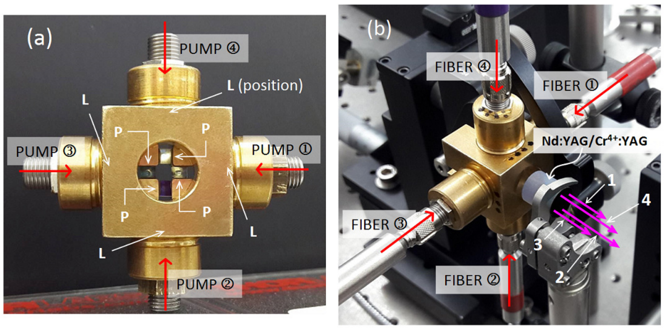

Fig. 7. a) Sistemul de pompaj. L: lentila; P: prisma. **b)** Laserul Nd:YAG/Cr^{4+}:YAG cu patru fascicule. Directiile celor patru fascicule 1, 2, 3 si 4 sunt indicate prin sageti.

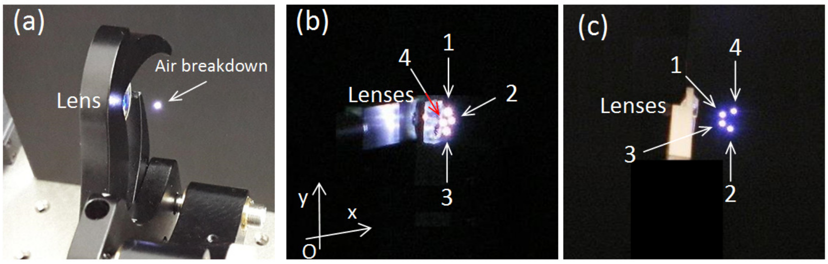

Fig. 8 Combinatii pentru focalizarea fasciculele laser: **a)** Focalizarea într-un singur punct; **b)** Focalizarea fasciculelor se face în acelasi plan, la distante egale de sistemul de focalizare; **c)** Fasciculele laser "1" și "3" sunt focalizate pe orizontala, inainte de fasciculele laser "2" și "4", care sunt plasate pe axa verticala.

In plus, se pot proiecta configuratii in care focalizarea fasciculelor laser sa se obtina in afara (sau in interiorul) fiecarei axe de propagare. Mai mult, deoarece fasciculele laser sunt emise independent, se poate controla fiecare moment cand un fascicul laser este emis si apoi focalizat. O astfel de sincronizare poate fi utila pentru a evita aprinderile ratate, in principal in cazul amestecurilor sarace aer-combustibil, sau pentru ardere in conditii de turbulenta.

Rezultatele au fost subiectul a trei comunicari poster, care au fost prezentate la conferinta The 4th Laser Ignition Conference, 17-20 May 2016, Pacifico Yokohama, Yokohama, Japan, la conferinta 7th EPS-QEOD EUROPHOTON CONFERENCE, Solid State, Fibre, and Waveguide Coherent Light Sources, 21-26 August, 2016, Vienna, Austria si la conferinta International Conference on Space Optics, ICSO 2016, 18-21 Oct. 2016, Biarritz, France. In plus, a fost publicat un articol in revista Photonics Research (ISI - Web of Science). De asemenea, in colaborare cu Renault Technologie Roumanie a fost scrisa o propunere de proiect care a fost depusa la OSIM, Romania si la INPI - Institut National de la Propriété Industrielle, Franta.

3. Posibilitati de Utilizare a Bujiei de Tip Laser in Aplicatii Alternative

O provocare majora ale societatii secolului XXI este respectarea restrictiilor impuse pentru emisiile de noxe generate de catre motoarele cu ardere interna si in acelasi timp a cerintelor in continua crestere in ceea ce priveste eficienta acestora [8, 9]. In acest sens, metoda de aprindere electrica tinde sa atinga limita tehnologica deoarece maximizarea eficientei necesita operarea motoarelor cu un raport de compresie mai ridicat si aprinderea de amestecuri aer-combustibil mai sarace. Astfel, au fost cautate solutii alternative la dispozitivele electrice de aprindere, cum ar fi bujii electrice cu energie ridicata, sisteme de aprindere cu jet de plasma sau de flacara, sisteme de aprindere cu laserul sau cele in care sunt recirculate gazele arse.

O solutie promintatoare este aprinderea combustibilor cu ajutorul unui dispozitiv laser. Un astfel de sistem produce pulsuri laser de durata foarte scurta (de ordinul ns sau <ns) si putere de varf ridicata. Aceste pulsuri sunt focalizate, generandu-se un camp electric de intensitate mare care creaza o plasma localizata cu temperaturi de ordinul 10^6 K si presiuni de 10^2 MPa. Energia laser este transferata intr-un interval de timp foarte scurt (ns), iar tot procesul de combustie dureaza cateva sute de milisecunde [10].

Aprinderea laser a fost implementata in diverse tipuri de motoare cu aprindere interna si pentru numeroase feluri de combustibili, dar progrese notabile au fost realizate in industria automobilelor, pentru propulsia aerospatiala si centralele pentru cogenerare de energie. Astfel, anii ’80 au reprezentat debutul studiilor de cercetare in domeniul aprinderii cu sisteme laser a motoarelor cu aprindere interna [11]. Evolutiile realizate in acest domeniu au fost limitate la experimente de laborator ce foloseau sisteme laser mari, costisitoare si relativ complicate, deci imposibil de integrat ca si modul auxiliar al motorului. In domeniul aerospatial, ignitia laser poate fi folosita pentru aplicatii variate, cum ar fi: turbine cu gaz, sisteme supersonice, avioanele cu reactie, sateliti si sisteme de propulsie nucleara. Aplicarea conceptului de aprindere laser la regimuri de propulsie aerospatiala este una din cele mai dificile, dar fructuoase preocupari in domeniul aviatiei. In acest caz, beneficiile apar datorita: posibilitatii de aprindere a combustibilui in puncte multiple in timp si spatiu, sincronizarea aprinderii este foarte precisa, procesul de combustie este mai stabil, aprinderea de amestecuri mai sarace si la presiuni ridicate [12, 13]. Astfel de motoare functioneaza in conditii extreme de temperatura, atmosferice etc., iar implementarea sistemelor laser ca metoda de aprindere poate fi o alegere optima. In plus, intretinerea unui astfel de dispozitiv este mult mai putin costisitoare decat alte metode de aprindere, ceea ce face ca perpectiva de aprindere cu laser sa fie promintatoare din punct de vedere economic.

Avand in vedere faptul ca turbinele cu gaz sunt utilizate la scara larga in domeniul generarii de energie, scopul principal este acela de a creste eficienta motorului si, in acelasi timp, de a diminua nivelul de compusi poluanti. Acest scop poate fi indeplinit daca, sunt intrebuintate amestecuri de combustibil mai sarace si care se gasesc la temperaturi si presiuni mai ridicate. Sistemele de aprindere electrice nu sunt capabile sa indeplineasca toate cerintele iar aprinderea cu laserul este privita ca un candidat serios pentru acestea. Astfel, folosind sisteme laser au fost realizate studii privind aprinderea amestecurilor sarace de metan-aer in conditii de temperatura si presiune ridicate [14].

Sistemele laser au fost intrebuintate pentru aprinderea in incinta de combustie a rachetelor. Exista studii experimentale in care aprinderea in mai multe puncte este caracterizata si analizata pentru acest gen de aplicatie [15]. De asemenea, exista grupuri a caror subiect de studiu il reprezinta metoda de aprindere cu laserul a combustibilor alternativi pentru sistemele de sateliti [16].

4. Automobil Echipat cu Bujii Laser

Pentru realizarea acestei etape a fost pregătit un autoturism Dacia Logan (tip L90) cu motor similar cu cel folosit pentru testele pe bancul motor (tip K7M). Calculatorul ECU (tip Simens) cu care era echipata mașina a fost modificat, au fost scoase fire pentru captarea semnalului pentru scanteia electrica si folosit pentru comanda echipamentului de aprindere laser. Automobilul Dacia Logan a fost echipat cu dispozitivele laser de tip 'bujie', fiind rulat in aceste conditii (adica aprindere obtinuta doar cu dispozitive laser). Primele experimente s-au facut fara sarcina, cu automobilul stationat intr-o camera de tip garaj. Cateva fotografii sunt prezentate in Fig. 9.

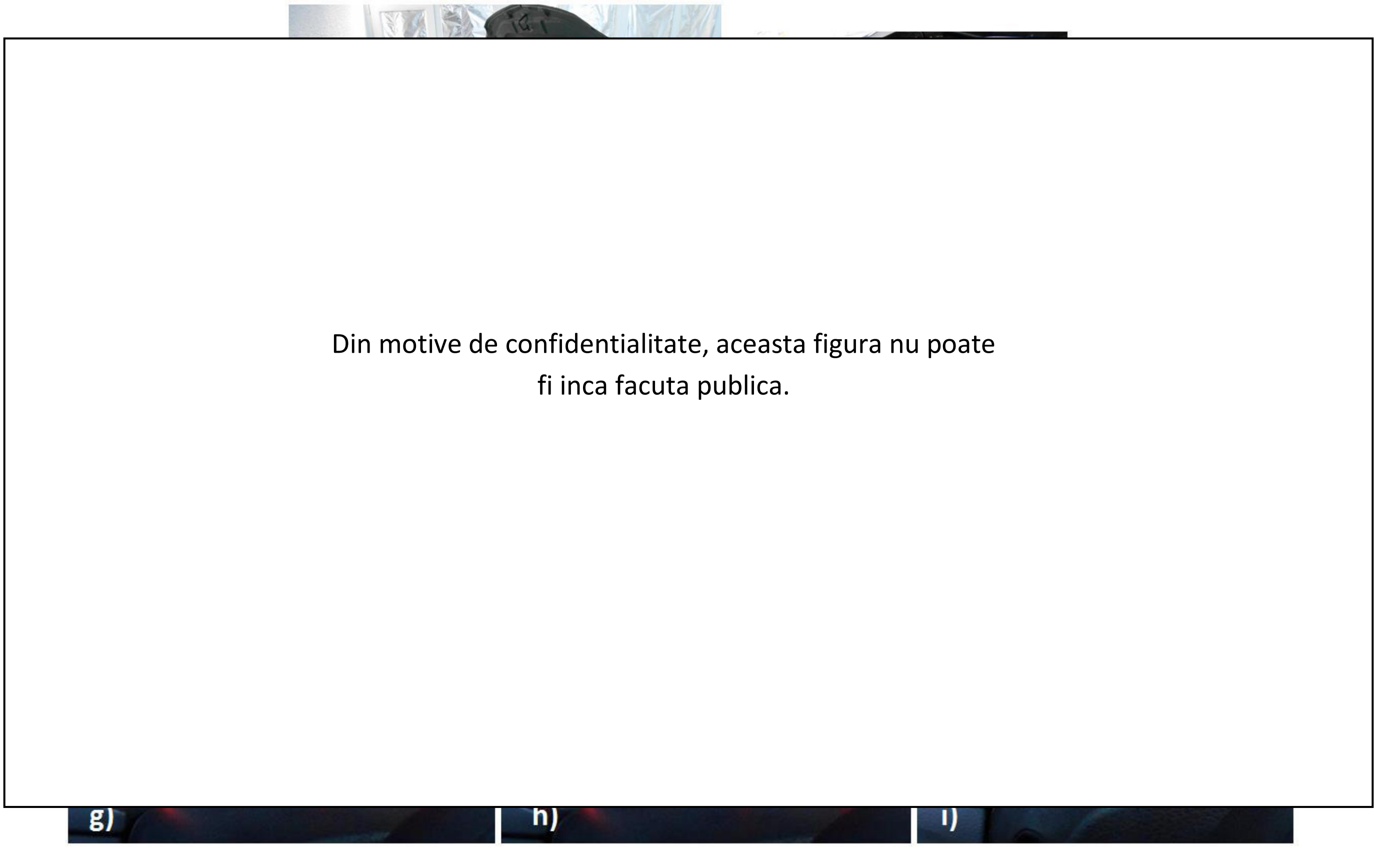

Fig. 9 Imagini din timpul rularii automobilului Dacia Logan, aprindere a motorului cu dispozitive laser de tip bujie: **a)** Vedere generala; **b)** Vedere de aproape a 'bujiilor' laser; **c)**, **d)** Imagini de pe partea stanga (a soferului); **e)**, **f)** Imagini dinspre partea dreapta; **g)**, **h)**, **i)** Imagini ale bordului, in care turatia este vizibila.

Urmatoarele experimente au fost facut in exterior, masina fiind rulata in fata (in viteza intai) si in marsarier. In Fig. 10 sunt aratate fotografii luate in timpul acestor incercari.

