RAPORT STIINTIFIC

Contractul de Finantare nr. 58/02.07.2012

Sistem Laser pentru Aprinderea Motoarelor de Automobile (LASSPARK)

Etapa IV / 2015: B. Motor de automobil aprins cu bujie laser.

1. Experimente privind performantele emisiei pentru 'bujia' de tip laser.

Un dispozitiv laser de tip 'bujie' realizat in cadrul acestui contract este aratat in Fig. 1a, iar o sectiune a acestui dispozitiv este prezentata in Fig. 1b. Mediul laser Nd:YAG/Cr^{4+}:YAG a fost o structura de tip compozit, Nd:YAG fiind lipit optic la cristalul cu absorbtie saturabila Cr^{4+}:YAG. Rezonatorul a fost de tip monolitic, obtinut prin depunerea oglinzii cu reflectivitate ridicata (reflectivitate R> 0.999) la lungimea de unda de emisie λ_{em}= 1.06 μm pe suprafata libera a Nd:YAG (fata dinspre optica pentru pompaj) si cu oglinda de extractie (reflectivitate R la λ_{em}) depusa pe fata libera a Cr^{4+}:YAG (suprafata inspre optica pentru focalizare); in plus, suprafata Nd:YAG a fost depusa cu transmisie ridicata (transmisie T> 0.98) la lungimea de unda de pompaj, λ_p. In experimente au fost investigate performantele pulsurilor laser obtinute de la medii 1.0-at.% de tip ceramic (Baikowski Co., Japan) precum si de tip cristal (cumparat din China). Pentru pompaj (la λ_p= 807 nm) am utilizat o dioda laser (JOLD-120-QPXF-2P, Jenoptik, Germania), cu diametrul fibrei ϕ= 600 μm si apertura numerica NA= 0.22, dioda functionand in regim repetitiv, cu rate de repetitie (frecventa) de pana la 100 Hz; durata pulsului de pompaj a fost de 250 μJ. Pentru transferul radiatiei de pompaj de la fibra la mediul Nd:YAG/$C4^{+:Y}$AG am utilizat doua configuratii ale opticii de pompaj.

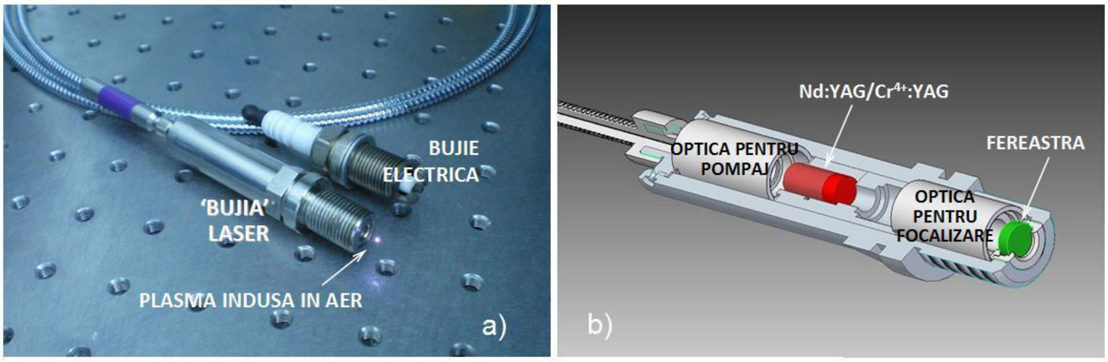

Fig. 1 a) Prototip de tip 'bujie' laser realizat in Laboratorul de Electronica Cuantica a Solidului din Institutul National de Cercetare-Dezvoltare pentru Fizica Laserilor, Plasmei si Radiatiei; b) o sectiune prin dispozitivul laser.

In prima varianta am folosit doar o lentila (L) cu distanta focala f; distanta dintre fibra optica si lentila L este notata cu d_1; d_2 este distanta dintre lentila si mediul Nd:YAG. Energia pulsului laser E_p si energia de pompaj la prag E_{pump} au fost masurate in functie de distantele d_1 si d_2. Figura 2 prezinta E_p (Fig. 2a) si E_{pump} (Fig. 2b) pentru un mediu ceramic Nd:YAG/Cr^{4+}:YAG avand Cr^{4+}:YAG cu transmisia initiala T_i= 0.40 si oglinda de extractie cu reflectivitatea R= 0.60. Pentru o lentila L cu f= 4.0 mm au fost obtinute pulsuri laser cu E_p= 5.5 mJ (Fig. 2a) plasand L la distantele d_1= 3.35 mm si d_2= 10.4 mm; energia de pompaj a fost E_{pump}= 47.5 mJ (Fig. 2b). Pentru o lentila L cu f= 6.2 mm pozitionata la d_1= 4.85 mm si d_2= 18.5 mm pulsul laser a avut energia E_p= 5.9 mJ, pompajul necesar fiind E_{pump}= 47.3 mJ.

A doua varianta pentru linia de pompaj a fost cea in care am utilizat o lentila L1 (cu distanta focala f_1) pentru colimare si o lentila L2 (avand distanta focala f_2) pentru focalizarea radiatiei de pompaj in Nd:YAG/Cr^{4+}:YAG; distanta dintre lentila f2 si mediul laser este notata cu d. Figura 3 prezinta E_p (Fig. 3a) si E_{pump} (Fig. 3b) pentru o lentila de colimare L1 cu f_1= 3.0 mm si diferite lentile de focalizare L2. In cazul in care L2 a avut distanta focala f_2= 4.0 mm, au fost obtinute pulsuri laser cu energia E_p= 2.6 mJ, plasand mediul la distanta d= 6.9 mm (Fig. 3a); energia de pompaj necesara operarii laserului a fost E_{pump}= 45.8 mJ (Fig. 2b). Pentru o lentila L2 cu f_2= 6.2 mm au fost emise pulsuri laser cu E_p= 3.5 mJ (la E_{pump}= 46.2 mJ) prin pozitionarea Nd:YAG/Cr^{4+}:YAG la d= 11.3 mm. In aceasta combinatie sistemul laser poate fi facut compact prin reducerea distantei d la 0.3 mm, rezultand E_p= 3.2 mJ cu E_{pump}= 33.4 mJ. Cea mai ridicata energie a pulsului laser, E_p= 4.5 mJ (E_{pump}= 47.3 mJ) a fost masurata cu o lentila de focalizare avand f_2= 7.5 mm, fata de care mediul a fost plasat la distanta d= 2.3 mm. Se observa prezenta unor minime ale E_p si E_{pump}, acestea fiind obtinute prin plasarea Nd:YAG/Cr^{4+}:YAG in punctele de focalizare a radiatiei de pompaj, pentru fiecare combinatie de lentile (L1 si L2).

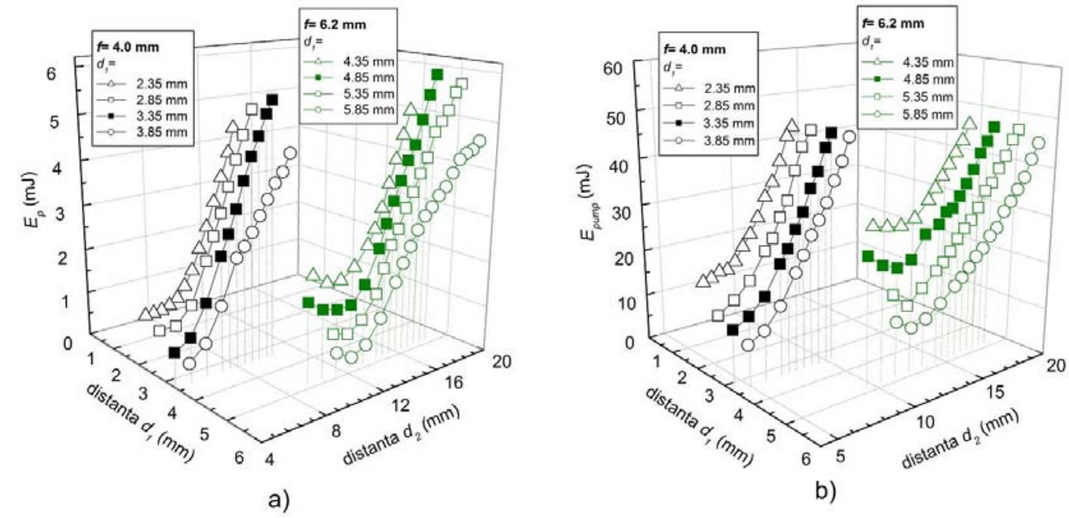

Fig. 2 a) Energia pulsului laser E_p si b) energia pulsului de pompaj E_{pump} in functie de distantele d_1 si d_2, considerand o singura lentila L pentru pompaj: f= 4.0 mm si apoi f= 6.2 mm.

