PHOTOINDUCED PROCESSES, RADIATION INTERACTION WITH MATERIAL AND DAMAGES – MATERIAL HARDNESS

by

***Milesa Ž. SREĆKOVIĆ* [1*], *Stanko M. OSTOJIĆ* [2], *Jelena T. ILIĆ* [3], *Zoran A. FIDANOVSKI* [4], *Sanja D. JEVTIĆ* [5], *Dragan M. KNEŽEVIĆ* [1], *and Marija D. OBRENOVIĆ* [1]**

[1] Faculty of Electrical Engineering, University of Belgrade, Belgrade, Serbia
[2] Faculty of Technology and Metallurgy, University of Belgrade, Belgrade, Serbia
[3] Faculty of Mechanical Engineering, University of Belgrade, Belgrade, Serbia
[4] RAF, Union University, Belgrade, Serbia
[5] Railway Technical School, University of Belgrade, Belgrade, Serbia

Scientific paper
DOI: 10.2298/NTRP1501023S

Photo and nuclear radiation induced processes are considered through the interaction of radiation with semiconducting, metallic and other materials, including the scintillator materials. The improvement of component efficiency by the use of quantum generators, trimming and hybrid processes with nuclear radiation has been analyzed. The studied processes can be positive or negative depending on application. Besides the experimental approach to the processes and chosen interactions, the analytical description of our experiments, as well as ones from other references, has been performed. The contemporary couplings between the nuclear physics, laser techniques and respective dosimetric aspects have been considered.

Key words: nuclear technology, laser, recording, damage, hardness

INTRODUCTION

Considering contemporary problems in power electronics, ecology, energy transformation, and power efficiency, radiation protections should occupy more important role. The current approach to the radiation protection was probably valid somehow isolated – separately, due to the gaps between different theoretical and engineering areas. The problems provoked by radiation, nuclear power, electrical phenomena, discharges, natural and artificial phenomena which were developed either in large laboratories or power plants cannot be treated separately. Today, at the level of theoretical scientific considerations, as well as in technology and metrology, a tremendous number of crossing areas exists, where the interaction of one type of radiation (or particles) uses the other types of radiation to modulate characteristics, or to perform some operations (cutting, annealing, efficiency increasing).

Particularly, the electron laser ion neutron (ELION) techniques are modern categories, where laser, ions, electrons, and neutrons are used directly in processing techniques and for modulation purposes (refraction index, resistivity, hardness, mechanical performances, *etc*.). The use of radiation in radiation protection monitoring and monitoring working regimes of power plants are always important topics. The laser role in fission, fusion, atom cooling, isotope selection, fiber laser, detectors and communications purposes, in real working processes (demonstrations or simulations) has many overlapping tasks.

The recording of existence and transmission of high power nuclear particles in polymer (plastic) materials, scintillator, *etc*. belong to a special area. Here we have the intention to analyze some problems from the analytical and experimental points of view. The modern techniques in diagnostics and high power application such as laser aided additive and subtractive manufacturing (LAASM), laser induced mass analysis (LIMA), ultra high peak power laser (UHPPL), and many other acronyms with W (where W could indicate weapons or waste for military or ecological applications in Space) demand the unified consideration of ELION techniques. The non-destructive techniques can be divided in two classes; the diagnostics by macro and micro levels. The scattering (elastic and inelastic), diffraction and interference effects are used in the diagnostic by macro-consideration. In micro-diagnostics, the methods of laser and Raman spectroscopy, ab-

* Corresponding author; e-mail: esreckov@etf.rs

sorption and calorimetric laser fluorescence analyses are defined. The lasing principle can be linked to nuclear radiation (pumping by nuclear particles and radiation: neutrons, ions, pre-ionised processes, *etc*.).