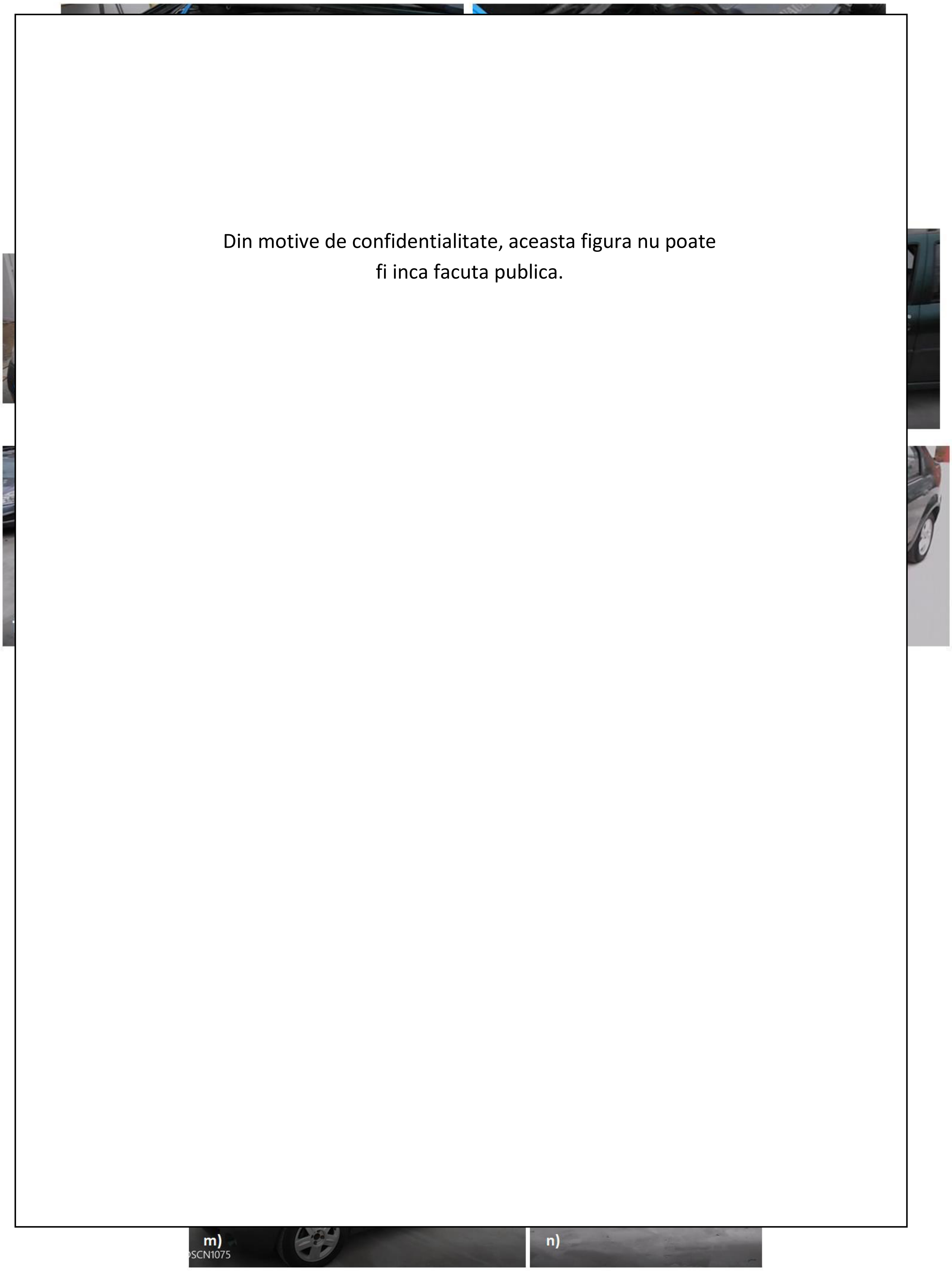

Fig. 10 Imagini luate in timpul rularii automobilului Dacia Logan in exterior: **a)** Bujiile laser inainte de instalare; **b)** Imagine cu dispozitivele laser de tip 'bujie' instalate; **c)**, **d)**, **e)** Rulare in fata; **f)**, **g)**, **h)**, Rulare in marsarier; **i)**, **j)** Imagini ale bordului, in stationare, motor ambalat. Rulare la un alt moment: **k)**, **l)** In fata si **m)**, **n)** In marsarier.

5. Concluzii. Diseminarea Rezultatelor

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

- Au fost efectuate experimente privind consumul de combustibil si stabilitatea in funcționare a unui motor pe benzina cu injecție indirecta MPI, motorul fiind echipat cu un sistem de aprindere format numai din dispozitive laser de tip ’bujie’, funcționând in puncte stabilizate de turație si sarcina la diferite concentrații ale amestecului aer-combustibil
- A fost propus si a fost realizat (montaj experimental) un laser cu patru fascicule. Aceasta solutie ar permite aprinderea de combustibil in mai multe puncte si ofera posibilitati de plasare a aprinderilor intr-un anumit volum sau de comanda a acestora in timp;
- Dispozitivele laser de tip bujie si sistemul de comanda au fost instalate pe un automobil Dacia, acesta ruland cu acest sistem de aprindere.

- Rezultatele au fost diseminate prin:
  a) Publicarea unui articol intr-o revista indexata ISI-Web of Science, Photonics Research;
  b) A fost publicat un articol in Optics Expres (revista indexata ISI - Web of Science), manuscrisul fiind trimis pentru evaluare si fiind acceptat in anul 2015;
  c) O comunicare orala si trei prezentari poster la conferinte internationale;
  d) O prezentare la "Workshop 1: History, Status and Future of Laser Ignited Combustion Engines," care s-a desfasurat in perioada 29-30 septembrie 2016 la INFLPR, Magurele, in cadrul proiectului European "691688 LASIG-TWIN: Laser Ignition - A Twinning Collaboration for Frontier Research in Eco-Friendly Fuel-Saving Combustion", sesiunea Automotive Applications - II -, 30 septembrie;
  d) O propunere de brevet care a fost inregistrata in Romania si in Franta.

- Mentionam ca rezultate obtinute in cadrul acestui proiect au fost popularizate in cadrul Renault Technologie Roumanie, intr-o nota interna din data de 30 octombrie 2016.

- INFLPR, Laboratorul de Electronica Cuantica a Solidului a aplicat, in anul 2015, pentru un proiect European de tip "twinning", subiectul fiind despre aprinderea cu laser. Propunerea a fost evaluata si proiectul a fost acceptat pentru finantare. Proiectul se numeste "691688 LASIG-TWIN: Laser Ignition - A Twinning Collaboration for Frontier Research in Eco-Friendly Fuel-Saving Combustion", iar partenerii externi sunt Bayreuth University, Bayreuth, Germania; University of Liverpool, Liverpool, UK; Centre National de la Recherche Scientifique,Châtenay-Malabry, Franta si Fraunhofer Institute, IOF, Jena, Germania. Informatii despre proiect se gasesc la: http://ecs.inflpr.ro/Proiect%20LASIG-TWIN%20691688.html si http://www.lasig-twin.eu/

ARTICOLE ISI

1. N. Pavel, T. Dascalu, G. Salamu, M. Dinca, N. Boicea, and A. Birtas, “Ignition of an automobile engine by high-peak power Nd:YAG/Cr^{4+}:YAG laser-spark devices,” Opt. Express **23**(26), 33028-33037 (2015). [Impact Factor: 3.188]
2. T. Dascalu, G. Croitoru, O. Grigore, N. Pavel, “High-peak power passively Q-switched Nd:YAG/Cr^{4+}:YAG composite laser with multiple-beam output,” Photonics Research, **4**(6), 267-271 (2016). [2015 Impact Factor: 3.179]

BREVET

1. A. Birtas, N. Boicea, T. Dascalu, N. Pavel, G. Salamu, O.-V. Grigore,:
   • “Bujie cu laser pentru un motor cu ardere,” OSIM application number A/10028/2016/ 18.05.2016, Romania;
   • “A laser spark plug for a combustion engine,” INPI - Institut National de la Propriété Industrielle, Numéro de soumission: 000347665 / 18.05.2016, France.

CONFERINTE

1. A. Birtas, G. Croitoru (Salamu), M. Dinca, T. Dascalu, N. Boicea, and N. Pavel, “The effect of laser ignition on a homogenous lean mixture of an automotive gasoline engine,” The 4th Laser Ignition Conference, 17-20 May 2016, Pacifico Yokohama, Yokohama, Japan, presentation LIC6-2 (oral presentation).
2. G. Croitoru (Salamu), O. V. Grigore, T. Dascalu, and N. Pavel, “Passively Q-switched Nd:YAG/Cr^{4+}:YAG laser with multiple-beam output,” The 4th Laser Ignition Conference, 17-20 May 2016, Pacifico Yokohama, Yokohama, Japan, presentation LICp-1 (poster presentation).
3. O. V. Grigore, G. Croitoru, T. Dascalu, M. Dinca, N. Pavel, “Edge-pumped Nd:YAG/YAG lens-shaped composite laser,” 7th EPS-QEOD EUROPHOTON CONFERENCE, Solid State, Fibre, and Waveguide Coherent Light Sources, 21-26 August, 2016, Vienna, Austria, presentation PO-2.1 (poster presentation).
4. T. Dascalu, G. Croitoru, O. V. Grigore, and N. Pavel, “Multiple-Beam Output High-Peak Power Nd:YAG/Cr^{4+}:YAG Laser for Laser Ignition,” International Conference on Space Optics, ICSO 2016, 18-21 Oct. 2016, Biarritz, France (presentation 254, poster presentation).
5. A. Birtas and T. Dascalu, "Development of a Laser Spark Plug for Internal Combustion Engines," prezentare orala la "Workshop 1: History, Status and Future of Laser Ignited Combustion Engines," 29-30 septembrie 2016, INFLPR, Magurele, in cadrul proiectului European "691688 LASIG-TWIN: Laser Ignition - A Twinning Collaboration for Frontier Research in Eco-Friendly Fuel-Saving Combustion", sesiunea Automotive Applications.

Referinte

[1] N. Pavel, T. Dascalu, G. Salamu, M. Dinca, N. Boicea, and A. Birtas, “Ignition of an automobile engine by high-peak power Nd:YAG/Cr^{4+}:YAG laser-spark devices,” Opt. Express **23**(26), 33028-33037 (2015).

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Ignition of an automobile engine by high-peak power Nd:YAG/Cr^{4+}:YAG laser-spark devices

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Abstract: Laser sparks that were built with high-peak power passively Q-switched Nd:YAG/Cr^{4+}:YAG lasers have been used to operate a Renault automobile engine. The design of such a laser spark igniter is discussed. The Nd:YAG/Cr^{4+}:YAG laser delivered pulses with energy of 4 mJ and 0.8-ns duration, corresponding to pulse peak power of 5 MW. The coefficients of variability of maximum pressure (COV_{Pmax}) and of indicated mean effective pressure (COV_{IMEP}) and specific emissions like hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NO_x) and carbon dioxide (CO_2) were measured at various engine speeds and high loads. Improved engine stability in terms of COV_{Pmax} and COV_{Pmax} and decreased emissions of CO and HC were obtained for the engine that was run by laser sparks in comparison with classical ignition by electrical spark plugs.

OCIS codes: (140.3580) Lasers, solid-state; (140.3530) Lasers, neodymium; (140.3540) Lasers, Q-switched; (140.5560) Pumping.

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1. Introduction

Laser ignition was investigated extensively in recent years and it was seen as a possible answer to human concern on environment impact of the automobiles that are powered by internal combustion engines. Such ignition, which is applicable to gasoline engines, can lower fuel consumption and decrease gas emission, but it still improves the automobile engine performances and efficiency. In comparison with classical ignition by an electrical spark plug laser ignition offers several advantages [1–3]. Thus, due to the absence of spark plug electrode there is no quenching effect of the developing flame kernel; furthermore, the position of the ignition point inside the combustion chamber can be chosen, whereas multiple-point ignition could provide better and more uniform combustion; moreover, laser ignition offers the possibility to ignite leaner air-fuel mixtures.

A rapid development of such a laser device was not possible due to technical or price-related problems. Thus, when the first air breakdown phenomenon was reported in 1963 by focusing the third harmonic of a Q-switch ruby laser, the authors have characterized their experiments as "the most expensive spark plug in automotive history" [4]. Still, motivated by the attractiveness and importance of this subject, commercially available lasers that delivered

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pulses of tens of mJ and several-ns duration experiments were used to determine the laser-induced breakdown threshold ignition or to ignite various gases (oxygen, argon, helium, or methane) [5–8]. The first laser ignition of an engine was made in 1978 with a CO_2 laser, using a single-cylinder engine [9,10]; moreover, Q-switched Nd:YAG lasers were used to ignite a four-cylinder engine in 2008 [11]. In these experiments the laser beams were directed to and then focused into the engine cylinders by common optics (lenses and mirrors).