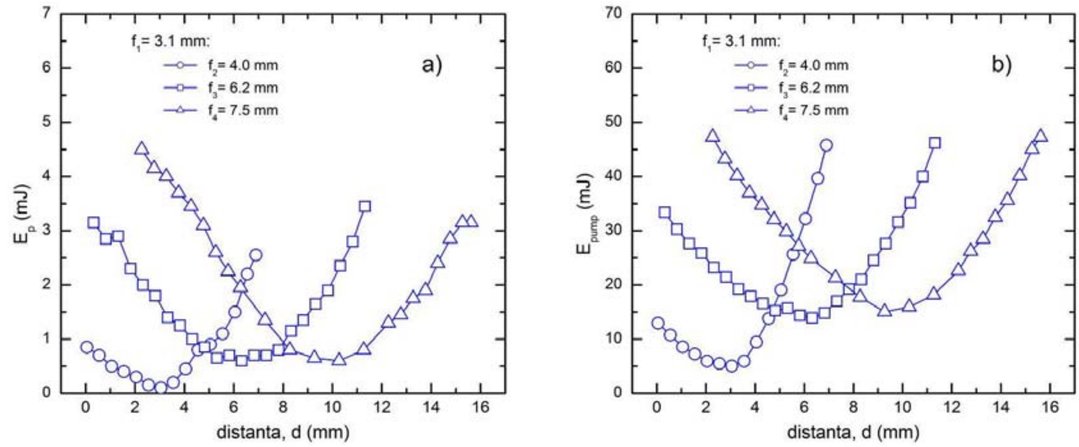

Fig. 3 a) Energia pulsului laser E_p si b) energia pulsului de pompaj E_{pump} in functie de distanta d. Pentru colimare s-a utilizat o lentila L1 cu f_1= 3.1 mm; focalizarea s-a facut cu diferite lentile L2 avand distanta focala f_2.

Pentru o lentila de colimare L1 cu f_1= 6.2 mm sistemul laser a functionat pe o distanta mai scurta d (in comparatie cu distantele corespunzatoare lentilelor de colimare f_1= 3.1 mm si f_2= 4.0 mm); mai mult, energia pulsul laser a fost scazuta pentru valori mici ale distantei d, imbunatatindu-se cu cresterea distantei d (Fig. 4a). S-au obtinut energii E_p de 3.4 mJ pentru focalizare cu lentila L2 avand f_2= 4.0 mm si Nd:YAG/Cr^{4+}:YAG plasat la d= 4.4 mm, E_p= 3.4 mJ pentru lentila L2 cu f_2= 6.2 mm plasata la d= 6.2 mm si energie E_p= 2.8 mJ pentru lentila L2 cu f_2= 7.5 mm pozitionata la d= 10.2 mm) Energiile pulsului de pompaj au fost E_{pump}= 45.1 mJ pentru f_2= 4.0 mm, 45.4 mJ pentru f_2= 6.2 mm si de 45.7 mJ pentru f_2= 7.50 mm (Fig. 4b).

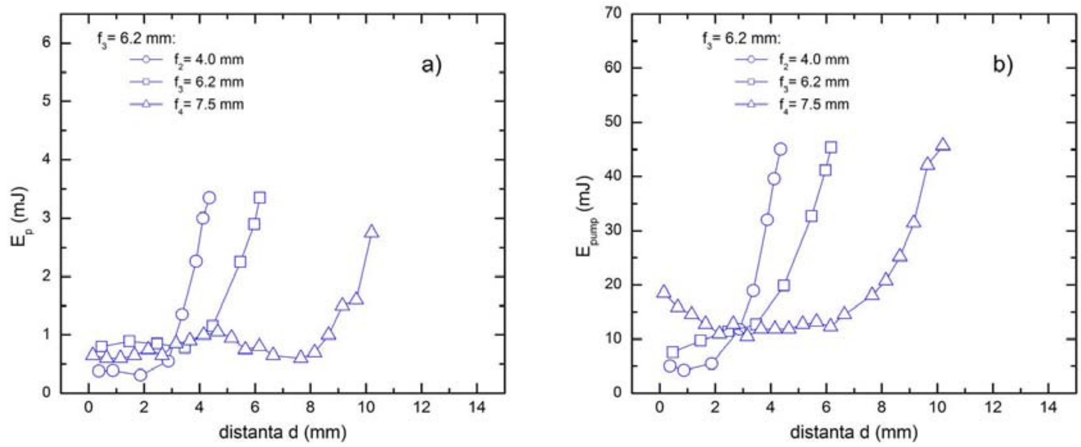

Fig. 4. Energiile a) E_p si b) E_{pump} pentru o lentila de colimare L1 cu f_1= 6.2 mm si diferite lentile de focalizare (L2, f_2); L2 este plasata la distanta d de mediul Nd:YAG/Cr^{4+}:YAG.

Experimente au fost facute si pe medii laser Nd:YAG/Cr^{4+}:YAG ceramice avand transmisia initiala a Cr^{4+}:YAG intre 0.30 si 0.50 si cu reflectivitatea oglinzii de extractie R= 0.60. Pentru fiecare linie de pompaj au fost gasite combinatiile necesare astfel incat mediul laser sa emita pulsuri cu energie suficienta pentru a initia fenomenul de 'spargere a aerului'. Pe de alta parte, mediul Nd:YAG/Cr^{4+}:YAG de tip cristal a avut performante E_p asemanatoare cu cel ceramic, find insa nevoie de energii de pompaj E_{pump} mai mari. Aceasta comportare a fost atribuita unor pierderi probabil mai mari la interfata optica dintre Nd:YAG si Cr^{4+}:YAG pentru mediul de tip cristal decat cel ceramic. In final, dispozitivele laser de tip bujie au fost realizate cu medii Nd:YAG/Cr^{4+}:YAG ceramice, fiecare laser fiind proiectat sa emita pulsuri cu energia E_p~4.0 mJ, durata pulsului laser fiind de 0.8 ns.

Optica de focalizare a fost constituita din cateva lentila, ultima (adica lentila de focalizare) avand distanta focala de 11 mm pana la 18 mm; astfel, prin schimbarea acestei lentile se poate modifica pozitia in care se aprinde amestecul de combustibil in cilindrul motorului. Fereastra optica (dintre 'bujia' laser si camera de ardere) a fost din safir, cu o grosime de ~2.0 mm; in experimente aceasta nu a cedat pana la presiuni (statice) de 20 MPa. Elementele optice au fost fixate in interiorul 'bujiei' laser cu un epoxy, acesta fiind elastic (totusi cu duritate ridicata) si avand un domeniu de functionare pentru temperaturi intre -70°C si 170°C.

2. Investigatii privind influenta temperaturii asupra emisiei 'bujiei' de tip laser.

Pentru a observa influenta temperaturii asupra emisie laser au fost efectuate diferite experimente, in care dispozitivul de tip 'bujie' laser a fost montat intr-un corp metalic a carui temperatura a fost modificata. Cu ajutorul unei camere termice FLIR T620 (avand domeniul de masura intre -40°C si +150°C cu acuratete de ±2°C) s-au determinat temperaturile in mai multe puncte ale 'bujiei' laser.

Figura 5 prezinta imagini ale unui mediu Nd:YAG/Cr^{4+}:YAG care a fost operat in aer (fara racire) timp de 30 min. In cazul in care rata de repetitie (ν) a fost mentinuta la 10 Hz (cu E_{pump}~ 23 mJ), temperatura maxima a Nd:YAG a atins 35.6°C (Fig. 5a). O crestere a frecventei ν la 60 Hz (cu E_{pump}~ 28 mJ) a dus la cresterea temperaturii (in acelasi punct al Nd:YAG) la 100.7°C.

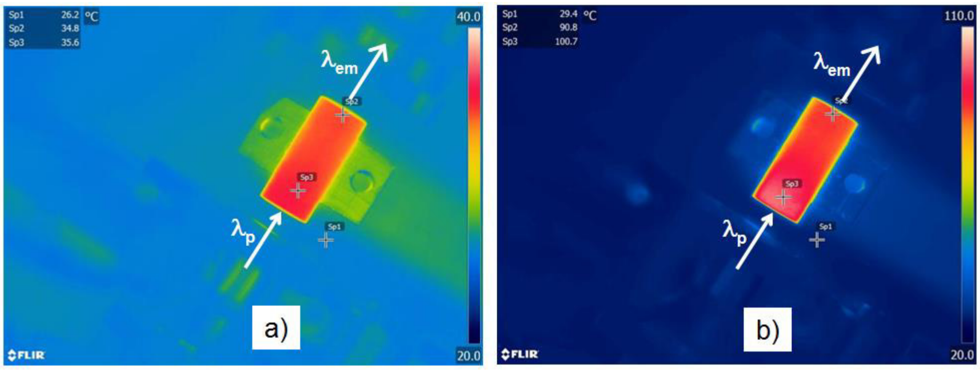

Fig. 5 Imagini ale unui mediu Nd:YAG/Cr^{4+}:YAG ceramic operand in aer si care a fost pompat timp de 30 minute la frecvente de repetitie de a) 10 Hz si b) 60 Hz.