In the interactions with living creatures it is of special importance to search and find the minimum threshold for defined radiation. In addition, a special attention is paid to lasing processes in preservation, cleaning and diagnostics of cultural artifacts, though ELION applications in heritage science also exist. It is important to find the advantages and disadvantages of different radiation types, interactions of laser and γ radiation processes with wood material and food (destroying microorganisms). The radiative processes in nuclear physics, general performances of nuclear reactions, coupled with signal processing and nuclear electronics, contain very strong criteria *vs*. new evaluation of measuring uncertainties.

Photo-induced processes in materials can be explained by three types of responses: photo-transfer of charged particles, phase-changes, and selective electron-phonon centre transformations. The first is associated with photo-chromic responses in ionic crystals and organic compounds as well as photo-refraction processes in electro-optical crystals. In halogen glass semiconductors, the photo-transfer is present in responses to intensities lower than 100 W/cm^2. At higher intensities, photo-thermal processes appear. The transition from photo-transfer to photo-thermal processes starts even at ~1 W/cm^2 [1]. The radiation and photo-induced processes were described by similar theoretical methods [2, 3].

Radiation defects and effects have to be included as the area of special attention. From the point of view of recording and information processing, a number of applications uses light, other forms of radiation, and particles (nuclear and electromagnetic). Referring to photons in UV-VIS-IR ranges, the role of quantum generators is increasing. Processes are complementary, so new techniques are being developed in the area of solid-state and nuclear physics, and optoelectronics (electron beams, ion implantation, laser annealing). This attitude could broaden ELION techniques, where plasma could also be included. In technological processes and information recording, the phase transitions from amorphous to crystal state and *vice versa* are achieved by using radiation, fig. 1 [3].

The material amorphization is generally important, with special role in semiconductor technology and opto- and micro-electronics. A lot of implemented work results are in the need for further fundamental research in areas such as phase transformations by laser beams, where a great instability of crystal-amorphous state transitions has been noted. Some indications of local amorphization have been observed in the study of pulse laser interactions with ferrites. The induced phase transitions possess a photo-thermal character and breaking of molecular bonds. Despite many issues

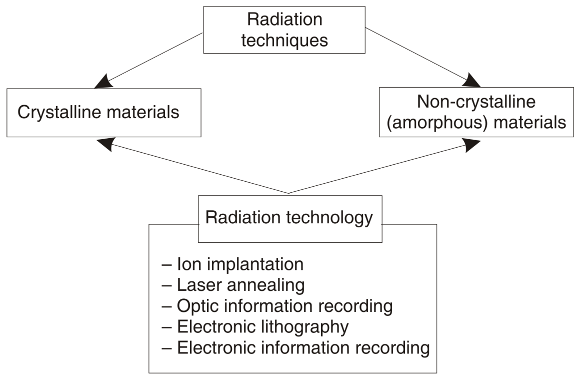

Figure 1. Phase crystal – amorphous transition

in experimental and theoretical studies, unanswered questions still exist and deserve further work. Photo-thermal records are the most studied in the references concerning halogen materials and semiconductor lasers. It can be linked to nuclear processes, trace detectors and respective mechanisms. A selective laser excitation often leads to the center transition to metastable or ionized states. These processes can exceed the diffraction limit of optical records.

All this belong to the couplings between nuclear and optical radiation implemented in order to change material performances for theoretical and application purposes [4-6]. Therefore, terms like damage of component, memory, optical record, trimming process, detector sensitivity, and emission efficiency for lasing processes could be treated as specific case that is of common interest [7-10]. Here, we have analyzed the chosen group of problems:

– diffraction efficiency,
– contrast by recording processes,
– laser interaction with scintillator material – the elements for establishing the relationship between the laser energy and the amount of ejected material,
– laser trimming, and
– interaction with metallic material (which are often used as substrates in various applications).

Some of the mentioned problems were performed through our (or from references) experimental work and we created analytics. We have also shown some damages made by laser beams.

The well-known modeling through thermal models cannot be performed to all possible processes provoked by laser material interaction, and many empirical models of limited values still exist. They and the presentation of experimental data through recognized mathematical functions could be of interest, for prognosis of the effects of photo induced processes. Note that by treating of optical constants, many efforts are united to cover all electromagnetic spectrum. It is well known that a low reflectance for γ radiation, does not make the possibility of γ-raser in the regime which is not progressive.