An important step toward realization of a compact laser-spark device was made in 2007, when a Nd:YAG laser that was passively Q-switched by Cr^{4+}:YAG saturable absorbed (SA) was proposed by H. Kofler et al. [12]. The laser (which was built of discrete elements) was end-pumped by a fiber-coupled diode laser and delivered pulses with energy up to 6.0 mJ and 1.5-ns duration. Furthermore, based on the same combination of active medium and SA crystal, a side-pumped laser that yielded pulses with long 3.0-ns duration but high energy of 25 mJ was reported in 2009 by G. Kroupa et al. [13]. Further performance optimization of an end-pumped Nd:YAG-Cr^{4+}:YAG laser [14] has enabled realization by Tsunekane et al. of the first spark-like micro-laser device [15]; the laser oscillator (made also of discrete components) delivered pulses with 2.7-mJ energy and short duration of 0.6 ns, corresponding to pulse peak-power of 4.5 MW. Successful ignition of stoichiometric C_3H_8/air mixture fuel was achieved with this laser in a constant-volume chamber at room temperature and atmospheric pressure.

A multi-beam laser spark that was built, for the first time, with a monolithic, all poly-crystalline ceramic diffusion-bonded Nd:YAG/Cr^{4+}:YAG media was reported in 2011 [16]. Such a laser possessed robustness, compactness and resistance to vibrations, suitable for direct use on an engine. Consequently, the first report of laser ignition of an automobile gasoline engine was made in 2013, by Taira et al. [17]. The laser medium was a square-shaped Nd:YAG/Cr^{4+}:YAG ceramic that delivered pulses with 2.4-mJ energy and 0.7-ns duration; in addition, a train of four-pulses was used for ignition of each engine cylinder. It is also worth to mention that data released recently by Bosch Co. showed this company interest in the field of laser ignition [18]. Thus, based on research that started around 2000, Bosch Co. has developed laser-spark igniters with monolithic diffusion-bonded Nd:YAG/Cr^{4+}:YAG single-crystals media, yielding pulses with high 12.3-mJ energy at long 2.4-ns duration, or shorter pulses of 0.9-ns duration and 8.1-mJ energy [19]. The laser ignition was also used for thrusters control and orbital maneuvering [20] or in natural gas engines [21,22]. Furthermore, recent published papers that reported on realization of side-pumped miniaturized Nd:YAG-Cr^{4+}:YAG or of end-pumped multiple-beam Nd:YAG-Cr^{4+}:YAG lasers suitable for ignition are proving the importance of this research subject [23,24].

The performances of an automobile engine that is ignited only by laser sparks are still to be investigated. Thus in [17], Taira et al., the coefficient of variance of the indicated mean effective pressure (COV_{IMEP}) was determined depending on the air-fuel ratio at 1.200 rpm engine speed and 73 N·m torque; comparable engine operation for both classical ignition and ignition by laser sparks was obtained. Recently we have reported laser ignition of a Renault car engine [25]; the coefficient of variance of maximum pressure (COV_{Pmax}) was measured at various engine speeds (1.200 rpm to 2.800 rpm) and light loads (330 mbar and 440 mbar, the intake manifold pressure); better engine stability was observed for the ignition by laser. In this work we are presenting new data regarding operation of this engine that was ignited only by laser sparks. The laser-spark prototype is described in section 2. A four laser-spark system that was controlled by the automobile electronic control unit was built. The system was used to ignite the Renault car engine; the in-cylinder pressure as well as HC, CO, NO_x and CO_2 specific emissions were measured at various speeds of the engine (1.500 rpm to 2.000 rpm) and high loads (770 mbar to 920 mbar). The results are given in section 3; improved engine stability, decreased values of CO and HC, but also slight increases of NO_x and CO_2 emissions have been obtained in comparison with classical ignition by electrical spark plugs.

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2. The Nd:YAG/Cr^{4+}:YAG laser spark

It is worthwhile to mention that in previous research we studied the influence of temperature on the laser performances of a Nd:YAG-Cr^{4+}:YAG laser [26]. Advantages of laser ignition in comparison with ignition by classical spark plugs were investigated in a static chamber filled with methane-air mixtures [27]. Based on these results, a first laser-spark prototype was built in 2011. The device, shown in Fig. 1, consisted of a diffusion-bonded Nd:YAG/Cr^{4+}:YAG ceramic medium that was end-pumped by a fiber-coupled diode and yielded laser pulses with energy up to 3 mJ and 1.0-ns duration. Also, a new configuration made of a diffusion-bonded Nd:YAG/Cr^{4+}:YAG medium that is pumped laterally through a prism was proposed recently by our group as a solution for a laser spark [28].

Fig. 1. A laser-spark prototype realized in 2011 in our laboratory.

The laser-spark device used in this work, which is an improved version of the first prototype, is presented in Fig. 2(a) in comparison with a classical spark plug; a cross-sectional view of this laser spark is shown in Fig. 2(b). The laser medium was a diffusion-bonded Nd:YAG/Cr^{4+}:YAG structure. The monolithic resonator was obtained by coating the high reflectivity HR (R> 0.999) mirror at lasing wavelength, λ_{em} = 1.06 μm on the free Nd:YAG side (i.e. toward the pump line, Fig. 2(b)) and the outcoupling mirror (OCM) with reflectivity R_{OCM} at λ_{em} on the Cr^{4+}:YAG opposite surface (toward the focusing line); also, the Nd:YAG side was coated for high transmission (T> 0.98) at the pump wavelength, λ_p = 807 nm.

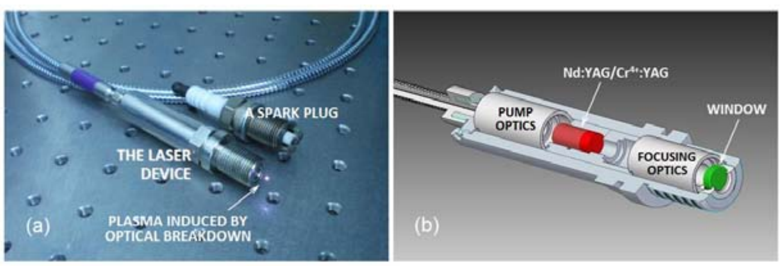

Fig. 2. (a) A laser spark plug based on monolithic, diffusion-bonded Nd:YAG/Cr^{4+}:YAG medium is presented in comparison with a classical spark plug. The plasma induced by optical breakdown of air is visible. (b) Sectional view of the laser device is shown.

The Nd:YAG/Cr^{4+}:YAG media that were investigated in the experiments consisted of either of all-polycrystalline media, i.e. ceramic media (Baikowski Co., Japan) or of single crystals (China supplier). The Nd:YAG characteristics (1.0-at.% Nd, length of 8 mm) were chosen such to obtain absorption efficiency higher than 90% at λ_p. The optical pump (at λ_p) was performed with fiber-coupled diode lasers (JOLD-120-QPXF-2P, Jenoptik, Germany) that were operated in quasi continuous-wave mode at repetition rate up to 100 Hz; the pump pulse duration was 250 μs and maximum energy of the pump pulse was nearly 50 mJ.

For the pump optics line [Fig. 2(b)] two configurations were used. The first one consisted of only one lens (L) of focal length f; the distances between the fiber end and the lens and between the lens and Nd:YAG are denoted by d_1 and d_2, respectively. The second pump optics scheme was made of a collimating lens L1 of focal length f_1 (for collimation, L1 was

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positioned at the working distance, as indicated by the manufacturer) and a focusing lens L2 of focal length f_2; the distance between L2 and Nd:YAG is d. The following experimental data were obtained with a Nd:YAG/Cr^{4+}:YAG ceramic with SA initial transmission T_i = 0.40 and an OCM with R_{OCM} = 0.60; the optical fiber had a 600-µm diameter.

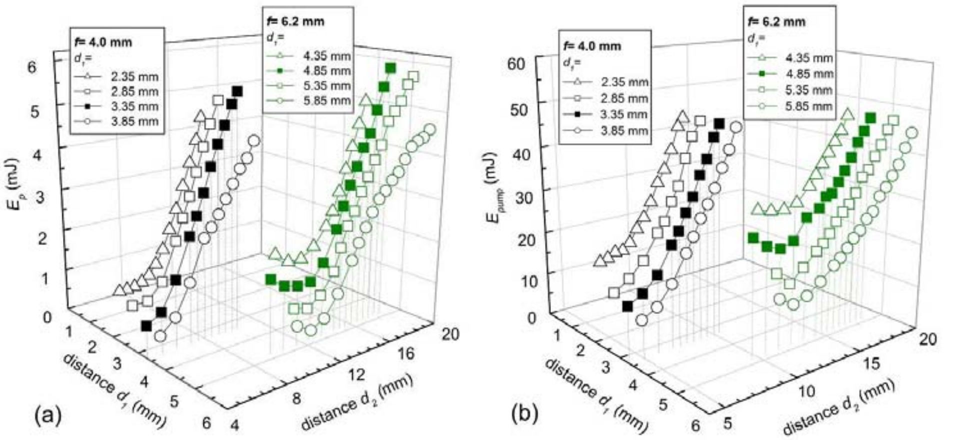

Fig. 3. (a) Laser pulse energy E_p and (b) corresponding pump pulse energy E_{pump} measured function of distance d_1 (between the fiber end and the lens) and d_2 (between the lens and the laser medium), pump line with a single lens of focal length f.

Figure 3(a) presents the laser pulse energy E_p as a function of distances d_1 and d_2 for two pump lines, each made of a single lens L. Laser pulses with 5.5-mJ maximum energy were obtained by positioning a lens L with f = 4.0 mm at d_1 = 3.35 mm and the laser medium at d_2 = 10.4 mm; the corresponding pump pulse energy E_{pump} [Fig. 3(b)] was 47.5 mJ. The ratio E_p/E_{pump}, which can be seen as the laser optical-to-optical efficiency η_o, was 0.115. A maximum energy of 5.9 mJ was obtained when L had f = 6.2 mm and it was placed at distances d_1 = 4.85 mm and d_2 = 18.5 mm; the pump pulse energy was E_{pump} = 47.3 mJ (at η_o = 0.12).

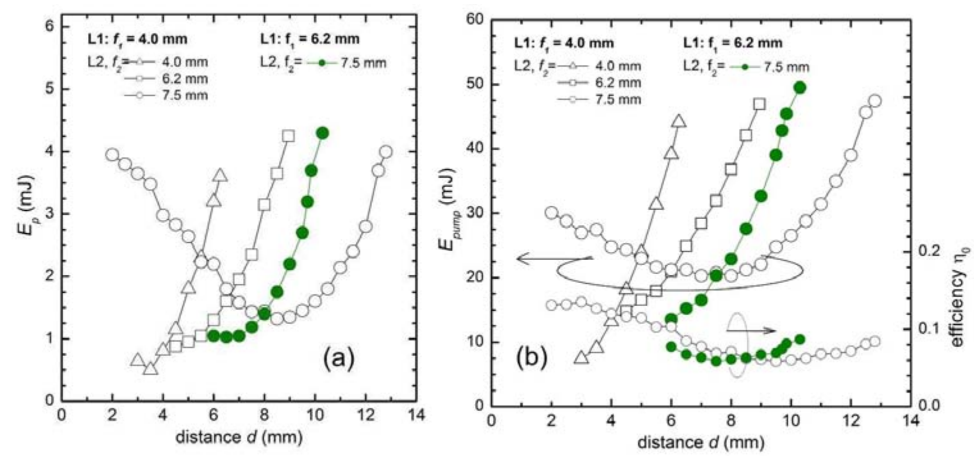

Fig. 4. (a) Laser pulse energy E_p and (b) pump pulse energy E_{pump} and efficiency $\eta_0 = E_p/E_{pump}$ versus distance d between the focusing lens (L2) and the laser medium, pump line made of two lenses (L1 and L2).

The laser performances obtained with several pump optics lines that were built with two lenses are given in Fig. 4. When the collimating lens L1 had a focal length f_1 = 4.0 mm, pulses with energy E_p = 3.6 mJ [Fig. 4(a)] were obtained by placing the Nd:YAG/Cr^{4+}:YAG

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ceramic at d = 6.3 mm from a focusing lens L2 with focal length f_2 = 4.0 mm; the pump energy was E_{pump} = 44 mJ [Fig. 4(b)], corresponding to efficiency η_0 = 0.08. Changing L2 to a lens with f_2 = 7.5 mm and increasing d at 12.8 mm improved the energy E_p to 4 mJ (at E_{pump} = 47.5 mJ, η_0 = 0.08). For this collimating lens (f_1 = 4.0 mm), the highest energy E_p = 4.3 mJ was achieved with L2 of f_2 = 6.2 mm at d = 8.9 mm; the pump energy amounted at E_{pump} = 46.9 mJ (at η_0 = 0.09). Similar pulse characteristics, with E_p = 4.3 mJ at E_{pump} = 49 mJ, were obtained with a lens L1 of f_1 = 6.2 mm and a lens L2 with f_2 = 7.5 mm, the laser medium being positioned at distance d = 10.3 mm. The optical efficiency η_0 was also plotted in Fig. 4(b) for combination of lenses (f_1 = 4.0 mm, f_2 = 6.2 mm) and (f_1 = 6.2 mm, f_2 = 7.5 mm).