Pentru a vizualiza temperatura mediului in 'bujia' laser, s-a taiat o fanta in dreptul acestuia si a fost indepartat corpul metalic care proteja si fixa mediul. In aceste conditii, temperatura suprafetei Nd:YAG dinspre pompaj a fost de 31.8°C pentru functionare la ν= 10 Hz si E_{pump}= 29 mJ (Fig. 6a); pentru ν= 60 Hz (E_{pump}= 30 mJ) temperatura a fost de 65.3°C (Fig. 6b). In plus, temperatura monturii metalice in care a fost plasat Nd:YAG/Cr^{4+}:YAG a fost de 29.3°C la frecventa ν= 10 Hz si de 35.4°C la frecventa ν= 60 Hz. Mentionam ca aceste masuratori s-au facut cu dispozitivul laser la temperatura camerei (~25°C).

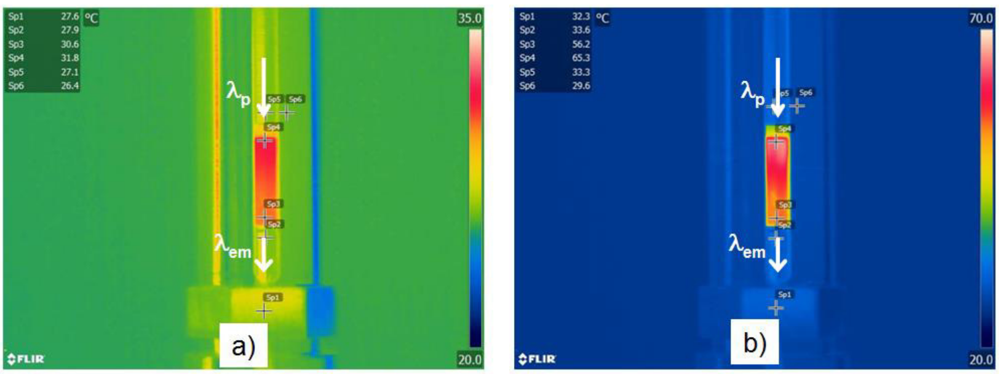

Fig. 6 'Bujia' de tip laser operand la frecvente de repetitie de a) 10 Hz si b) 60 Hz, fara a fi incalzita.

In cazul in care 'bujia' laser a fost incalzita (la capatul cu fereastra de safir), in jurul ei a fost montat un sistem de racire care a constat dintr-o manta de cupru (aceasta fiind racita cu apa la 25°C). Astfel, cand laserul a fost operat la frecventa ν= 10 Hz si temperatura bazei a fost de 150°C, temperatura in dreptul Nd:YAG (suprafata dinspre optica de pompaj) a fost de 36.9°C, in timp ce temperatura Cr^{4+}:YAG (suprafata dinspre optica de focalizare) a ajuns la 40.1°C (Fig. 7a). Pentru o temperatura a bazei de 250°C, temperatura maxima a Nd:YAG a fost de 45.8°C iar temperatura Cr^{4+}:YAG a crescut pana la 51.5°C (Fig. 7b).

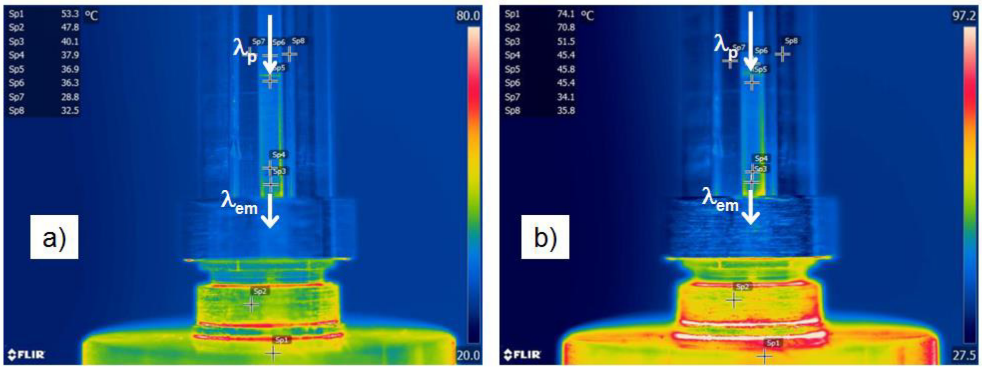

Fig. 7 'Bujia' de tip laser operand la frecventa ν= 10 Hz, racita cu o manta de cupru si incalzita la baza la temperatura de a) 150°C si b) 250°C.

Au fost efectuate astfel de masuratori pentru fiecare dispozitiv laser de tip 'bujie', determinandu-se temperaturile in diferite puncte ale corpului 'bujiei' la frecvente de repetitie intre 10 Hz si 60 Hz. A fost masurata influenta temperaturii asupra energiei pulsului de pompaj (E_{pump}) necesara pentru a mentine operarea laserului. In urma acestor masuratori s-a decis ca dispozitivele laser de tip 'bujie' sa fie racite in timpul functionarii pe motor. Racirea s-a facut prin suflarea de aer sub presiune (pe fiecare dispozitiv) in determinarile ale caror rezultate vor fi prezentate in continuarea acestui raport.

3. Motor Renault aprins doar cu dispozitive laser. Masuratori ale noxele emise.

Testele au fost facute pe un motor tip K7M 812 k (cu volum de 1.6-litri, pe benzina) echipat cu un sistem de injectie multipla; motorul a fost instalat pe un banc de lucru (Fig. 8). Comanda sistemului laser, format din patru dispozitive de tip 'bujie', a fost facuta de la unitatea electronica a motorului. Presiunea in cilindru (cilindrul 1) a fost masurata cu un dispozitiv piezoelectric AVL GU-21D. Pentru a caracteriza stabilitatea in functionare a motorului au fost calculati coeficientul de variatie ciclica a presiunii maxime in cilindru, COV_{Pmax} (definit ca raportul dintre deviatia standard si media presiunii maxime), precum si coeficientul de variatie ciclica a presiunii efective medii, COV_{IMEP} (definit ca raportul dintre deviatia standard si media presiunilor efective in cilindru). Compozitia gazele emise de motor a fost analizata cu un sistem Horiba Mexa, determinandu-se CO (monoxidul de carbon), HC (hydrocarbon), NOx (oxizi de azot) si CO_2 (dioxidul de carbon). Achizitia de date s-a facut pentru 500 de cicluri consecutive ale motorului, la viteze intre 1.500 rpm si 2.000 rpm si incarcari ale motorului de 770 mbar, 880 mbar si 920 mbar. Motorul a fost operat aproape de amestec stoichiometric aer-combustibil Un exemplu pentru presiunile maxime masurate la viteza de 1.500 rpm si incarcare a motorului de 880 mbar este aratat in Fig. 9, folosind aprinderea cu bujii clasice si aprinderea cu dispozitivele laser; din astfel de date s-au calculat coeficientii COV_{Pmax} si COV_{IMEP}.

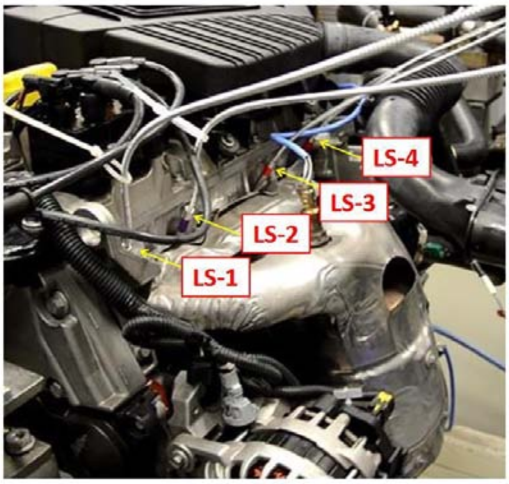

Fig. 8 Este prezentat motorul Renault K7M 812 k in timpul operarii cu dispozitivele laser de tip 'bujie'. LS: sistem laser de tip bujie.