Belonging to different areas of research, the authors tried to consider the areas of both laser and nuclear techniques from different sides. The link between the research of interaction in visible and gamma (including particles) ranges is the material – for recording in holography and for scintillators (detectors in nuclear physics, but same type of materials could be active materials). On the other hand, the materials frequently used in optics serve in nuclear detectors for high energies. In this work, the purpose was to continue activities of some authors and further to process experimental data on ejected mass during the interaction, and to compare the damages made by laser beams of similar energies in different types of materials.

MATERIALS AND METHODS

Some analysis, calculations and dependencies based on references

For chosen experimental results, we made a theoretical study of the obtained results from our experiments and other authors. We searched for characteristic analytical functions by using the appropriate numerical approaches. Therefore the interpolations in more general sense could be obtained and for some cases we made it.

Some relations for optical recording and analytic treatment

The optical recording, as large area of investigation, deals with many materials. The holographic records due to different laser beams (for recording and reconstruction) deserve further analyses and tasks for solving. The recording is performed by continuous wave (CW) as well as by shorter laser pulses (ps, ultrafast holography). What will be with atto and zepto photons in visible, X (or γ) ranges and recording, rests in the future.

We have analyzed the parameters of photoinduced reactions in organic compounds for holographic recordings *i. e.*, the chosen material was alphabiketone and camphorquinone. The parameters of recording in solid solution of camphorquinone and polyacrilate obtained by Ar^+:ion laser (514.5 nm and 488 nm) were studied experimentally [11]. The changes in refraction index n present the basic results, which are analyzed and measured by interference and holographic methods. The diffraction efficiency of recording depending on the performed methods is expressed through various final analytic formulas (tab.1). The changes of n were obtained by the saturation processes at laser beam exposition 800-1000 J/cm^2. The change Δn_{max} depends on camphorquinone concentration and increases with temperature of photo-induced reaction. It was obtained $\Delta n_{max} = 5\cdot10^{-4}$ for 328 K. The increasing Δn is used for light sensitivity improvement of recording material (the development of records, the increase of Δn and η), tab.1 [1].

The holograms with phase transmission and reflection in 2-D and 3-D were also analyzed versus the diffraction efficiency. The Bessel, modified Bessel and Hänkel functions of the first and second kind, spherical Bessel and Hankel functions, as well as Riccati-Bessel functions have to be implemented in analytical studies.

They were performed in order to obtain the dependence of diffraction efficiency by various laser expositions. Using them, we depicted the dependences for solid solutions of camphorquinone *vs.* exposition and sensitivity by increasing recording temperature (it can increase more than 1000 times). The analytical expression could be of interest to obtain a generalized function for processes. On the bases of them, the shape of generalized behavior *vs.* expositions (parameters like pulse energy, solution concentrations, cw power density, replacing of laser wavelength), the spreading and shifts can be foreseen for new parameters.

Table 1. Diffraction efficiency η on sinusoidal holograms

Holograms	η_{max} (calculation)	η_{max} (experiment)	Formula
Amplitude 2-D transmission	6.25	6.0	$\eta \quad \frac{\beta^2 m^2}{4} \quad \eta_{max}, m \quad 1, \beta \quad \frac{1}{2}$
3-D transmission	3.7	3.0	$\eta \quad \exp \frac{2\kappa_0 d}{\cos\theta} \; sh \; \frac{\kappa_A d}{2\cos\theta}$ η_{max} by $\frac{\kappa_A d}{2\cos\theta} \quad \ln 3, \kappa_A \quad \kappa_0$
3-D reflection	7.2	3.8	$\eta \quad \frac{\kappa_A}{2\kappa_0 \quad \sqrt{4\kappa_0^2 \quad \kappa_A^2}\, cth \frac{d}{2\cos\theta} \sqrt{4\kappa_0^2 \quad \kappa_A^2}}$ η_{max} by $\theta \quad \frac{\pi}{2}, \kappa_A \quad \kappa_0$