Simulations on the laser pulse energy E_p were performed on a rate equation model [29,30], in which the spatial overlap between the laser beam and the pump beam was considered by the ratio $a = w_p/w_g$, where w_p and w_g denotes the pump-beam radius and the laser-beam radius, respectively. For better understanding, we remember that the laser pulse energy can be written by [30,16]:

$$E_p = \frac{h\nu}{2\gamma_g \sigma_g} A_g \times \ln\left(1 - R_{OCM}\right) \times \ln\left(\frac{n_{gf}}{n_{gi}}\right) \quad (1)$$

where $h\nu$ is the photon energy at λ_{em}, γ_g is the inversion factor and σ_g denotes the Nd:YAG emission cross section. A_g represents the laser beam cross-section area in Nd:YAG. The initial population inversion density is $n_{gi} = \beta/(2\sigma_g \ell_g)$, with ℓ_g the Nd:YAG length, and the final population inversion density n_{gf} can be deduced from the transcendental equation:

$$\left(1 - r_n\right) + \left(1 + \frac{(1-\delta)\times \ln T_i^2}{\beta}\right) \times \ln r_n + \frac{1}{\alpha} \times \frac{(1-\delta)\times \ln T_i^2}{\beta} \times \left(1 - r_n^{\alpha}\right) = 0 \quad (2)$$

where r_n is the ratio $r_n = n_{gf}/n_{gi}$. The parameter $\beta = (-\ln R_{OCM} + L_i - \ln T_i^2)/[1-\exp(-2a^2)]$ includes the ratio a and takes into account the double-pass residual losses L_i of Nd:YAG/Cr^{4+}:YAG. Also, δ is the ratio $\delta = \sigma_{ESA}/\sigma_{SA}$, with σ_{ESA} the excited-state absorption cross section and σ_{SA} the absorption cross section of Cr^{4+}:YAG, and $\alpha = (\gamma_{SA}\sigma_{SA})/(\gamma_g\sigma_g) \times (A_g/A_{SA})$, with γ_{SA} the inversion reduction factor for Cr^{4+}:YAG. Due to the compact structure of Nd:YAG/Cr^{4+}:YAG, A_{SA} the laser beam area in Cr^{4+}:YAG and A_g were considered equals.

In modeling various points were chosen for all the pump lines used in the experiments. Furthermore, knife-edge method (10%-90% level) was used to determine, for each of these points, the pump-beam propagation after lens L or L2, the radius of the laser beam near the OCM and the laser beam M^2 factor. It was found out that M^2 was in the range of 1.5 to 2 for laser pulses with energy E_p below 2 mJ and increased up to 5 for laser pulses with E_p higher than 3 mJ. Therefore, in the simulations the pump beam was taken as having uniform (like top hat) distribution, whereas the laser beam distribution was considered Gaussian but also top-hat like. The Nd:YAG emission cross section was taken as $\sigma_g = 2.63 \times 10^{-19}$ cm^2 and absorption cross section and excited-state absorption cross section of Cr^{4+}:YAG were σ_{SA} = 4.3×10^{-18} cm^2 and $\sigma_{ESA} = 8.2 \times 10^{-19}$ cm^2, respectively. Figure 5 shows results of modeling by continuous and by dashed lines for laser beam of Gaussian and uniform (top-hat like) distribution, respectively. The parameter used in simulations was the double-pass residual losses (L_i) of the monolithic medium. We found out that a value L_i~0.05 (that should account for Nd:YAG losses as well as for the final transmission of Cr^{4+}:YAG) described well the experimental data. Moreover, in our pump conditions with $a = w_p/w_g < 1.0$, differences between experiments and simulations were small whatever the laser beam was Gaussian or top-hat like in the modeling.

We performed further experiments and concluded that with an OCM of R_{OCM} = 0.60 and Cr^{4+}:YAG having the initial transmission T_i ranging from 0.30 or 0.50, each pump line and Nd:YAG/Cr^{4+}:YAG medium could be arranged such to deliver pulses with energy E_p higher than 3 mJ. Then, a diffusion-bonded Nd:YAG/Cr^{4+}:YAG medium with wedged Cr^{4+}:YAG SA (and thus with variable initial transmission of Cr^{4+}:YAG), similar to that recently proposed in [31] by Cho et al., can be used to realize a laser spark.

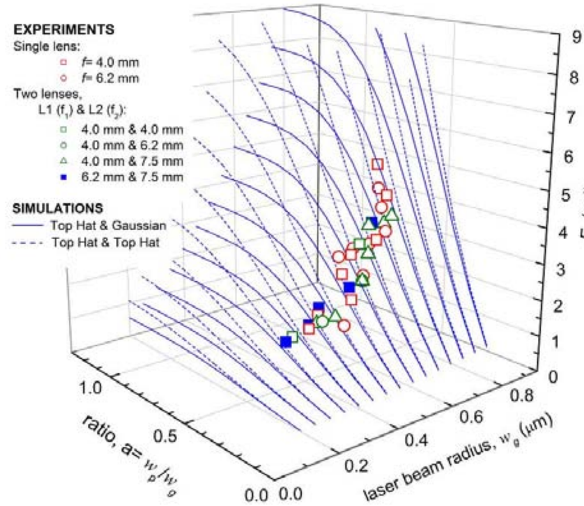

Fig. 5. Modeling of laser pulse energy versus pump beam radius, w_p and laser beam radius, w_g; a is the ratio $a = w_p/w_g$.

The diffusion-bonded Nd:YAG/Cr^{4+}:YAG made of single crystals delivered pulses with energy close to those yielded by the ceramic counterpart, but at increased (by up to 20%) E_{pump}. The increased pump pulse energy could come from higher losses at the bonding interface between Nd:YAG and Cr^{4+}:YAG SA single crystals, in comparison with a ceramic medium. Finally, for realizing the laser sparks we used diffusion-bonded Nd:YAG/Cr^{4+}:YAG ceramic media; both kinds of pump optics lines, consisting of one or two lenses were used. Typically, the laser was designed to deliver pulses with energy E_p = 4.0 mJ and duration of 0.8 ns, corresponding to a pulse peak power of 5.0 MW.

The focusing line [Fig. 2(b)] assured collimation and then focusing of the laser beam. Position of ignition inside the engine cylinder can be varied by changing the focusing lens. In the preliminary experiments (before testing on the engine) lenses with focal length between 11 mm and 18 mm were used to obtain air breakdown, indicating the set-up usability for laser ignition. As interface between laser spark and the engine chamber a sapphire window was used [Fig. 2(b)]. The windows thickness was around 2.0 mm, chosen such to withstand static pressures higher than 20 MPa. The optical components were fixed with an epoxy adhesive, having high shear and peel strength and a service temperature between −70°C and 170°C.

3. Ignition of the Renault automobile engine

The laser ignition experiments were performed on a K7M 812 k, 1.6-litter gasoline Renault engine with a multi-point injection system (indirect fuel injection, outside the combustion chamber); the engine was mounted on a test bench. An integrated four laser-sparks system was built, tested and then installed on the engine; the ignition triggering was realized by the electronically control unit of the car. The in-cylinder pressure was measured with an AVL GU-21D piezoelectric transducer. The exhaust gases were sampled from the valve gate with a Horiba Mexa 7100 analyzer. The acquisitions were made on 500 consecutive cycles for engine speeds between 1.500 rpm and 2.000 rpm and high loads of 770 mbar, 880 mbar and 920 mbar (the load was the absolute pressure from the intake manifold). The engine was running steady near the stoichiometric air-fuel ratio (λ = 1) for all investigated engine modes. This is normal value for a classic gasoline engine, which means that the mass ratio of air to fuel is ~14.7 and it is calculated so each carbon atom from the fuel to react with one oxygen atom from the air and to result just CO_2 in a theoretical combustion. Figure 6(a) presents the

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laser system during preliminary testing (before being installed on the engine). A comparison between the plasma generated in air by a laser spark and the discharge of a classical spark plug is given in Fig. 6(b). The engine is shown in Fig. 6(c) during running with the laser ignition system.

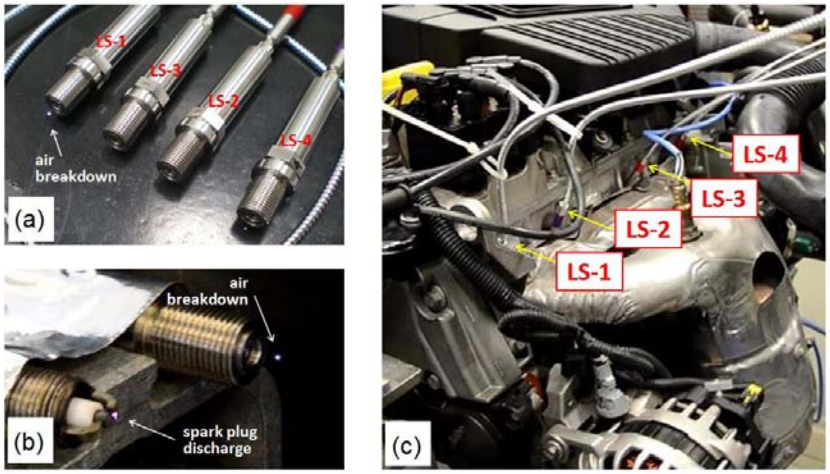

Fig. 6. (a) The four laser-spark system is shown before installation on the engine. (b) A discharge of a classical spark plug and plasma air breakdown initiated by a laser spark are presented. (c) The Renault engine is shown while running with laser-spark devices (see Visualization 1).

We mention that after the first ignition experiments [25] a temperature test of one of our laser spark was performed. Thus, a slit was cut in the laser spark body and a FLIR T620 thermal camera (−40°C to + 150°C range, ± 2°C accuracy) was used to measure the Nd:YAG/Cr^{4+}:YAG temperature at both Nd:YAG/Cr^{4+}:YAG medium ends. When operating at room temperature (24°C) and 50 Hz repetition rate for more than 30 min., the temperature of Nd:YAG (near the input surface, toward the pump line) and that of Cr^{4+}:YAG (near the exit side, toward the focusing line) reached 37°C and 29°C, respectively. The laser spark was then mounted on a metallic block that was heated at various temperatures. For example, an increase of this temperature up to 250°C (i.e. the temperature of the laser spark around the sapphire window) resulted in an increase of Nd:YAG temperature to 75°C and of Cr^{4+}:YAG to ~55°C. Consequently, the pump-pulse energy has to be raised in order to maintain laser operation. Next, cooling of the laser spark was made with a thin copper jacket (that was also cooled with water at its free end). In similar conditions of operation (50-Hz repetition rate, metallic base at 250°C temperature) the Nd:YAG and the Cr^{4+}:YAG temperature (at the same points, as explained before) increased up to 55°C and 40°C, respectively. Little adjustment of the pump-pulse energy was necessary in order to maintain laser operation. These measurements are not absolute (thus, additional heat comes from the engine body that surrounds the laser spark, or maximum temperature is reached on the central axis of Nd:YAG/Cr^{4+}:YAG); however, the results indicate that cooling of the laser sparks could be beneficial for operation on the automobile engine. Considering some technical issues, in the ignition experiments cooling was done by a device (not shown in Fig. 6(c)) that blew air toward each laser spark. A short movie of the engine while operating with laser sparks was associated to Fig. 6(c).

An example of maximum pressures recorded in the engine cylinder (cylinder 1) is shown in Fig. 7. The engine stability was characterized by the coefficient of variability of maximum pressure COV_{Pmax} (defined as the ratio between standard deviation and the average peak pressure) and by the coefficient of variability of mean effective pressure, COV_{IMEP} (defined as the ratio between standard deviation and the average of mean effective pressure).