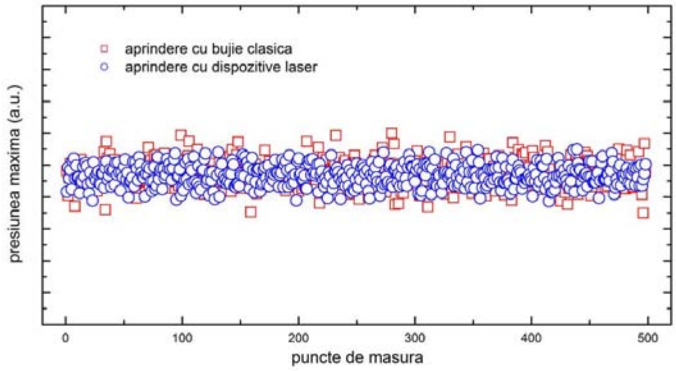

Fig. 9 Comparatie intre presiunile maxime masurate pentru aprinderea cu bujiile clasice si aprinderea cu dispozitivele laser, la viteza a motorului de 1.500 rpm si incarcare de 880 mbar.

In Tabelul I am prezentat rezultatele principale obtinute din aceste masuratori. Se observa ca pentru viteze medii, coeficientii de variabilitate ciclica a presiunilor s-au imbunatatit cand aprinderea s-a realizat cu dispozitivele laser. Astfel, COV_{Pmax} s-a redus cu ~15% pentru viteza de 1.500 rpm, iar la aceeasi viteza COV_{IMEP} s-a imbunatatit cu 22.6% la incarcare de 880 mbar si cu 18.5% la incarcare de 920 mbar. Pe de alta parte, se stie ca variatia ciclica a unui motor este mai stabila la viteze ridicate si incarcari mari; in consecinta, in aceste conditii de functionare este de asteptat ca influenta aprinderii cu dispozitive laser sa fie mai mica asupra coeficientilor respectivi. Intr-adevar, la viteza de 2.000 rpm si incarcare de 920 mbar, coeficientul COV_{Pmax} a scazut cu numai 2.6% iar COV_{IMEP} a crescut cu 2.5% (oarecum contradictoriu, insa in limite acceptabile) pentru aprinderea cu dispozitivele laser fata de aprinderea cu bujii clasice. Astfel, din punct de vedere al stabilitatii in functionare, aprinderea cu 'bujii' laser prezinta avantaje la viteze medii si incarcari mici, in comparatie cu aprinderea cu bujii clasice, electrice.

Tabelul I. Rezultate obtinute in timpul testelor pe motor ale dispozitivelor de tip 'bujie' laser. Semnul (-) corespunde unei scaderi (adica o imbunatatire) a parametrului respectiv pentru aprinderea cu 'bujii' laser fata de aprinderea cu bujiile clasice; semnul (+) inseamna o crestere a parametrului respectiv.

Incarcarea (mbar)	Viteza (rpm)	COV_{Pmax}	COV_{IMEP}	CO (%)	HC (%)	NOx (%)	CO_2 (%)
770	2.000	-10.2	-14.6	-18.7	-3.8	+1.6	+1.1
880	1.500	-15.8	-22.6	-22.4	-14.4	+8.0	+0.7
920	1.500	-15.1	-18.5	-21.9	-17.5	+7.6	+0.8
	2.000	-2.6	+2.5	-25.1	-3.0	+2.6	+1.1

Emisiile de HC si CO au fost mai mici pentru aprinderea cu 'bujiile' laser. Astfel, scaderea CO a fost in domeniul 18% la 25% pentru toate masuratorile efectuate. Pentru viteza de 1.500 rpm, descresterea emisiei de HC a fost de 14.4% la incarcare de 880 mbar si de 17% pentru incarcare de 920 mbar. Pentru viteza de 2.000 rpm scaderea emisiilor de HC a fost de ~3%. Aceste reduceri de noxe pot fi datorate unei arderi mai complete a combustibilului pentru ignitia cu dispozitivele laser. Pe de alta parte, s-a observat o crestere a NOx, aceasta fiind de 8% la 1.500 rpm si de ~2% la 2.000 rpm. Aceasta crestere a NOx pentru aprinderea cu dispozitivele laser, in comparatie cu aprinderea cu bujii clasice, poate fi explicata printr-o temperatura mai ridicata a flacarii in prima parte a arderii, cand se produce NOx. O solutie la aceasta problema poate fi recircularea gazelor emise de motor. Cresterea CO_2 este normala in conditiile in care CO se reduce, deoarece cantitatea de carbon care intra in camera de ardere trebuie sa se regaseasca la iesire.

Evaluarile asupra performantelor motorului au dus la concluzia ca puterea motorului a crescut cu ~3% pentru aprinderea cu dispozitive laser fata de puterea dezvoltat la aprinderea cu bujii clasice. Mentionam ca in teste recente s-a determinat avansul optim de aprindere la viteza de 2.000 rpm si diferite sarcini. S-au facut teste la diferite amestecuri de aer-carburant, saracindu-se acest amestec pana la limita de stabilitate. Aceste date sunt in curs de interpretare.

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

- Au fost evaluate diferite configuratii ale opticii care asigura transferul radiatei de pompaj de la dioda laser la mediul Nd:YAG/Cr^{4+}:YAG, astfel incat laserul sa emita pulsuri cu energia mai mare de 4 mJ;
- Sistemul laser de tip bujie a fost testat in diferite conditii de temperatura;
- A fost operat un motor laser de tip Renault numai cu 'bujii' laser si s-au masurat diferiti parametrii de stabilitate (COV_{Pmax} si COV_{IMEP}), precum si emisiile de HC, CO, NOx si CO_2. In general, in comparatie cu aprinderea cu bujii clasice, pentru aprinderea cu dispozitive laser s-a obtinut o imbunatatire a stabilitatii motorului la viteze medii (pana la 2.000 rpm) si incarcari mici (pana la 880 mbar), precum si o reducere a noxelor HC si CO. Emisiile de NOx si CO_2 au crescut;
- Rezultatele au fost diseminate prin a) trimiterea unui manuscris pentru publicare intr-o revista ISI; b) o prezentare poster la o conferinta internationala (Germania), c) o prezentare orala la o conferinta

internationala (Germania) si c) o prezentare poster si o prezentare invitata la doua conferinte cu participare internationala, desfasurate in Romania.

DISEMINAREA REZULTATELOR

ARTICOLE ISI

1. N. Pavel, T. Dascalu, G. Salamu, M. Dinca, N. Boicea, and Adrian Birtas, “Ignition of an automobile engine by high-peak power Nd:YAG/Cr^{4+}:YAG laser-spark devices,” *trimisa spre publicare in Optics Express*; [2014 Impact Factor: 3.488]

CONFERINTE

1. N. Pavel, T. Dascalu, M. Dinca, G. Salamu, N. Boicea, A. Birtas, ”Laser Ignition of an Automobile Engine by a High-Peak Power Nd:YAG/Cr^{4+}:YAG Laser,” Advanced Solid State Lasers Conference and Exhibition (ASSL), 04 - 09 October 2015, WISTA-Technology Park, Adlershof-Berlin, Germany; presentation ATh2A.2 (poster presentation).
2. G. Salamu, O. Grigore, T. Dascalu, and N. Pavel, “High energy, high-peak power passively Q-switched Nd:YAG/Cr^{4+}:YAG composite ceramic laser,” ROMOPTO 2015, 11th International Conference on Optics “Micro- to Nano-Photonics IV”, September 1-4, 2015, Bucharest, Romania; presentation I.P.1 (poster presentation).
3. N. Pavel, G. Salamu, O. V. Grigore, M. Dinca, T. Dascalu, N. Boicea, and A. Birtas, “High-Peak Power Passively Q-switched Nd:YAG/Cr^{4+}:YAG Lasers for Successful Ignition of an Automobile Engine,” The 15th International Balkan Workshop on Applied Physics, July 2-4, 2015, Constanta, Romania, presentation S2-L3, Book of Abstracts, pgs. 80-81 (invited presentation).
4. N. Pavel, T. Dascalu, M. Dinca, G. Salamu, N. Boicea, and A. Birtas, “Automobile Engine Ignition by a Passively Q-switched Nd:YAG/Cr^{4+}:YAG Laser,” CLEO Europe - EQEC 2015 Conference, 21-25 June 2015, Münich, Germany, presentation CA-5b.2 (oral presentation).

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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 coefficient of pressure variance and specific emissions like hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NOx) and carbon dioxide (CO_2) were measured at various engine speeds and high loads. Improved engine stability, decreased CO and HC and increased values of NO_x and CO_2 emissions 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.

References and links

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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 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 T. 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 has proven 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 Ref. [17] 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 load; 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); 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, NOx 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 NOx and CO_2 emissions have been obtained in comparison with classical ignition by electrical spark plugs.

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

It was 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 media 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. 2a in comparison with a classical spark plug; a cross-sectional view of this laser spark is shown in Fig. 2b. 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 (toward the pump line, Fig. 2b) 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. 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 better 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.