Designation: η – diffraction efficiency, β – amplitude transparency, the transmitted/incident amplitudes, m – coefficient of the modulation, κ_A – modulation of absorption, κ_0 – mean coefficient of absorption after exposition, d – thickness of photorecording material, θ – incident angle

The scintillators of inorganic compounds VIII-I groups are exposed to Nd^{3+}: YAG as well as to CO_2, lasers with the pulse energies: 100 mJ, 350 mJ, and 700 mJ for the first and 50 W for the second one. The scintillators were used for many years in detections of ^{60}Co, ^{13}Cs, ^{192}Ir, ^{54}Mn, and ^{32}P, where γ rays were from 0.661 MeV to 1.33 MeV. The cumulative nature of the processes is still of interest in various power ranges. For this purpose, we repeated 10-45 pulses starting with single expositions. The damages are analyzed by vertical profiling, light and SEM microscopes [12]. We used pulsed Nd^{3+}:YAG laser (1 J-10 J), with 2-7 ms pulses and in *Q*-switch regime with 8 ns pulses.

RESULTS AND DISCUSSION

Modeling of experimental curves

The results of our modeling of experimental curves from references are presented in figs. 2(a-d) for various concentrations and in figs. 3(a-c) after thermal developing. The fitting was made after using program Digitizer to obtain starting points from experimental data. All fitted curves are followed by the criteria of the least squares methods and appropriate fitting is presented.

Modeling of processes for materials for irreversible records and analytical analyses

The other chosen analyses concerning optical recording by laser processes could be performed for: material choice, protective thin coatings, transparent layers, fast evaporation layers, inter layers for hardness improvement of multilayer systems, layers with barriers, processes for discrete recording in Te-based materials and alloys on various thin films, F-centers, polymers for discrete records, thermo-optical record in gelatine with dispersed metal and records with bub-