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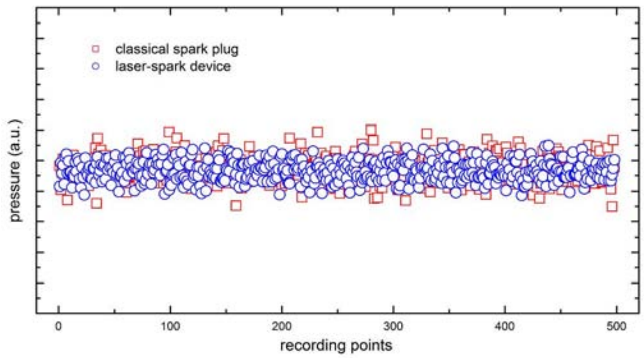

Fig. 7. The peak pressure in a cylinder for 500 consecutive cycles at 1.500-rpm speed and 880-mbar load, ignition by electrical spark plugs and ignition by laser sparks.

Table 1 summarizes comparative results regarding operation of the engine that was ignited by classical spark plugs and by laser sparks. Improvements of the coefficients of variability were measured at medium speed of the engine ignited by laser sparks. For example, when the engine speed was 1.500 rpm the reduction of COV_{Pmax} was about 15%, whereas the COV_{IMEP} improvement was in the range of 18.5% (at 920-mbar load) to 22.6% (at 880-mbar load). On the other hand, it is known that cyclic variability of an engine is better at both high speed and load; therefore, less influence of laser ignition on the coefficients of variability was expected in these conditions. Indeed, it was observed that differences for COV_{Pmax} and COV_{IMEP} between the two types of ignition were small at 2.000 rpm and high 920-mbar load. These results indicate a better stability of the car engine that was operated at medium speeds by laser sparks, resulting in reduced noise, vibrations and mechanical stress. It is worthwhile to comment that improvements of COV_{IMEP} were also observed in the first car engine that was ignited only by laser sparks [17] or in experiments of ignition that were performed with laser beams that were directed into a four-cylinder car engine [3]; an improvement of COV_{IMEP} in the range of 20% to 10% was measured from a single-cylinder gasoline direct injected engine that was ignited by multiple pulses [32].

Table 1. Engine stability and emisions. Sign minus and plus indicates a decrease (which corresponds to an improvement), respectively an increase of the parameter in comparison with ignition by electrical spark plugs.

Load (mbar)	Engine speed (rpm)	Torque (N·m)	COV_{Pmax} (%)	COV_{IMEP} (%)	CO (%)	HC (%)	NO_x (%)	CO_2 (%)
770	2.000	89	−10.2	−14.6	−18.7	−3.8	+ 1.6	+ 1.1
880	1.500	101	−15.8	−22.6	−22.4	−14.4	+ 8.0	+ 0.7
920	1.500	106	−15.1	−18.5	−21.9	−17.5	+ 7.6	+ 0.8
	2.000	108	−2.6	+ 2.5	−25.1	−3.0	+ 2.6	+ 1.1

It is known that the regulated emissions are CO, HC, NO_x and particulate matter, as well as the greenhouse gas CO_2 with limits becoming more stringent. Lower CO and HC emissions were measured for the engine ignited by laser sparks. Thus, the decrease of CO was in the range of ~18% to ~25% for all measurements. HC emissions were by ~14% to ~17% lower at 1.500 rpm speed, whereas a decrease of ~3% was observed at higher 2.000-rpm speed. These improvements can be associated with a more efficient combustion under ignition by laser, meaning a better oxidation of the carbon and hydrogen atoms in the fuel. On the other hand, an increase of NO_x, up to nearly 8% at 1.500 rpm speed and around 2% at 2.000 rpm speed, was measured for laser ignition in comparison with ignition by classical spark plugs. This, however, is a compromise between unburned fuel and NO_x for the internal combustion engine calibration [33]. The increase of NO_x can be explained by a higher flame temperature in the first part of combustion, when much NO_x is produced. A solution to reduce

NO_x could be, for example, an increased re-circulating rate of the exhaust gases. On the other hand, the amount of carbon entering into and resulting from the combustion reaction is constant; this explains the increase of CO_2 under laser ignition. Measurements concluded that for the range of loads used in these investigations, the power of the engine ignited by laser increased by ~1.7% at 1.500-rpm speed and by ~3% at 2.000-rpm speed in comparison with classical ignition.

Regarding the laser spark operation, one issue was the damage of the optical element coatings used to build the focussing line and seldom damage of the lenses from the pump line. However, as all lenses were purchased from market they had no special coatings. This problem is expected to be solved by coating the lenses with high-damage threshold layers, or even using uncoated lenses at critical (high intensity laser beam) points in the laser beam; this solution was already used. Combustion deposits on the sapphire window were also observed. A solution proposed and investigated by H. Ranner et al. [34] for this problem is the window cleaning by the laser beam itself (or self-cleaning). We have considered this method in several ways. First, the laser pulse energy was high (E_p = 4 mJ) and thus the initial part of it was supposed to clean partially the window. Secondly, the pump pulse duration was lengthened such to obtain two laser pulses; in this way the first pulse is used for cleaning, a more efficient method than the first approach. On the other hand, however, at this stage of the experiments we cannot rule out that the first laser pulse is not contributing to the ignition, similar to the pulse-train ignition by laser spark plugs [32,35]. Thirdly, as the engine allowed twice triggering per cycle we made use of this feature by applying laser pulses in cylinder 4 (on the exhaust stoke) while ignition was realized in cylinder 1; thus, the window of cylinder 4 was cleaned before a new ignition. The same procedure was applied for cylinders 2 and 3. Furthermore, efficient cooling of each laser spark was realized by a compact cooling system with re-circulating water. Based on these approaches, the car engine could be continuously operated for few hours, without noticing coatings problems of the optics and maintaining clean the window. We comment, however, that additional research and work are needed before such a laser system could meet requirements for integration in an automobile engine and commercial application.

4. Conclusions

In summary, a Renault car engine was operated only by laser sparks that were built with high-peak power passively Q-switched Nd:YAG/Cr^{4+}:YAG lasers. Several engine parameters, like coefficients of pressure variance and HC, CO, NO_x and CO_2 specific emissions were determined for engine speeds ranging from 1.500 rpm to 2.000 rpm and high (up to 920 mbar) loads. Improved engine stability at medium (below 2.000 rpm) speed was observed for the engine that was ignited by laser sparks. Furthermore, decreases of CO and HC emissions and a slight increase of NO_x and CO_2 were determined for laser ignition in comparison with ignition by classical spark plugs. In recent experiments, the optimum spark advance was determined for various speeds and loads of the engine and the influence of air-fuel combustion on the engine operation was investigated; results are to be reported. Although hindered by various technical issues and still uncompetitive price, laser ignition is considered an attractive research subject that could lead to further improvement and optimization of gasoline engines.

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High-peak-power passively *Q*-switched Nd:YAG/Cr^{4+}:YAG composite laser with multiple-beam output

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We report on the design, realization, and output performance of a diode-pumped high-peak-power passively *Q*-switched Nd:YAG/Cr^{4+}:YAG composite medium monolithic laser with four-beam output. The energy of a laser pulse was higher than 3 mJ with duration of 0.9 ns. The proposed system has the ability to choose independently the focus of each beam. Such a laser device can be used for multipoint ignition of an automobile gasoline engine, but could also be of interest for ignition in space propulsion or in turbulent conditions specific to aeronautics.

OCIS codes: (140.3580) Lasers, solid-state; (140.3530) Lasers, neodymium; (140.3540) Lasers, *Q*-switched; (140.5560) Pumping.
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1. INTRODUCTION

Ignition induced by laser is currently viewed as an alternative technique to ignition realized by a spark plug, especially for vehicles with internal combustion engines [1–4]. Among the advantages of this new ignition method, one could mention: (i) the absence of the quenching effect of the developing flame kernel due to the lack of a spark plug electrode, resulting in a shorter burn duration; (ii) the possibility to ignite at an optimal position into the engine chamber for efficient combustion; (iii) lowering fuel consumption and decreasing exhaust gas emissions under conditions of normal engine operation, i.e., near the stoichiometric air–fuel ratio, or (iv) the possibility to ignite lean air–fuel mixtures and thus to further reduce engine impact on the environment.

A CO_2 laser was used to obtain in 1978, for the first time, the ignition by laser of a single-cylinder engine [5]. Furthermore, a four-cylinder engine was ignited, in 2008, by a *Q*-switched Nd:YAG laser [6]. Because of the experimental conditions, the bulky lasers were placed outside of the engines and the laser beams were directed into the engine cylinders by adequate optics.

A solution for realization of a compact spark-like laser device was proposed in 2007 by Kofler *et al.* [7]. Thus, it was shown that a Nd:YAG laser medium that is passively *Q*-switched by a Cr^{4+}:YAG crystal with saturable absorption (SA) can deliver pulses with few-millijoule energy and nanosecond-order duration, suitable for laser ignition. The first high-peak-power passively *Q*-switched Nd:YAG-Cr^{4+}:YAG spark-plug laser was realized in 2010 by Tsunekane *et al.* [8]; furthermore, the same research group has investigated the characteristics of a Yb:YAG-Cr^{4+}:YAG discrete media combination for laser ignition applications [9]. Several other approaches, like the passively *Q*-switched diffusion-bonded Nd:YAG/Cr^{4+}:YAG laser with wedged Cr^{4+}:YAG SA [10] or the diffusion-bonded Nd:YAG/Cr^{4+}:YAG laser pumped laterally through a YAG prism [11], could also be considered and optimized in order to be used for ignition by a laser. It is worth mentioning that the majority of these lasers were pumped longitudinally with fiber-coupled diode lasers. On the other hand, side pumping with a diode array enabled the realization of a high-energy Nd:YAG-Cr^{4+}:YAG laser (the so-called HiPoLas laser) [12]; the same pumping scheme was employed to build a passively *Q*-switched Nd:YAG-Cr^{4+}:YAG pulse-burst laser for laser ignition [13].

For the first time, in 2013 an automobile gasoline engine was ignited with only laser sparks by Taira *et al.* [14]. Recently, we have also operated a four-cylinder engine with laser sparks [15]. Measurements at average speeds (below 2.000 rpm) concluded that ignition by laser improves engine stability and decreases emission of CO and HC in comparison with the same engine that was ignited by classical spark plugs. In these experiments, laser sparks that were built with diffusion-bonded Nd:YAG/Cr^{4+}:YAG composite media and that delivered single-beam output have been used [14,15]. On the other hand, a laser offers the possibility to obtain ignition at multiple points, thus better and more uniform combustion in comparison with ignition by electrical spark plugs. For example, increased pressure and shorter combustion time were measured for laser ignition in two points of CH_4/air and H_2/air mixtures in a static chamber [16]. Also, experiments realized with H_2/air mixtures (in a static chamber) concluded that ignition at two points assures faster combustion in comparison with single-point ignition [17].

To generate multiple points of ignition, several solutions have been proposed. Thus, end pumping with three independent lines of a passively *Q*-switched diffusion-bonded Nd:YAG/Cr^{4+}:YAG composite ceramic medium allowed realization of the first spark-plug-like laser device with three focusing points, at fixed locations [18]. In another approach, a spatial light modulator was applied to a single laser beam to obtain multipoint laser-induced spark generation with arbitrary geometrical location in three dimensions or at different distances on the central axis of propagation [19]. The energetic beam (with long, 10 ns duration at 1064 nm) was, however, delivered by a flash-lamp-pumped *Q*-switched Nd:YAG laser. Also, a 2×2 lens array was employed to transfer the pump beam from a fiber-coupled diode laser to a Nd:YAG-Cr^{4+}:YAG laser and thus to realize a device with four-beam output [20]. Each laser beam operated in burst mode, and every pulse burst contained two to five pulses of low (0.12–0.22 mJ) energy and long (10.5–11.5 ns) duration at a kilohertz-order repetition rate. In this case, further increase of the laser pulse energy is necessary to obtain air breakdown.

In this work we report on the design, realization, and performance of a high-peak-power passively *Q*-switched Nd:YAG/Cr^{4+}:YAG composite monolithic laser that yields four independent beams, each beam having appropriate characteristics for laser ignition. A compact optical system was made to transfer every pump beam into Nd:YAG/Cr^{4+}:YAG, keeping the compactness of the device and assuring millimeter-order distance between laser beams. Typically, the energy of a laser pulse was higher than 3 mJ with duration shorter than 1 ns. The focusing system was designed for various purposes, aiming focusing and air breakdown in four points (in the same plane or at different distances from the laser) or in a single point. This laser can be used for multipoint ignition of an automobile engine; it could be also of interest in space propulsion systems [21,22] or for ignition in turbulent conditions specific to aeronautical combustion [23].

2. THE LASER CONFIGURATION

A. Design: Single Line, Experiments, and Modeling

The laser configuration is shown in Fig. 1. The laser medium is an Nd:YAG/Cr^{4+}:YAG composite structure of 10 mm diameter; it was made of an 8.5 mm long, 1.1 at. % Nd:YAG medium that was bonded to a 2.5 mm thick Cr^{4+}:YAG SA with initial transmission (T_i) of about 40%. Such an Nd:YAG/Cr^{4+}:YAG medium assures robustness and compactness, as well as a high resistance at vibrations of the laser [14,15,18].