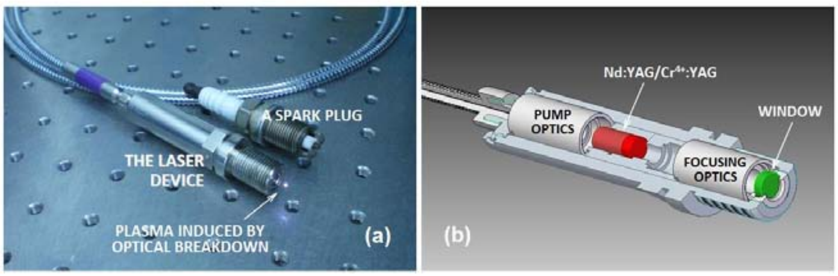

Fig. 2. (a) A laser spark plug based on monolithic, diffusion-bonded Nd:YAG/Cr^{4+}:YAG medium is presented in comparison with a classical spark plug. The plasma induced by optical breakdown of air is visible. (b) Sectional view of the laser device is shown.

For the pump optics line (Fig. 2b) 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 line scheme was made of a collimating lens L1 of focal length f_1 (for collimation, L1 was 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.

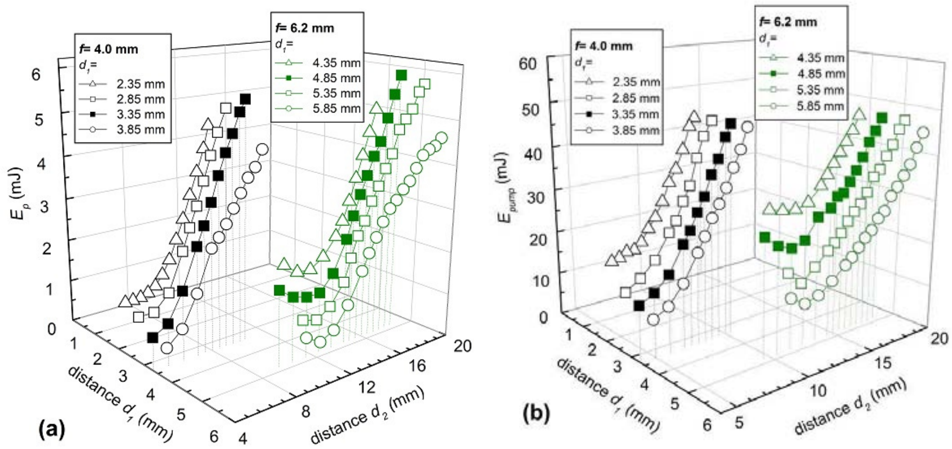

Fig. 3. (a) Laser pulse energy E_p and (b) corresponding pump pulse energy E_{pump} measured function of distance d_1 (between the fiber end and the lens) and d_2 (between the lens and the laser medium), pump line with a single lens of focal length f.

Figure 3a 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. 3b) was 47.5 mJ. A maximum energy of 5.9 mJ was yielded by the laser when the lens 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.

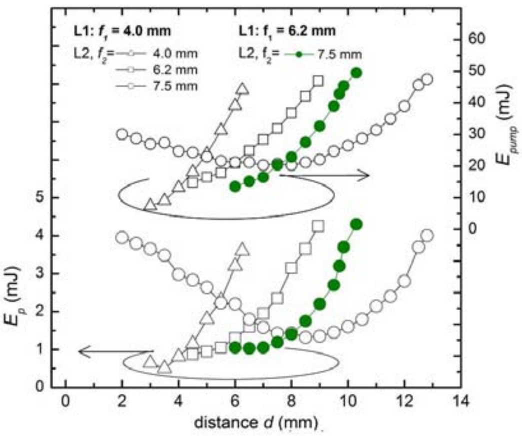

Fig. 4. Laser pulse energy E_p and pump pulse energy E_{pump} versus distance d between the focusing lens (L2) and the laser medium, pump line made of two lenses (L1 and L2).

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 were obtained by placing the Nd:YAG/Cr^{4+}:YAG 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. 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). 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. 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.

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]:

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

where $h\nu$ is the photon energy at λ_{em}, γ_g is the inversion factor and σ_g 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:

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

where r_n is the ratio $r_n= n_{gf}/n_{gi}$. The parameter β = $(-\ln R_{OCM}+L_i-\ln T_i^2)/[1-\exp(-2a^2)]$ 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.

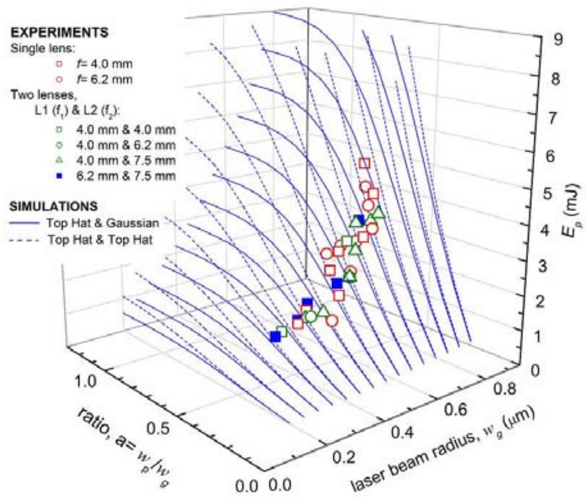

Fig. 5. Modeling of laser pulse energy versus pump beam radus, w_p and laser beam radius, w_g; a is the ratio $a= w_p/w_g$.

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 σ_g= 2.63×10^{-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 σ_{ESA}= 8.2×10^{-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 Ref. [31] can be used to realize a laser spark.

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 employed 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 nearly 5.0 MW.

The focusing line (Fig. 2b) 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. 2b). 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; 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 analyzer. The acquisitions were made on 500 consecutive cycles for engine speeds between 1.500 rpm and 2.000 rpm and high loads (770 mbar, 880 mbar and 920 mbar). The engine was running near the stoichiometric air-fuel ratio for all investigated points. Figure 6a presents the 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. 6b. The engine is shown in Fig. 6c during running with the laser ignition system.

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 at the center 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. 6c) that blew air toward each laser spark. A short movie of the engine while operating with laser sparks was associated to Fig. 6c.

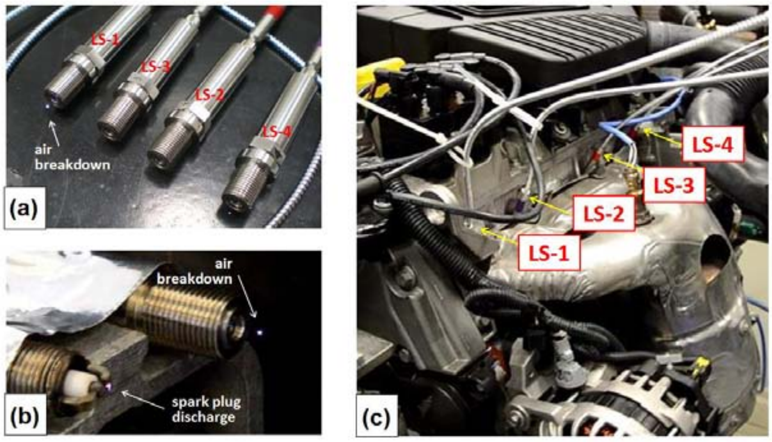

Fig. 6. (a) The four laser-spark system is shown before installation on the engine. (b) A discharge of a classical spark plug and plasma air breakdown initiated by a laser spark are presented. (c) The Renault engine is shown while running with laser-spark devices (see **Visualization 1**).

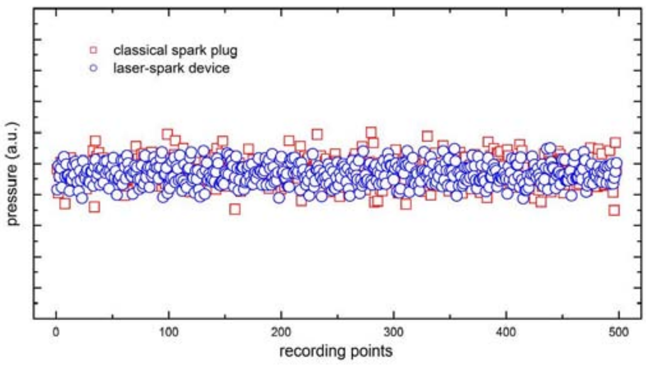

Fig. 7. The peak pressure in a cylinder for 500 consecutive cycles at 1.500-rpm speed and 880-mbar load, ignition by electrical spark plugs and ignition by laser sparks.

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). 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.

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 better combustion under ignition by laser. On the other hand, an increase of NOx, 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 NOx for the internal combustion engine calibration [32]. The increase of NOx can be explained by a higher flame temperature in the first part of combustion, when much NOx is produced. A solution to reduce NOx 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, which explains the increase of CO_2 under laser ignition. Measurements concluded that for the range of speed and load used in these investigations the power of the engine ignited by laser increased by ~3% in comparison with classical ignition.