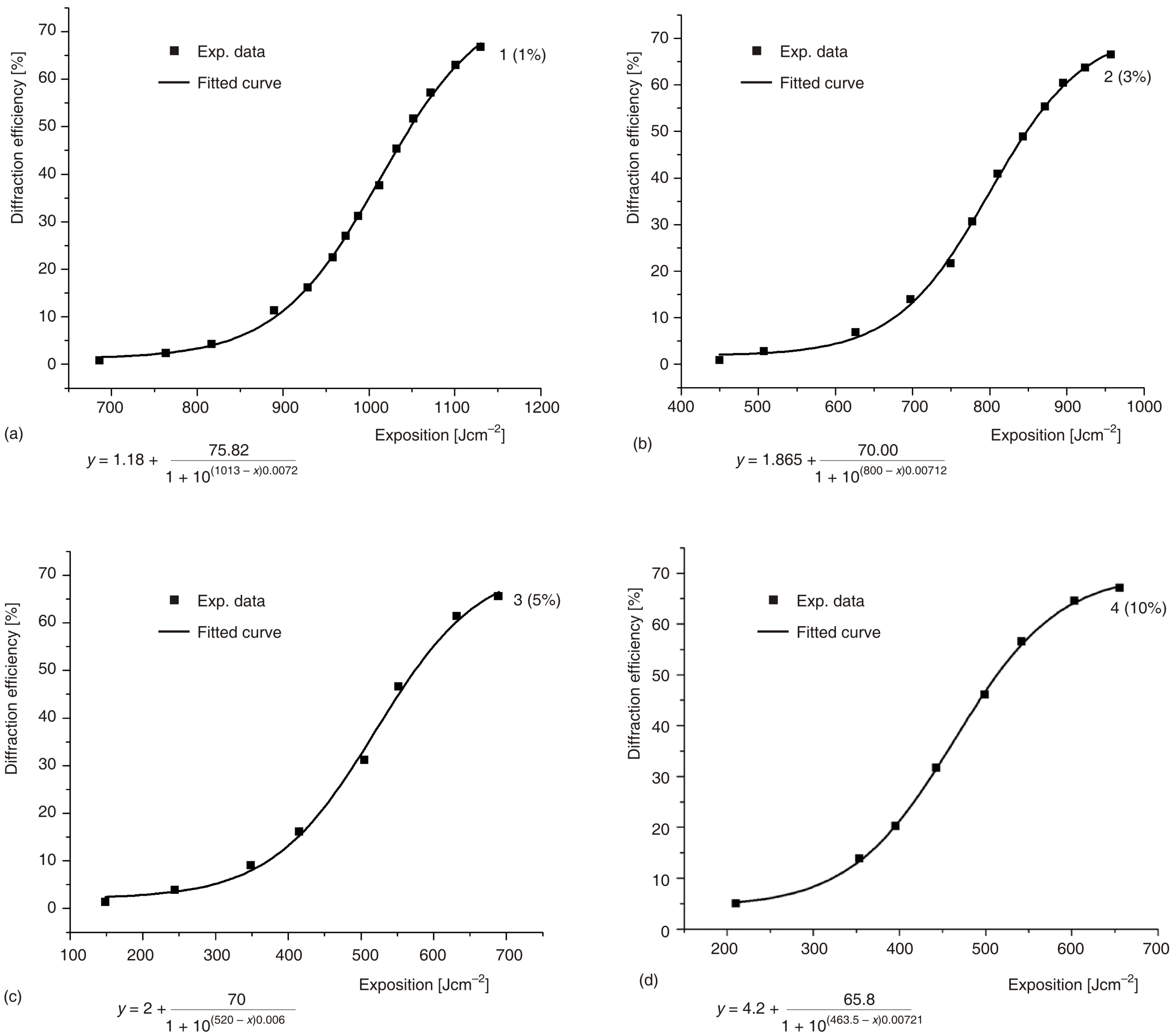

Figure 2. The fitted diffraction efficiency for solid solution of camphorquinone in polyacrilate for various concentrations