A monolithic resonator was obtained by coating the surface S1 of Nd:YAG with a high-reflectivity mirror (HRM, reflectivity $R > 0.999$) at the laser wavelength $\lambda_{em} = 1.06$ μm and the out-coupling mirror (OCM) with transmission $T_{OCM} = 50\%$ ($\pm 5\%$) on surface S2 of Cr^{4+}:YAG. Surface S1 was also coated with a high transmission layer ($T > 0.98$) at the pump wavelength $\lambda_p = 807$ nm. It is worth mentioning that, in this design, the pump-beam absorption efficiency in Nd:YAG was evaluated to be around 0.95. Therefore, the Cr^{4+}:YAG SA properties were not influenced by the residual pump beam. We mention that Nd:YAG/Cr^{4+}:YAG single crystals as well as Nd:YAG/Cr^{4+}:YAG fabricated by ceramic techniques were used in experiments. The best results were obtained with Nd:YAG/Cr^{4+}:YAG ceramic (or polycrystalline) media from Baikowski Co., Japan.

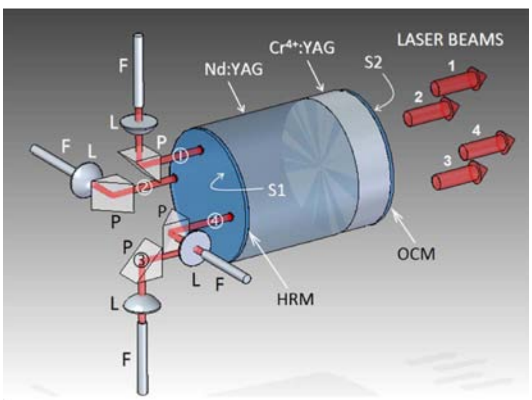

Fig. 1. Laser configuration (patent pending) is shown. Each pump beam (①,②, ③, and ④) is directed from the corresponding optical fiber (F) to the composite Nd:YAG/Cr^{4+}:YAG medium through a lens (L) and a folding prism (P). Four (1, 2, 3, and 4) laser beams are obtained.

The pump was made at $\lambda_p = 807$ nm with fiber-coupled (diameter of 400 μm and numerical aperture NA = 0.22) diode lasers (JOLD-120-QPXP-2P, Jenoptik, Germany) that were operated in quasi-continuous-wave regime; in the experiments, the pump pulse duration was set at 250 μs and the repetition rate was increased up to 60 Hz. To keep the pump line simple, the pump beam delivered through a fiber (F) was focused into Nd:YAG with only a single lens (L). A small prism (P) was used to fold each pump line and thus to accommodate four fibers around surface S1 of Nd:YAG.

The pump-line configuration was decided first. For this purpose, the Nd:YAG/Cr^{4+}:YAG composite ceramic medium was pumped directly from fiber F with only one lens, L. The distance between F and L was noted by d_1 and the distance from L to the Nd:YAG/Cr^{4+}:YAG was denoted by d_2. Several aspherical lenses L, with focal length f between 3.1 and 7.5 mm were employed; for each lens, the laser pulse energy E_p was measured as a function of d_1 and d_2.

Figure 2(a) shows several results obtained with two lenses, the first with focal length $f = 4.0$ mm and a second one with $f = 6.2$ mm. In these investigations the repetition rate was set at 5 Hz. When the lens with $f = 4.0$ mm was placed at $d_1 = 3.4$ mm from optical fiber F, laser pulses with energy $E_p = 2.9$ mJ were obtained for Nd:YAG/Cr^{4+}:YAG positioned at distance $d_2 = 7.5$ mm [Fig. 2(a)]. The corresponding pump pulse energy was $E_{pump} = 26$ mJ [Fig. 2(b)]. Increasing d_2 at 10 mm improved E_p at 5.2 mJ, whereas E_{pump} reached the level of ~45 mJ. In the case of lens L with $f = 6.2$ mm placed at $d_1 = 4.9$ mm, laser pulses with $E_p = 3.0$ mJ were measured for Nd:YAG/Cr^{4+}:YAG situated at distance $d_2 = 15$ mm; the requested pump pulse energy was $E_{pump} = 31.8$ mJ. For this lens, the laser could be operated up to a distance $d_2 = 18.5$ mm; at this point, the laser pulse energy increased to $E_p = 5.9$ mJ and the available pump energy $E_{pump} = 47$ mJ delivered by the diode was reached. The colored points for E_p shown in Fig. 2(a) were used in modeling (as will be explained below). We have also measured the laser beam M^2 factor using the knife-edge method (10%–90% level, ISO 11146/2005). For laser pulses with energy E_p around 3 mJ (a minimal value of interest for realizing air breakdown in our experimental conditions), the M^2 factor was around 4.1; the beam quality decreases with increasing the laser pulse energy, with M^2 factor of about 5.2 for pulses with $E_p \sim 5$ mJ.

To explain the laser pulse performance, we have applied a model developed in our previous work [15,18]. Thus, we remember that the laser pulse energy can be written by [24,25]

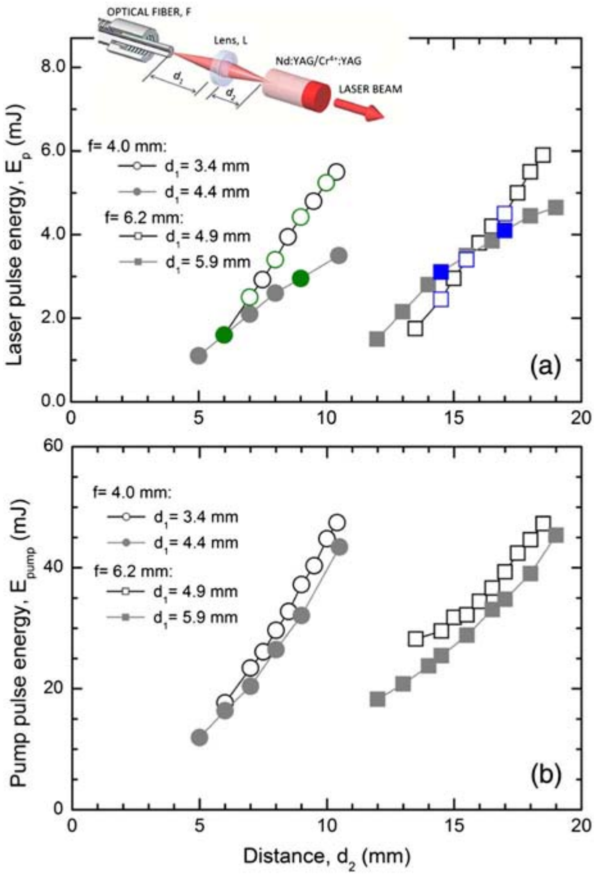

Fig. 2. (a) Laser pulse energy E_p versus distance d_2 between lens L and surface S1 of Nd:YAG. Data for two lenses, first with focal length $f = 4.0$ mm placed at distances $d_1 = 3.4$ and 4.4 mm from F, and the second with $f = 6.2$ mm positioned at $d_1 = 4.9$ and 5.9 mm from F, are shown. The inset is a sketch of the single pump-beam arrangement. (b) The corresponding pump pulse energy, E_{pump}, is plotted.

$$E_p = \frac{h\nu}{2\gamma_g \sigma_g} A_g \times \ln \frac{1}{R_{\text{OCM}}} \times \ln\left(\frac{n_{gf}}{n_{gi}}\right), \tag{1}$$

where $h\nu$ is the photon energy at λ_{em}, γ_g is the inversion factor, and σ_g represents the Nd:YAG emission cross section. A_g is the laser beam cross-section area in Nd:YAG and the OCM reflectivity is $R_{\text{OCM}} = (1 - T_{\text{OCM}})$. The density of the initial inversion of population is $n_{gi} = \beta/(2\sigma_g \lambda_g)$, with λ_g the Nd:YAG length. The density of the final inversion of population n_{gf} was obtained from the transcendental equation [15,18]:

$$(1 - r_n) + \left(1 + \frac{(1-\delta) \times \ln T_i^2}{\beta}\right) \times \ln(r_n) + \frac{1}{\alpha} \times \frac{(1-\delta) \times \ln T_i^2}{\beta} \times (1 - r_n^{\alpha}) = 0, \tag{2}$$

where r_n is the ratio $r_n = n_{gf}/n_{gi}$. The element $\beta = (-\ln R_{\text{OCM}} + L_t - \ln T_i^2)/[1 - \exp(-2a^2)]$ includes the parameter a, defined as the ratio between the pump-beam radius ω_p and the laser-beam radius ω_g in Nd:YAG, $a = \omega_p/\omega_g$. L_t is the double-pass residual loss of the monolithic Nd:YAG/Cr^{4+}:YAG laser, accounting for the Nd:YAG losses (L_i) as well as for the final transmission (T_f) of Cr^{4+}:YAG SA. Also, δ is the ratio $\delta = \sigma_{\text{ESA}}/\sigma_{\text{SA}}$, with σ_{ESA} the excited-state absorption cross section and σ_{SA} the absorption cross section of Cr^{4+}:YAG; α is $\alpha = (\gamma_{\text{SA}}\sigma_{\text{SA}})/(\gamma_g \sigma_g) \times (A_g/A_{\text{SA}})$, with γ_{SA} the inversion reduction factor for Cr^{4+}:YAG. The laser beam area in Cr^{4+}:YAG, A_{SA}, and A_g were considered equal, a fair approximation due to the short length of the Nd:YAG/Cr^{4+}:YAG medium. For the simulations, the Nd:YAG emission cross section was taken as $\sigma_g = 2.63 \times 10^{-19}$ cm^2; the absorption cross section and excited-state absorption cross section of Cr^{4+}:YAG SA were $\sigma_{\text{SA}} = 4.3 \times 10^{-18}$ cm^2 and $\sigma_{\text{ESA}} = 8.2 \times 10^{-19}$ cm^2, respectively. Because of the high value of the M^2 factor, the pump beam as well as the laser beams were considered to have uniform (like top-hat) distributions.

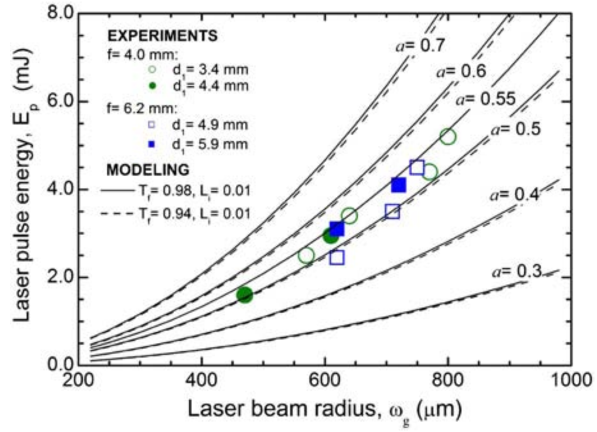

Fig. 3. Laser pulse energy E_p versus laser beam radius ω_g. Losses $L_i = 0.01$, and, for Cr^{4+}:YAG, final transmission T_f of 0.94 and 0.98 were considered in simulations.

Figure 3 presents modeling of laser pulse energy E_p function of laser beam radius ω_g; the value of ω_g was determined for each configuration by an ABCD formalism using the data recorded during M^2 factor measurements. In simulations, losses L_i were taken as 0.01 (a typical value for Nd:YAG with the doping level and length used in our experiments). Also, values of 0.94 and 0.98 for the final transmission T_f of Cr^{4+}:YAG were considered. One could observe that, for a fixed value of parameter a, the influence of total losses L_t on laser pulse energy is not too significant; more important is the value of a.

B. Four-Beam Output Laser

A typical laser module made in this work is shown in Fig. 4. The four prisms, P [Fig. 4(a)], were used to fold and redirect each pump beam from the corresponding optical fiber F toward the Nd:YAG/Cr^{4+}:YAG medium [Fig. 4(b)]. Several geometries were considered and realized. For example, a first one was built with identical aspherical lenses L of focal length $f = 4.0$ mm; distance d_1 was 3.4 mm and the Nd:YAG/Cr^{4+}:YAG medium was positioned at $d_2 = 8$ mm (we remember that, as shown in Fig. 1, on each folding arm, d_2 accounts for the distance from a lens L to Nd:YAG/Cr^{4+}:YAG). For a second arrangement (which will be discussed below) we used aspherical lenses with focal length $f = 6.2$ mm; distance d_1 was 4.9 mm and the distance d_2 was chosen as $d_2 = 15.5$ mm. Uncoated, 3 mm right-angle prisms were employed in this scheme, each prism being nearly 5 mm away from the corresponding lens L.