Table 1. Summary of engine performances. Sign minus and plus indicates a decrease (it corresponds to an improvement), respectively an increase of the parameter in comparison with ignition by electrical spark plugs.

Load (mbar)	Rotational speed (rpm)	COV_{Pmax}	COV_{IMEP}	CO (%)	HC (%)	NOx (%)	CO_2 (%)
770	2.000	-10.2	-14.6	-18.7	-3.8	+1.6	+1.1
880	1.500	-15.8	-22.6	-22.4	-14.4	+8.0	+0.7
920	1.500	-15.1	-18.5	-21.9	-17.5	+7.6	+0.8
	2.000	-2.6	+2.5	-25.1	-3.0	+2.6	+1.1

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. [33] 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. 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. Base 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 coefficient of pressure variance and HC, CO, NOx 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.

Acknowledgments

This work was financed by a grant of the Romanian National Authority for Scientific Research, CNCS - UEFISCDI, project number PN-II-PT-PCCA-2011-3.2-1040 (58/2012) and partially supported by Renault Technology Roumanie.

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Laser Ignition of an Automobile Engine by a High-Peak Power Nd:YAG/Cr^{4+}:YAG Laser

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Abstract (35 Word Limit): High-peak power passively Q-switched Nd:YAG/Cr^{4+}:YAG lasers were employed to operate the engine of a Renault automobile. Improved engine stability and decreased CO and HC emissions were measured in comparison with ignition by electrical spark plugs.

Laser Ignition of an Automobile Engine by a High-Peak Power Nd:YAG/Cr^{4+}:YAG Laser

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Abstract: High-peak power passively Q-switched Nd:YAG/Cr^{4+}:YAG lasers were employed to operate the engine of a Renault automobile. Improved engine stability and decreased CO and HC emissions were measured in comparison with ignition by electrical spark plugs.
OCIS codes: (140.0140) Lasers and laser optics; (140.3530) Lasers, neodymium; (140.3540) Lasers, Q-switched.

The ignition of an automobile engine by a laser device has been regarded in the last years as a method to improve the engine performances, aiming low fuel consumption and decreased gas emission [1]. In this way the impact on the environment of an internal combustion car is expected to be reduced in comparison with that of an engine ignited by electrical spark plugs. The best configuration for such laser igniters was proposed in 2007 and it consisted of an end-pumped Nd:YAG laser that was passively Q-switched by Cr^{4+}:YAG saturable absorber (SA) crystal [2]. Side-pumping scheme was also used to build a high-pulse energy Nd:YAG-Cr^{4+}:YAG laser suitable for ignition [3]. Following more research, monolithic scheme of a Nd:YAG medium that is optically bonded to a Cr^{4+}:YAG SA allowed realization of laser devices with dimensions close to an electrical spark plug [4-7].

On the other hand, it is known that such a laser device has to withstand rough conditions of vibrations or temperatures, yet ordinary for a classical spark plug. Therefore, laser ignition of a multi-cylinder engine was firstly obtained by external Q-switched lasers, the laser beams being redirected to and inserted into the engine cylinders by a set of lenses and mirrors [8]. Recently, in 2013, following sustained research and experiments, the ignition of a gasoline car engine was reported for the first time [9]. In 2015 we have also reported laser ignition of a four-cylinder Renault engine; at low engine speeds and loads, better engine stability in terms of peak pressure was observed in comparison with classical spark-plug ignition [10]. In this work we are presenting additional data on the laser device design and the laser ignition of a Renault car engine, from which HC, CO, NOx and CO_2 specific emissions were measured.

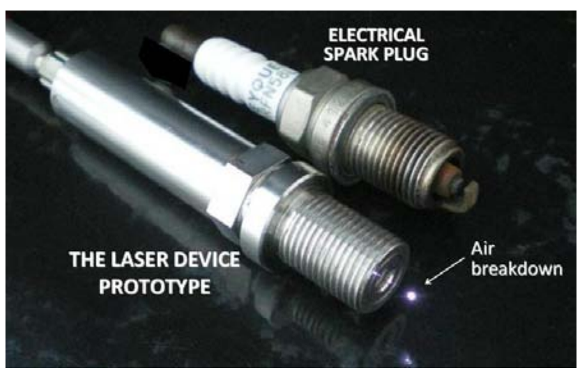

Fig. 1. The laser device used for the ignition of the automobile engine is shown in comparison with an electrical spark plug. Air breakdown induced by the laser is illustrated.

A laser-spark prototype developed by our group and that has been used in the experiments is shown in Fig. 1. The laser medium was Nd:YAG/Cr^{4+}:YAG composite structure, made of 1.1-at.% Nd:YAG active element that was optically bonded to a Cr^{4+}:YAG; the SA thickness was ~2.5 mm and the composite medium length was nearly 11.0 mm. Monolithic configuration was obtained by coating the resonator high-reflectivity mirror directly on the Nd:YAG free surface and the out-coupling mirrors (OCM) on the free side of Cr^{4+}:YAG SA [6]. In comparison with the previous work [6], Nd:YAG/Cr^{4+}:YAG ceramics (Baikowski Co., Japan) as well as Nd:YAG/Cr^{4+}:YAG single crystals (Atom Optics Co. Ltd., China) were employed, both schemes performing well. The design of the pump line allowed a variety of Cr^{4+}:YAG SA with initial transmission between 40% and 50% and OCM's with transmission among 0.40 and 0.55 to deliver laser pulses at 1.06 μm with characteristics suitable for air breakdown.

The pump was made at 807 nm with fiber-coupled (400 µm or 600 µm diameter, NA= 0.22) diode lasers (Jenoptik Laser GmbH, Germany) that were operated in quasi-continuous wave mode. The maximum pump-pulse energy was 47 mJ. The repetition rate was limited to 60 Hz and the pump-pulse duration was adjusted to obtain single- or multi-pulse (three or four pulses) emission.

For the transfer of the pump radiation from the optical fiber to Nd:YAG we considered the use of a single lens or a combination of two lenses. Various lenses, with focal length between 3 mm and 8 mm were used to establish the pump line. For example, Fig. 2 shows the laser pulse energy, E_p that was measured when the pump was made through a single lens with focal length f= 3.10 mm (the open rectangles) or when two lenses (a collimating lens with f= 3.10 mm and various focusing lenses) were employed (the circles). The pump-beam radius, w_p was varied by changing the distance between the lens and the fiber and/or by choosing the pump-beam focusing position in Nd:YAG; the laser-beam radius, w_ℓ was measured for each configuration. The pump with a single lens delivered pulses with energy up to 4.8 mJ, whereas pulses with highest E_p= 5 mJ were obtained from the line with two lenses. For these data the pulse duration was around 0.8 ns, corresponding to the highest peak power of 6.25 MW. Fig. 2 presents also modelling of laser pulse energy E_p based on a model that takes into account the ratio a= w_p/w_ℓ and the beam distributions (top-hat like for the pump beam and Gaussian laser beam).

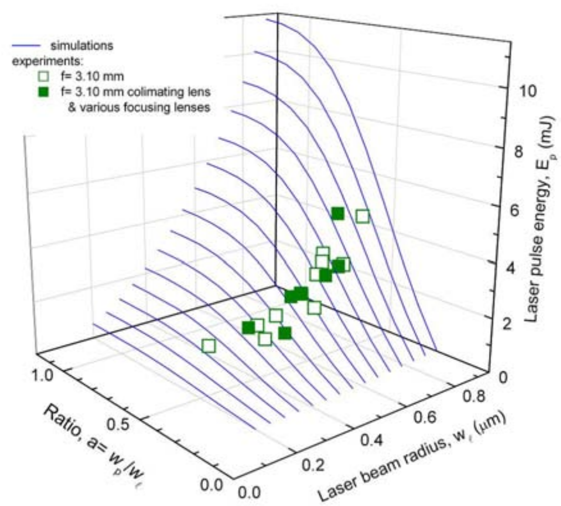

Fig. 2. A 3D plot of the laser pulse energy, E_p versus the ratio a= w_p/w_ℓ (w_p: the pump-beam radius; w_ℓ: the laser beam radius) and w_ℓ, the pump line with a single lens of 3.10-mm focal length or with two lenses. Signs for experiments and modelling by continuous lines.

The laser beam was expanded, collimated and then focussed to a suitable spot size such to obtain air breakdown. A sapphire window, whose thickness (of few mm) was chosen to withstand static pressures higher than 20 MPa, was used as interface between the laser device and the engine cylinder. Furthermore, in preliminary experiments the laser device was operated to temperature conditions close to those of the automobile engine. Following extensive investigations of the temperature influence on the laser pulse performances we concluded that cooling is necessary. Therefore, during engine operation the laser devices were purged with air.