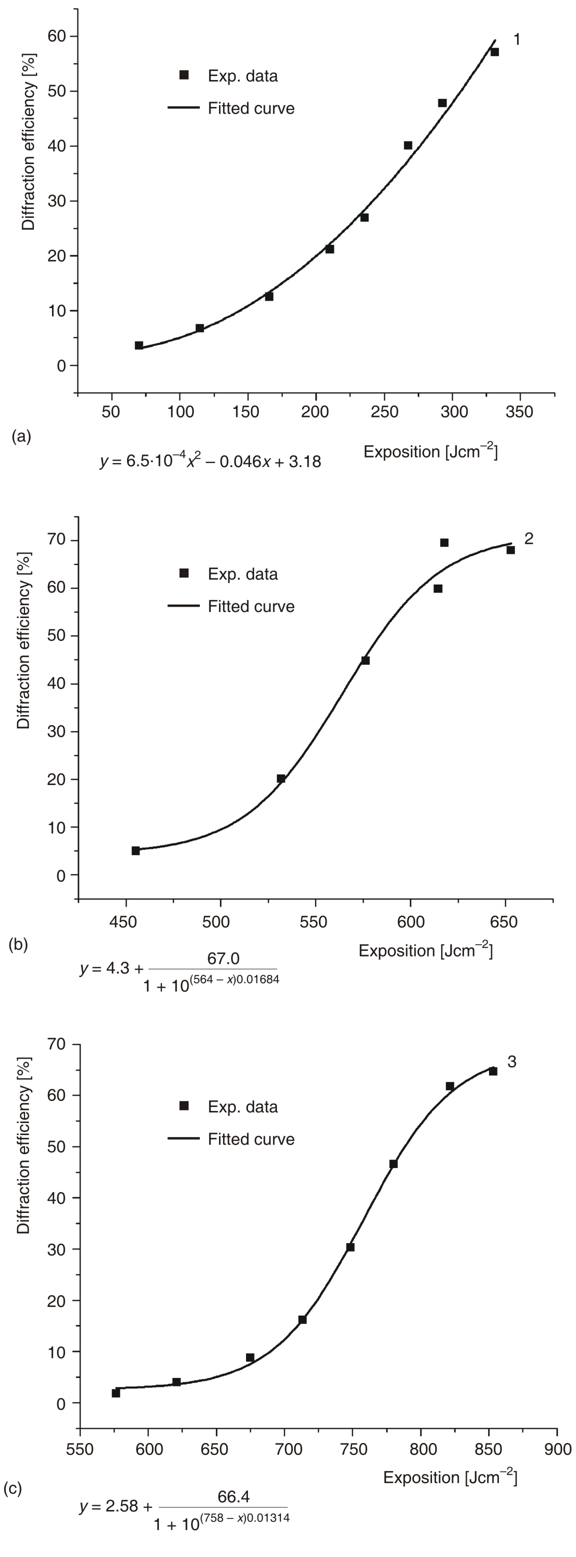

Figure 3. The dependence of experimental diffraction efficiency for solid solutions of camphorquinone in polyacrilate after thermal developing for: (a) T = 340 K by exposition intensity of laser beam 0.002 W/cm^2, (b) T = 313 K by 0.27 W/cm^2, (c) T = 296 K by 0.27 W/cm^2

bles, *etc*. We will analyze the role of protecting layers [1]. The selected references have presented a great number of parameters, as well as broad vision of recording processes and in our opinion, they could be a starting point for further analysis. The photo-induced processes are important for holographic records, too, as it is the case of solid organic solutions in benzoate saharose $(C_6H_5CO)_2O$. Some facts are that the records could be deleted after 3 days-3 weeks, and the diffraction efficiency could be lowered down to 35%; the other records are long-stored, they are stable in normal (room) temperatures.

For decreasing reflections losses, the interference processes are used for compensations. The multilayer systems have: substrate (glass, polymethilmetacrilate – PMMA), photo-sensitive-, transparent-, reflective-, fast evaporated-, complementary for increasing hardness and diffusion (barriers) and, protective layers. Optimum data for 632.8 nm are n = 1.5 and $d = \lambda/4n$ = 10 nm. Starting from the reference [1] , for contrast coefficient *vs*. laser irradiations we made analytical study. The selected data were taken by adequate digitizer and fitted by appropriate numerical procedures. The fitted curves are presented in figs. 4(a-d), as well as the mathematical functions.

The dependences of optical thin films thickness and performances depending on grain size

Considering the experimental results [4, 5] we modeled the dependences, the function shape and maximum`s shifts. Various physical constants for material depend on the thickness of the sample and especially the constants are different for bulk and thin films. We fitted the experimental data for thin films *vs*. grain sizes and results are presented in figs. 5(a-e).

Scintillator materials in the field of nuclear detection and lasing materials

The scintillators have had for a long time various roles in the field of nuclear detections in large power ranges for single particles or high fluxes. Their application in detectors with photo-processes is defined by technical demands of devices. The sensitivity is dependent on maximal anode current and voltage of photomultiplier as well as on a sensitivity threshold (which depends on dark current), secondary emission from dynodes, *etc*. They have a special role in low intensity fluorescence measurement. Some experiments with irradiation of scintillator materials, nuclear detectors and solar cells were performed where exposition to laser beam improves scintillation efficiency. The best known old scintillators were made of inorganic material (I-VII compounds activated with heavy ions). The activations with some light elements were made, too. They affected the rise-time of the signals and it was of interest for pulse shape discrimination tech-