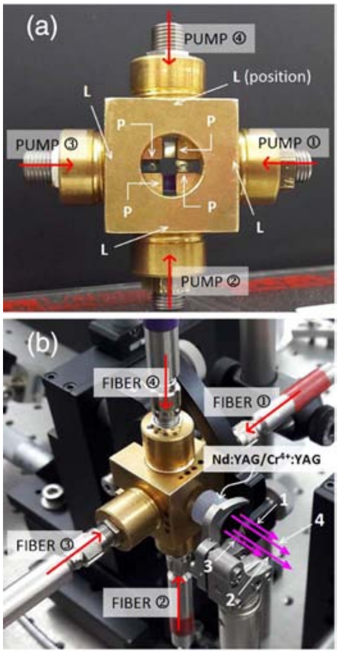

Fig. 4. (a) The module with the four folding prisms is presented. Each lens (L) position is indicated. P: prism. (b) A photo of the Nd:YAG/Cr^{4+}:YAG laser with four-beam output is shown. The directions of laser beams 1, 2, 3, and 4 are given by the colored lines with arrows.

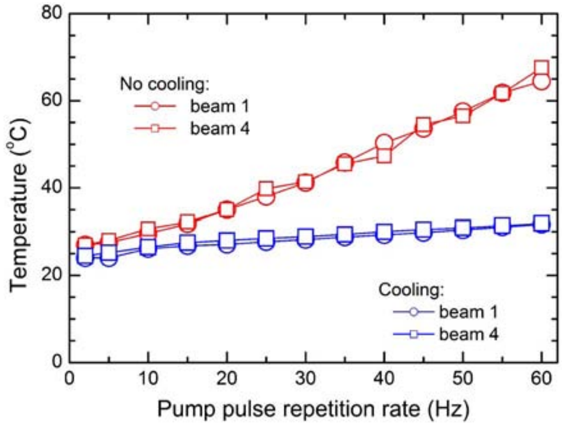

Fig. 5. Maximum temperature of surface S2 of Nd:YAG/Cr^{4+}:YAG at central locations of beams 1 and 4 versus the pump pulse repetition rate.

At 5 Hz repetition rate, the laser pulse energies were 3.25 mJ for beam 1, 3.30 mJ for beam 2, 3.60 mJ for beam 3, and 3.20 mJ for beam 4. The small differences from the expected value of 3.4 mJ [according to Fig. 2(a)] could be attributed to some length differences in every pump line, as well as the fact that each pump was not made in the center of the Nd:YAG/Cr^{4+}:YAG medium but on its circumference (in this case, small differences in Nd concentration or coatings can affect the results). Moreover, differences in the four diode lasers used for pumping can influence the laser pulse energy. The pump pulse energies were 30.5 and 32 mJ for beams 1 and 2, respectively; E_{pump} amounted to 33 mJ for beam 3 and to 30 mJ for beam 4. Thus, the overall optical-to-optical efficiency (defined as the ratio between the laser pulse energy and the pump pulse energy, E_p/E_{pump}) was in the range of 0.103 for beam 2 up to 0.109 for beam 3. The pulse duration (which was determined with an ultrafast InGaAs photodetector, rise time shorter than 35 ps) was around 0.9 ns for each beam, and therefore the laser pulse peak power was in the range of 3.55 MW for beam 4 to 4.0 MW for beam 3.

Important for stable laser emission is the Nd:YAG/Cr^{4+}:YAG temperature. We have used an FLIR T620 thermal camera (−40°C to +150°C range, ±2°C accuracy) to measure the temperature of surface S2 of the Nd:YAG/Cr^{4+}:YAG medium. As shown in Fig. 5, when the laser medium was kept in air and with no cooling [as shown in Fig. 4(b)], after a few minutes of operation the maximum temperature of surface S2 at the location of beam 1 increases from 27°C at 2 Hz repetition rate up to 64.5°C at 60 Hz repetition rate. Similar results were recorded for all lines (and Fig. 5 presents also the temperature for the central axis of beam 4). Longer time operation could not be performed, especially at high repetition rate, as the medium temperature increased further and the laser emission eventually ceased. Therefore, in the next experiments, the Nd:YAG/Cr^{4+}:YAG medium was wrapped in indium foil and then clamped in a copper holder; a fan was used to cool the metallic holder. The temperature of surface S2 was much lower in comparison with the previously described operation regime. Thus, as illustrated in Fig. 5, only a small increase in temperature, from 24.5°C at 2 Hz operation rate up to 30.8°C at repetition rate of 60 Hz was measured in the central position of beam 1. The laser pulse energy E_p was also stable at high rates of repetition. For operation at 60 Hz, the increase of E_p in comparison with the values measured at 5 Hz were below 3.7% for beams 1, 2, and 4; a slightly higher increase of 5.5% was measured for the energy of beam 3.

The laser device described in this work can be used (after further optimizations, testing, and integration) for multipoint ignition of an automobile engine, especially for ignition of lean air–fuel mixtures. Furthermore, it could be of interest for ignition of propellants in space applications or for ignition in turbulent conditions that are specific to aeronautics. For this purpose, different focusing schemes that allow access of a defined volume of fuel can be designed.

For example, as shown in Fig. 6(a), all beams could be focused in the same point; an aspherical lens with focal length of 8.1 mm (NA = 0.50) was used in this scheme. In another arrangement, each beam could be focused in a point on its axis of propagation, using identical lenses. Such a layout is presented in Fig. 6(b), where aspherical lenses with focal lengths from short, $f = 7.5$ mm (NA = 0.30), to long, $f = 18$ mm (NA = 0.15), could be used to obtain air breakdown. We mention that the distance between the central axes of beams 1 and 3 and that between beams 2 and 4 was 7.0 mm. A larger volume could be accessed by focusing the beams at different distances from the optics. For example, Fig. 6(c) illustrates the air breakdown obtained with beams 1 and 3 from the horizontal plane that were focused in front of beams 2 and 4 (that are in vertical plane). A similar case is shown in Fig. 6(d), where beams 2 and 4 were focused close to the optics. Other combinations of optics could allow the focusing of each beam outside (or inside) its propagation axis, thus offering more possibilities for location of the ignition points in space. Furthermore, the timing between each beam could be controlled; in this way a method for avoiding misfiring, an event that usually happens in the case of igniting lean

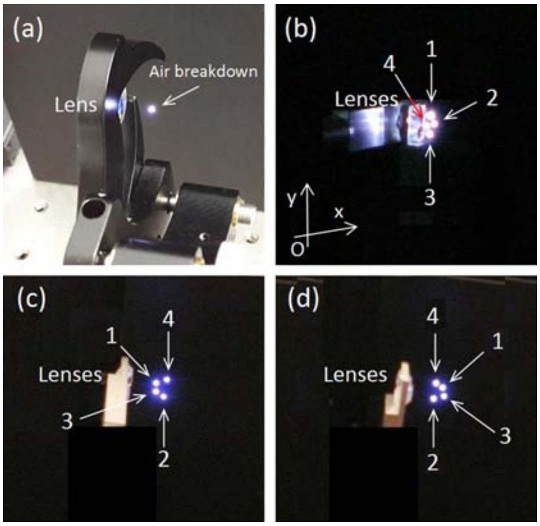

Fig. 6. Several combinations for focusing the laser beams are shown: (a) focusing in a single point; (b) focusing all beams in the same plane, at equal distances from the optics; (c) beams 1 and 3 (from the horizontal plane) are focused before beams 2 and 4 (from the vertical plane); (d) beams 2 and 4 are focussed close to the optics, in front of beams 1 and 3.

air–fuel mixtures, or for fuel in turbulent conditions. In addition, one more laser beam could be easily obtained by pumping the Nd:YAG/Cr^{4+}:YAG ceramic medium on its central axis. These approaches are under investigation and will be reported later.

3. CONCLUSION

We have proposed a high-peak-power passively Q-switched Nd:YAG/Cr^{4+}:YAG laser with four-beam output. Each pump line has a simple design, containing a lens and a folding prism. The laser yielded four beams, with energy per pulse of 3.25 mJ for beam 1, 3.30 mJ for beam 2, 3.60 mJ for beam 3, and 3.20 mJ for beam 4 at 5 Hz repetition rate. The pulse duration was about 0.9 ns. When the repetition rate was increased to 60 Hz, the laser pulse energy increased, in the range of 2.4% for beam 2 up to 5.5% for beam 3. Different focusing arrangements were presented to obtain air breakdown in variable volume. Some applications of such a laser device include ignition of lean air–fuel mixtures in automobile gasoline engines, ignition of a propeller under high-altitude conditions and even in space propulsion, or ignition in turbulent conditions that are specific to aeronautics.

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The effect of laser ignition on a homogenous lean mixture of an automotive gasoline engine

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Abstract: The tendency of reducing the fuel consumption resulted in increasing the number of engines running on lean stratified air-fuel mixtures (with excess air). A classical ignition system cannot deliver high ignition energy without encountering the electrode erosion phenomenon, especially for the homogeneous lean air-fuel mixture; therefore the interest in using an ignition system to avoid this inconvenient is high. The present investigation outlines the effect of ignition by a laser system based on high-peak power passively Q-switched Nd:YAG/Cr^{4+}:YAG that could improve the internal combustion engine efficiency. It was found that ignition by laser sparks, compared with the conventional ignition by electrical spark plugs, have a favorable effect on cyclic variability and brake specific fuel consumption at different homogeneous lean air-fuel mixtures with small engine speed and load.

The ignition by laser of a gasoline direct injected engine has become an interesting field of research because the engine performances can be improved, aiming low fuel consumption, ignition of leaner mixtures, decreased gas emission and increased engine efficiency [1,2]. A diffusion-bonded Nd:YAG/Cr^{4+}:YAG composite medium pumped in quasi-continuous wave mode by diode lasers is to date the best configuration that assures compactness of the spark-like laser device simultaneously with robustness and resistance to vibrations [3-5].

The first report on the operation of an automobile engine that was ignited only by laser-spark plugs was made by Taira et al. in 2013 [6]. Measurements of the coefficient of variance of the indicated mean effective pressure (COV_{IMEP}) at different air-fuel ratio (λ), with 1.200 rpm engine speed and 73 N·m torque, concluded that the engine operation for classical ignition and ignition by laser sparks was comparable. Recently, our group has ignited a Renault car engine by laser sparks. Several engine parameters, like the coefficient of variability of maximum pressure (COV_{Pmax}) and COV_{IMEP} as well as HC, CO, NO_x and CO_2 specific emissions were determined for engine speeds ranging from 1.500 rpm to 2.000 rpm and high (up to 920 mbar, or 108 N·m torque) loads. In comparison with ignition by electrical spark plugs, improved stability of the engine that was ignited by laser sparks was obtained at engine speeds below 2.000 rpm. Also, decreases of CO and HC emissions were determined for this automobile engine that was equipped with laser sparks.

In this work we are presenting recent data on fuel consumption and engine stability of an engine that was ignited by laser-spark devices at different air-fuel mixtures. The engine behavior at lean mixtures is discussed.

The engine was a naturally aspired indirect injection gasoline engine with four cylinders in line having an engine capacity of 1598 cm^3, the nominal power of 62 kW, the maximum torque of 135 N·m and the compression ratio of 9.5. Pressure traces were recorded with an AVL GU-21D piezoelectric transducer that was mounted on one cylinder of the engine; 500 consecutive cycles were considered for all investigated air-fuel mixture points, at 2.000 rpm engine speed and 2.0 bar of brake mean effective pressure (BMEP). The engine was mounted on an engine test bench equipped with four laser sparks triggered by the electronic control unit. Additional details about the design and characteristics of the laser-sparks system can be found in [7].

The variation of brake specific fuel consumption (BSFC) function of the excess-air factor λ, which was measured with Horiba MEXA 730 air-to-fuel ratio analyzer, is shown in Fig. 1 for ignition by laser sparks as well as by electrical spark plugs. The difference between the two curves is higher at λ= 1.02 (i.e. near the stoichiometric mixture), where the fuel consumption was decreasing by ~3.4% for ignition by laser sparks compared to classical spark-plug ignition. This trend is less pronounced at lean mixtures where λ is 1.2.

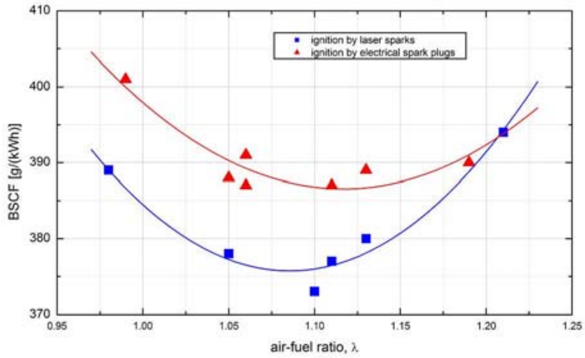

Fig. 1. The variation of BSFC with λ for ignition by laser sparks and by electrical spark plugs for 2000 rpm engine speed and BMEP= 2 bar. Lines are fitting curves with a second degree polynomial function.