An integrated four-laser device for ignition that could be triggered directly from the engine electronic control unit was assembled (Fig. 3a). Each laser delivered pulses at 1.064 µm with 4.0-mJ energy and ~0.8-ns duration. The system was mounted on a test-bench, equipped with 1.6-litter gasoline engine from Renault, with a multi-point injection system. An AVL GU-21D piezoelectric transducer was used to measure the in-cylinder pressure. The exhaust gases were sampled from the valve gate of a cylinder with a Horiba Mexa analyzer. Acquisitions were made on 500 consecutive cycles for each point of engine speed (1500 and 2000 rpm) and load (770 mbar to 920 mbar). A comparison between the flame discharge in air of an electrical spark plug and the air-breakdown induced plasma by a laser device is illustrated in Fig. 3b. The Renault engine is shown in Fig. 3c during running with the laser ignition system.

Various parameters are compared between these two ignition systems in Table 1. The coefficient of variability for maximum pressure (COP_{Pmax}) was smaller for laser ignition in comparison with the ignition by conventional spark plugs; this means a better engine stability in terms of traction. Both the CO and HC emission decreased, which can be explained by a better combustion due to an improved flame kernel formation. An increase of NOx was observed for laser ignition, this being attributed to a higher flame temperature in the first part of combustion when the NO is best produced. A slight increase of CO_2 was measured, being consistent with the decrease of CO and HC.

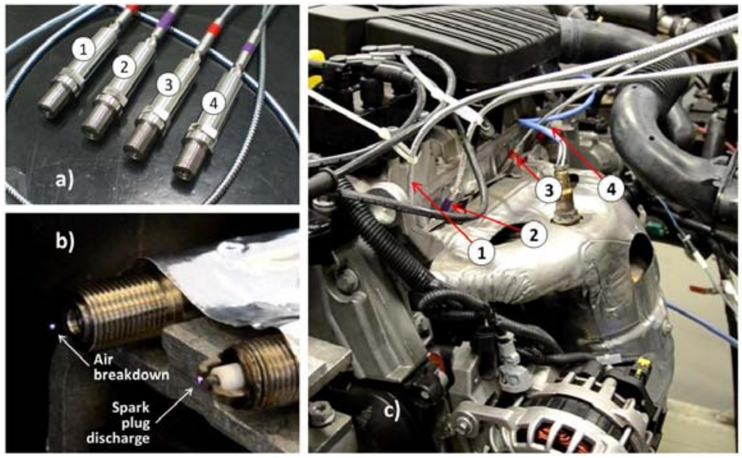

Fig. 3. a) The four laser devices ready for installing on the engine are shown. **b)** Comparison between a spark-plug discharge in air and air breakdown initiated by a laser device is presented. **c)** A photo of the engine while running with all four-laser devices mounted on it is shown.

Table 1. Summary of the measured performances for the Renault engine ignited by the laser devices. Sign minus and plus indicates a decrease, respectively an increase of the parameters in comparison with ignition by electrical spark plugs.

Load (mbar)	Speed (rpm)	COV_{Pmax}	CO (%)	HC (%)	NOx (%)	CO_2 (%)
770	2000	-10.2	-18.7	-3.8	+1.6	+1.1
880	1500	-15.8	-22.4	-14.4	+8.0	+0.7
920	1500	-15.1	-21.9	-17.5	+7.6	+0.8
	2000	-2.6	-25.1	-3.0	+2.6	+1.1

In conclusion, employing high-peak power passively Q-switched Nd:YAG/Cr^{4+}:YAG lasers we have realized an integrated laser system for ignition of an automobile engine. Investigations considered the choice of the laser medium, the design of the optical pump line and of the laser-beam focusing line, selection of the sapphire window that was positioned between the laser and the engine cylinder, as well as a study of temperature influence on the laser system performances. The system was employed to run a four-cylinder Renault engine. Measurements showed improvements of the engine stability (up to 15%), reduction of CO and HC emissions (by up to 25% and 17.5%, respectively) whereas, on the other hand, NOx increases (up to 7.6%) in comparison with the classical spark-plugs ignition. It is well known this compromise between unburned fuel (HC and CO) and NOx for the internal combustion engine calibration [11]. Further experiments aim to determine the effect of laser ignition system on a higher diluted mixture with hot combustion products. These residual burnt gases should lead to a decrease in NOx emissions due to smaller in-cylinder peak temperature.

Acknowledgments. This work was financed by a grant of the Romanian National Authority for Scientific Research, CNCS - UEFISCDI, project number PN-II-PT-PCCA-2011-3.2-1040 (58/2012).

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ROMOPTO 2015

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International Year of Light 2015

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PROGRAMME

Section I. Lasers and Radiation Sources

I.P.1. High energy, high-peak power passively Q-switched Nd:YAG/Cr^{4+}:YAG composite ceramic laser

G. Salamu, O. Grigore, T. Dascalu, N. Pavel

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We have investigated the performances of laser pulses yielded by a monolithic Nd:YAG/Cr^{4+}:YAG composite ceramic laser that consisted of a 8.5-mm thick, 1.1-at.% Nd:YAG bonded to a Cr^{4+}:YAG saturable absorber of initial transmission T_0= 0.40. Laser pulses with energy up to 5.1 mJ and 0.8-ns duration, corresponding to peak power of nearly 6.4 MW, were obtained under the pump with pulses at 807 nm of 46.6-mJ energy. In order to explain the experimental results modeling has been performed based on the rate equations for such a laser system.

The 15th International Balkan Workshop on Applied Physics

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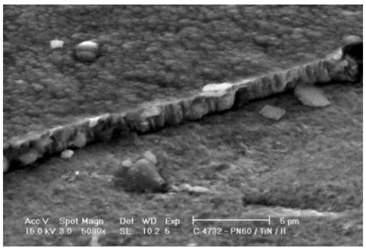

Figure 1. Surface morphologies of coating.

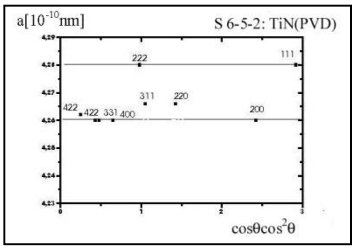

Figure 2. The Cohen-Wagner plot

Keywords: atomic force microscopy, crystal structure, residual stress

Acknowledgments: The authors would like to thank to The Scientific Council of Serbia supported this work by grant.

S2 L3

HIGH-PEAK POWER PASSIVELY Q-SWITCHED Nd:YAG/Cr^{4+}:YAG LASERS FOR SUCCESFUL IGNITION OF AN AUTOMOBILE ENGINE

Nicolaie PAVEL[1], Gabriela SALAMU[1], Oana Valeria GRIGORE[1], Mihai DINCA[2], Traian DASCALU[1], Niculae BOICEA[3], and Adrian BIRTAS[3]

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A promising solution for reduction of fuel consumption and decreasing the noxes exhausted by a car engine is the laser ignition [1, 2]. Extensive research has been done in the last years in order to realize a laser-spark device [3, 4]. However, due to various technical problems, related in principal to the realization of a laser with dimensions close to an electrical spark or to the installation of it on a real engine, such a task was very challenging. Therefore, only recently automobile engines were ignited by laser sparks [5, 6]. In this presentation we review our work performed for building a laser spark with small size and pulse characteristics suitable for engine ignition, and report successful ignition of a Renault automobile engine with a laser spark.

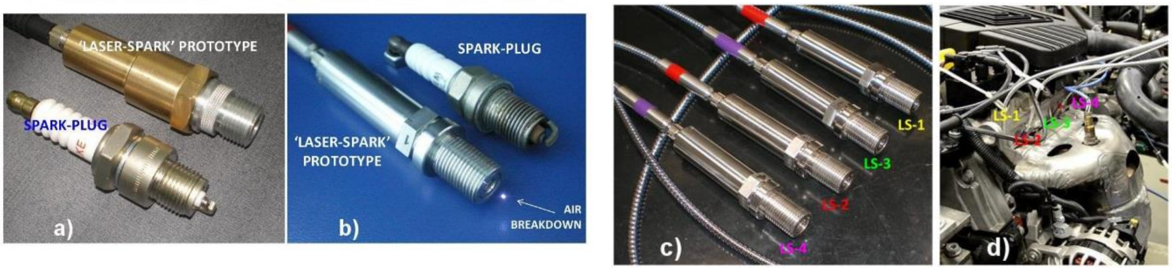

Fig. 1. a), **b)** Laser-spark prototypes developed in our laboratory. **c)** The four laser-sparks system and **d)** The Renault engine operated by laser sparks (LS).