The engine stability in terms of COV_{IMEP} parameter at different air-fuel ratio λ is presented in Fig. 2. A significant increase of COV_{IMEP}, from ~4% to 11%, was obtained at λ= 1.08 for the ignition by laser sparks; the same trend was observed at leaner mixtures (λ= 1.2). Near the stoichiometric mixture (of λ= 1) the coefficient COV_{IMEP} has low values for both ignition systems; the differences in COV_{IMEP} between these two systems are therefore small near this air-fuel ratio. Furthermore, a better repeatability was obtained, at the same investigated point, for the laser-spark ignition system compared with the ignition by the classic system; this feature is clear in Fig. 2 for λ= 1.05 and λ= 1.13.

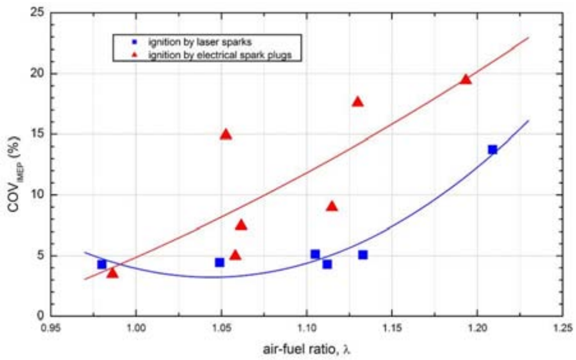

Fig. 2. The variation of parameter COV_{IMEP} with λ for ignition by laser sparks and by electrical spark plugs for 2000 rpm engine speed and BMEP= 2 bar.

This undesired behavior of higher cyclic variability that is encountered with ignition by electrical spark plugs mainly at small loads and towards the ends of ignition limits (in this case lean mixtures) leads to partial burn and misfire and results in emissions of unburned hydrocarbons and lower engine efficiency [8]. This problem can be effectively approached by using the laser-spark device. The difference of shape and energy concentration of the laser spark ignition compared with the classic spark could lead to a better flame kernel formation leading to a more stable combustion from cycle to cycle.

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Passively Q-switched Nd:YAG/Cr^{4+}:YAG laser with multiple-beam output

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Abstract: We report on the design and output performances of a diode pumped, high-peak power Nd:YAG/Cr^{4+}:YAG laser with four-beam output. The system posses the ability to chose independently the focus of each laser beam, being seen as a solution for a laser spark with multiple-point ignition.

The laser ignition of a gasoline direct injected engine has several advantages in comparison with ignition by electrical spark plugs, like absence of quenching effect during the developing flame kernel, ability in positioning the ignition point inside the engine cylinder or the possibility to ignite leaner air-fuel mixtures [1]. Based on extensive research, the first report on an automobile that was fully ignited by laser sparks was presented in 2013 [2]. Recently, a Renault automobile engine was also run only by laser sparks [3]. Several key parameters were measured at various engine speeds and loads, proving the advantages of laser ignition in comparison with classical ignition, such as better engine stability or reduced CO and HC emissions. The laser sparks were built using diode-pumped Nd:YAG laser media that were passively Q-switched by Cr^{4+}:YAG saturable absorbers. This configuration, which was proposed by Koefler et al. in 2007 [4], was further improved such to make it more compact (i.e. comparable to an electrical spark plug), as well as robust and resistant to vibrations and high temperatures [5]. The best solution for the laser medium was then a diffusion-bonded Nd:YAG/Cr^{4+}:YAG composite structure (of single-crystal or polycrystalline nature), whereas monolithically scheme was adopted for the laser resonator. These lasers delivered one output beam.

Ignition by a laser device opens the possibility to obtain ignition in multiple points [6,7] aiming better and more uniform combustion in comparison with ignition by electrical spark plugs. Several experiments were devoted to this subject, showing improved combustion for the ignition in two points [6]. A diode-pumped Nd:YAG/Cr^{4+}:YAG laser spark with three-beam output was also developed for laser ignition [8].

In this work we are reporting on the realization of a laser device that delivers four independent beams with performances suitable for ignition. The laser medium is a composite Nd:YAG/Cr^{4+}:YAG polycrystalline structure (10-mm diameter, 1.1-at.% Nd of ~9-mm length); monolithically resonator was obtained by coating the high-reflectivity mirror on Nd:YAG input side and the out-coupling mirror on the exit surface of Cr^{4+}:YAG. The pump was made by four fiber-coupled (400-µm or 600-µm diameter fibers, numerical aperture NA= 0.22) diode lasers (JOLD-120-QPXF-2P; Jenoptik, Germany) in quasi-continuous wave regime. A compact optical system was design in order to transfer the pump radiation into Nd:YAG/Cr^{4+}:YAG, keeping the compactness of the device and assuring mm-order distance between each laser beam. Typically, the laser pulse energy for every beam was up to 3 mJ with duration shorter than 1 ns. The focusing system was designed for various purposes, aiming focusing and air-breakdown realization in four points (in the same plane or at different distances from the laser) or in a single point. This laser device could be used for multiple-point ignition of an automobile engine.

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Edge-pumped Nd:YAG/YAG lens-shaped composite laser

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The thin-disk laser concept, for the first time developed at Stuttgart University [1], offers the advantage of excellent thermal management; the reduction of the medium thickness up to few hundreds of microns requires multi-pass pumping for efficient absorption of the pump beam. This concept has been proven to be extremely suitable for Yb:YAG [2]. The radial- (or edge-) pumping of a composite Yb:YAG/YAG medium, which consists of a circular Yb:YAG core surrounded by a circular undoped YAG both of the same thickness, posses the advantage of simplicity for the optical system employed for pumping [3,4]. Also, a circular Yb:YAG core can be bonded to an undoped YAG cap; the pump beam is inserted through the edges of this cap and it propagates through total-internal reflections toward the Yb:YAG core were it is absorbed [5]. In this work we present the performances of an Nd:YAG/YAG composite medium that is made of a circular Nd:YAG core bonded by diffusion to a circular undoped YAG. The pump is made through the edges of the undoped YAG, directly from the diode-laser optical fiber. Furthermore, the composite structure has the shape of a thin plane-concave lens.

The experimental set-up is presented in Fig. 1a. The composite ceramic medium is made of a 2.0-mm in diameter, 1.0-at.% Nd:YAG core that is surrounded by a circular (10.0-mm in diameter) undoped YAG. It was shaped as a plane-concave divergence lens, with a thickness of 180 μm at the center of the Nd:YAG core and of 500-μm at the YAG edge [6]. The plane surface, which was coated high-reflectivity at the lasing wavelength of 1.06 μm, was glued to a water-cooled copper finger. The medium concave side was coated antireflection at 1.06 μm. The pump was made at 807 nm with three fiber-coupled (400-μm in diameter, NA= 0.22) diode lasers (Jenoptik Co., Germany) in quasi-cw regime (250-μs pulse duration, variable repetition rate). The resonator, of 25-mm length, was made between the flat surface of Nd:YAG/YAG and a concave mirror with 50-mm radius.

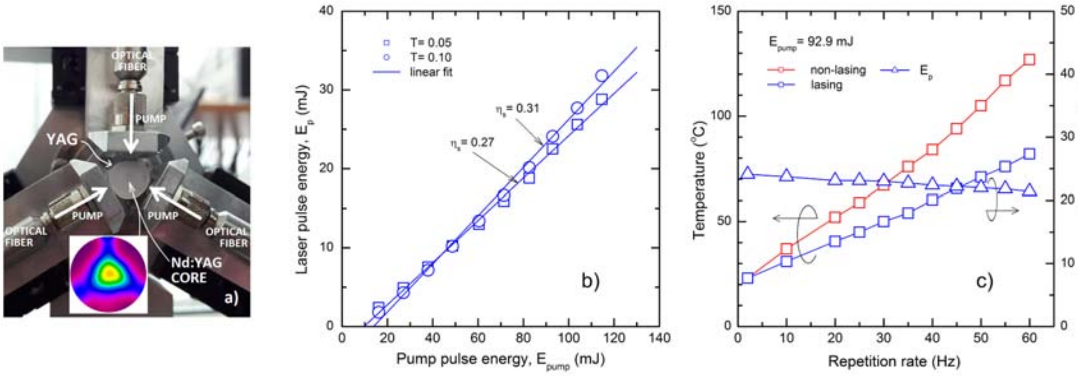

Fig. 1 a) The experimental set-up is shown.; inset is a fluorescence image of the Nd:YAG core. b) Laser pulse energy vs. pump pulse energy at 2-Hz repetition rate. c) Temperature of the Nd:YAG core (in lasing and non-lasing) and laser pulse energy vs. repetition rate.

The laser pulse energy, E_p is shown in Fig. 1b as function of pump pulse energy, E_{pump} at low, 2-Hz repetition rate. With an output mirror of transmission T= 0.10, the laser delivered pulses with E_p= 31.8 mJ; the total pump energy was E_{pump}= 114.6 mJ and thus overall optical-to-optical efficiency reached η_o~0.28. Slope efficiency was η_s= 0.31. A fluorescence image of the Nd:YAG core is shown in the inset of Fig. 1a. Various parameters were investigated. As shown in Fig. 1c, a decrease of pulse energy E_p was observed when the repetition rate was increased. Thus, for the pump with E_{pump}= 92.9 mJ at 60-Hz repetition rate, the energy E_p reduced from 24.1 mJ at 2 Hz to 21.4 mJ. The Nd:YAG core temperature (measured with a FLIR T620 thermal camera, -40°C to +150°C range, ±2°C accuracy) reached 82°C during lasing and increased to 127°C when lasing was stopped. The laser resonator could be increased up to 40 mm without noticeable decrease of the laser pulse energy. Better results are expected by metal soldering of the Nd:YAG/YAG composite medium to the cooling finger.

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MULTIPLE-BEAM OUTPUT HIGH-PEAK POWER Nd:YAG/Cr^{4+}:YAG LASER FOR LASER IGNITION

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Alternative propellant combinations for orbital manoeuvring system and reaction-control system require new ignition devices for a new generation of thrusters. Such thrusters need to withstand large, from hundred to thousand range, number of cycles. Additional requirements are concerning the replacement of the toxic propellants with green ones. The classical methods of ignition are based on pyrotechnical and electrical effects. Recently, a lot of efforts are made to develop an alternative ignition technology based on solid-state lasers [1]. The energy required for a reliable ignition depends on the working conditions and one alternative to single high-energy laser pulse is a multiple-pulse laser system that allows the focusing of several pulses in a small volume. Single and multipoint ignition [2-5] has been also studied for car engine ignition.

In this work we are reporting on the realization of a compact laser that delivers four independent output beams. The device, shown in Fig. 1a, is made of a composite Nd:YAG/Cr^{4+}:YAG structure. Monolithically resonator was obtained by coating the high-reflectivity mirror on Nd:YAG input side and the out-coupling mirror on the exit surface of Cr^{4+}:YAG.

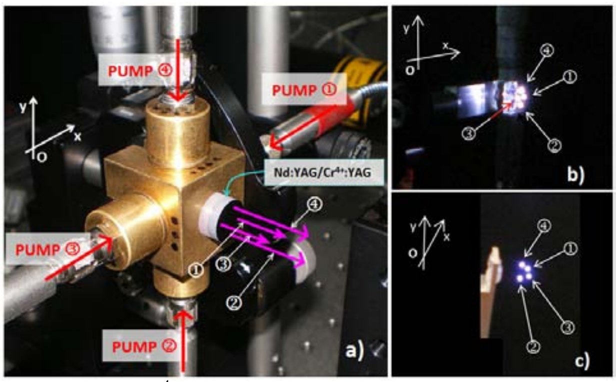

Fig. 1. a) A photo of the Nd:YAG/Cr^{4+}:YAG laser with four-beam output is shown. Each laser beam can be focused **b)** in the same plane, at equal distances from the optics or **c)** in different points.

The pump was made by four fiber-coupled diode lasers (Jenoptik, Germany) in quasi-continuous wave regime. A simple optical system was designed in order to transfer the pump radiation into Nd:YAG/Cr^{4+}:YAG, keeping the compactness of the device and assuring mm-order distance between each laser beam. The laser pulse energy for each beam was up to 5 mJ with duration below 1 ns. The four beams were focused such as to obtain plasma in points placed in the same plane (Fig. 1b) or in points chosen in different planes (Fig. 1c), in order to access a large volume of the inflammable mixture. This laser device could be used for multiple-point ignition in automobile car engine, natural-gas stationary engines, or orbital manoeuvring thrusters.

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