The first laser-spark prototype built in our laboratory is shown in Fig. 1a. Ignition was performed with this device in a static combustion chamber filled with methane-air mixture gas. Through further design and improvements, a laser-spark tool similar to a classical spark plug was realized (Fig. 1b).

This laser delivered pulses with energy up to 4.0 mJ and 0.8-ns width; repetition rate could be increased up to 100 Hz. A sapphire window was used to transfer the laser beam into each engine cylinder. In the next step, an integrated system consisting of four laser sparks that was powered and controlled by computer was built (Fig. 1c). This laser-spark system was mounted on a test-bench K7M (1.6 MPI, gasoline) Renault car engine (Fig. 1d) and it was used to successfully ignite and run the engine. A better stability in terms of maximum pressure and a significant decrease of CO and HC were measured for various points of engine speed and load. Further experiments aim better characterization of engine performances under laser ignition.

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S2 L4

OPTIMISATION OF MECHANICAL PROPERTIES OF NANOLAMINATE COATINGS

Vilma BURŠÍKOVÁ[1], Jiří BURŠÍK[2], Pavel SOUČEK[1], Lukáš ZÁBRANSKÝ[1], Petr VAŠINA[1]

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Recently, there has been an increased interest in boron and carbon based films with X_2BC composition. Theoretical ab-initio models predict unusual combination of high stiffness and moderate ductility for these types of films when X=Ta, Mo or W. The aim of the present work was to prepare thin Mo_2BC films at different deposition temperatures using magnetron sputtering technique and to evaluate the dependence of their mechanical properties on the deposition parameters. The film structure and composition were studied using X-ray diffraction technique, XPS and Ruthefor Backscattered Spectroscopy combined with Elastic Recoil Detection Analysis. The microstructure of layers was studied using a Tescan LYRA 3XMU SEM×FIB scanning electron microscope (SEM), a Philips CM12 STEM transmission electron microscope (TEM) and a JEOL 2100F high resolution TEM. The quasistatic and dynamic nanoindentation response of the films was studied using wide range of testing conditions. The friction coefficient, sratch and wear resistance of the coatings were studied using nanoscratch and nanowear tests. The fracture toughness of the coatings was evaluated using nano and microindentation techniques. The modulus mapping capability was applied to obtain quantitative maps of the storage and loss stiffness and the storage and loss modulus. The modulus mapping combines the in-situ imaging capabilities with the ability to perform nanodynamic

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CA-5b.1 *(1477)* Mon 15:45

High repetition rate 1.34 um Nd:YVO_4 microchip laser Q-switched with GaInNAs SESAM — •J. Nikkinen, V.-M. Korpijärvi, I. Leino, A. Härkönen, and M. Guina — Optoelectronics Research Centre, Tampere University of Technology, Tampere, Finland

We demonstrate 1.34-um Nd:YVO_4 microchip laser Q-switched with a GaInNAs/GaAs-based SESAM. The laser produced 204 ps long pulses with 24 mW average power and 2.3 MHz repetition rate.

CA-5b.2 *(1614)* Mon 16:00

Automobile Engine Ignition by a Passively Q-switched Nd:YAG/Cr^{4+}:YAG Laser — •N. Pavel[1], T. Dascalu[1], M. Dinca[2], G. Salamu[1], N. Boicea[3], and A. Birtas[3] — [1]National Institute for Laser, Plasma and Radiation Physics, Solid-State Quantum Electronics Laboratory, Bucharest 077125, Romania — [2]University of Bucharest, Faculty of Physics, Bucharest 077125, Romania — [3]Renault Technologie Roumanie, North Gate Business Center, B-dul Pipera, Nr.2/III, Voluntari, Jud. Ilfov 077190, Romania

We report ignition of a Renault automobile engine using compact passively Q-switched Nd:YAG/Cr^{4+}:YAG lasers. Improved engine stability in terms of peak pressure was observed at low engine speeds and loads in comparison with classical-spark-plug ignition.

CA-5b.3 *(358)* Mon 16:15

Passive Q-switching and Self-Raman Conversion in Yb:KLu$(WO_4)_2$ Microchip Laser — •P. Loiko[1,2], J.M. Serres[2], X. Mateos[2], V. Jambunathan[2,3], K. Yumashev[1], V. Petrov[4], U. Griebner[4], M. Aguiló[2], and F. Díaz[2] — [1]Center for Optical Materials and Technologies, Belarusian National Technical University, Minsk, Belarus — [2]Física i Cristallografia de Materials i Nanomaterials (FiCMA-FiCNA), Universitat Rovira i Virgili (URV), Tarragona, Spain — [3]HiLASE Centre, Institute of Physics ASCR, Dolní Břežany, Czech Republic — [4]Max Born Institute for Nonlinear Optics and Short Pulse Spectroscopy, Berlin, Germany

Diode-pumped Yb:KLu$(WO_4)_2$ microchip laser Q-switched with Cr:YAG delivers an average output power of 1.51 W with 8 ns pulse duration. Self-Raman conversion is observed at 1151 nm with the average power of 119 mW.

Automobile Engine Ignition by a Passively Q-switched Nd:YAG/Cr^{4+}:YAG Laser

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Laser ignition has been regarded in the last years as a promising ignition technique for reduction of fuel consumption and exhaust gas emissions in automotive engine vehicles, with beneficial impact on the environment. The benefits of laser ignition were discussed [1,2] and extensive research was performed to develop a viable laser-ignition device [3]. Still, due to some technical problems laser ignition seems to be more suitable for stationary gas engines [4]; thus, the ignition of an automobile engine using a laser device with the dimensions close to a classic spark plug was realized quite recently [5]. In this work we report ignition of a Renault automobile engine using high-peak power, passively Q-switched Nd:YAG/Cr^{4+}:YAG laser devices.

The spark-plug like Nd:YAG/Cr^{4+}:YAG laser is shown in Fig. 1a. The device delivers pulses with energy up to 4 mJ and 0.8-ns duration, corresponding to a peak power of nearly 5 MW. In comparison with a previous scheme [6,7], the pump could be performed through fibers of 400 μm or 600 μm diameters and ceramic as well as single crystals were used as Nd:YAG/Cr^{4+}:YAG composite media; sapphire window (withstanding static pressure higher than 200 atm.) was employed to transfer the laser beam into the engine cylinder.

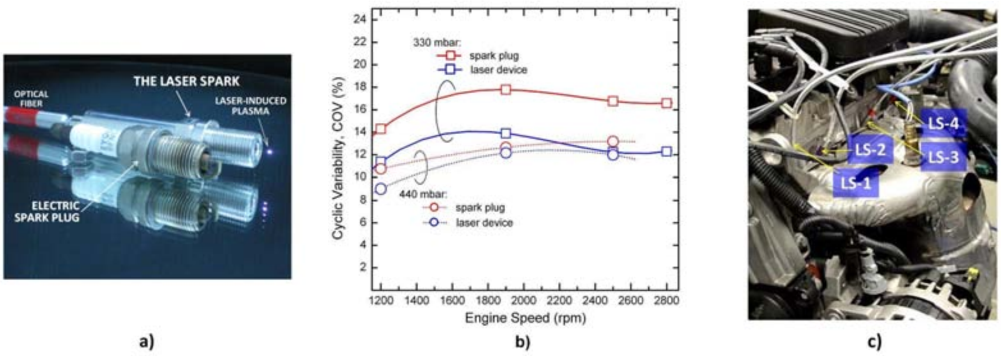

Fig. 1 a) The Nd:YAG/Cr^{4+}:YAG laser spark is presented. **b)** The COV variation is plotted function of the engine speed at 330 mbar and 440 mbar load. **c)** The Renault engine running with 4 (four) laser devices (LS-1, LS-2, LS-3 and LS-4) is shown.

For the first experiments a laser device was mounted on cylinder 4 of a K7M (1.6 MPI, gasoline) Renault engine that was placed on a test bench. An AVL GU-21D piezoelectric transducer was used to measure the in-cylinder pressure of 1000 consecutive cycles for various points of stabilized engine speed (from 1200 rpm to 2800 rpm) and light loads (330 mbar and 440 mbar). A better engine stability in terms of maximum pressure was observed. Thus, the coefficient of cycling variability (COV) was improved (it decreased by 27% for 2500 rpm speed and 330 mbar load), when the laser device was used in comparison with a spark plug (Fig. 1b).In a second experiment, the engine was equipped with laser sparks on all 4 cylinders (as shown in Fig. 1c) and it was successfully operated. Measurements of HC, CO, NOx and CO_2 specific emissions are under investigations and the results will be presented.

In summary, we report ignition of a Renault automobile engine by laser spark devices. The effect of laser ignition consists in improving the combustion stability by acting on the initial combustion stage. The COV coefficient can therefore be maintained in a convenient range at idling speeds smaller than normal. Thus, the fuel consumption and emissions might be decreased without influencing substantially the engine performances.

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