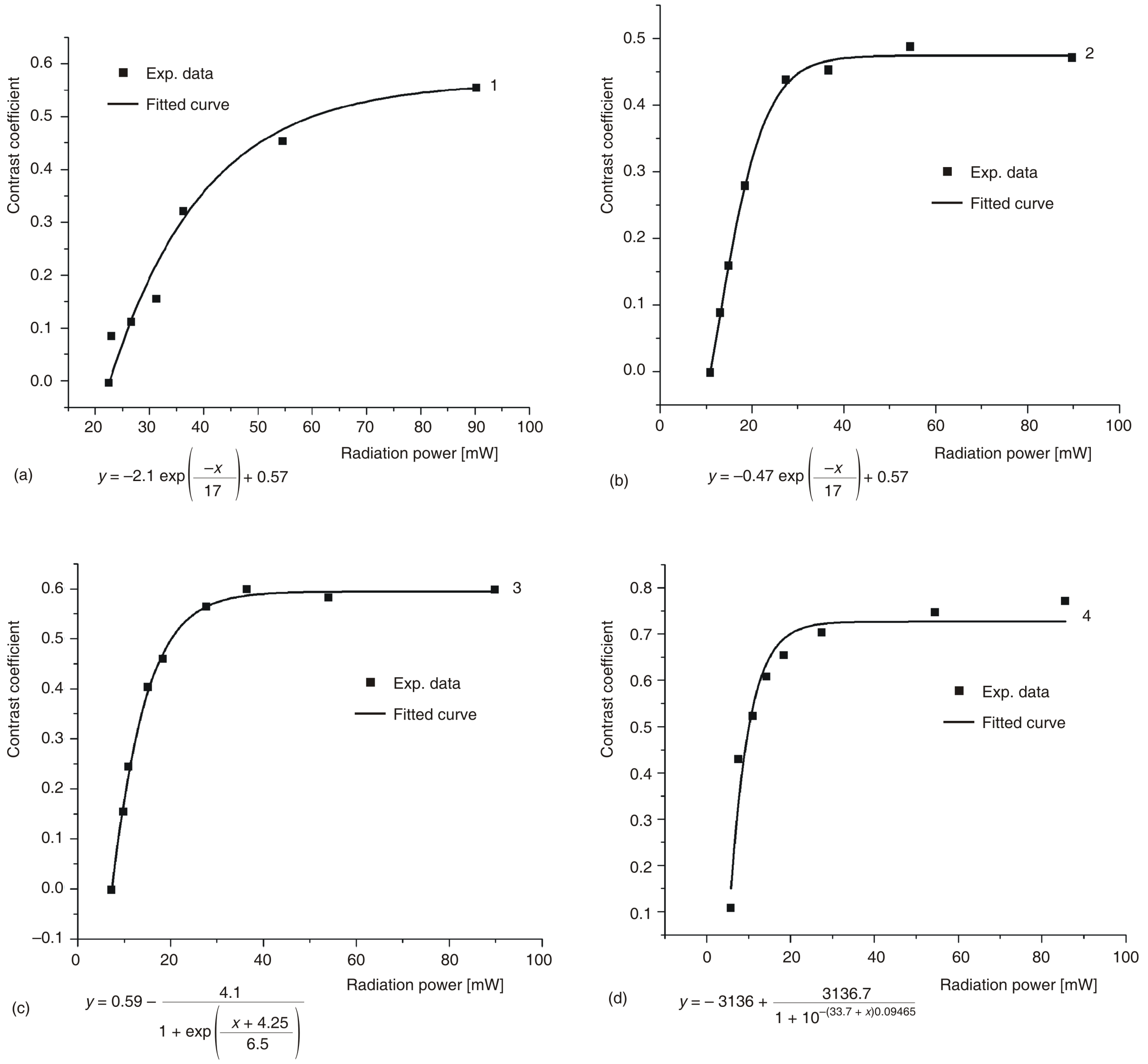

Figure 4. Coefficients of contrast *vs*. laser radiation for Te films, 30 nm thickness on the substrate of PMMA by various thicknesses of protective coatings based on SiO_2; (a) 1 nm-500 nm, (b) 2 nm-100 nm, (c) 3 nm-30 nm, and (d) 4-without coating, fitted curves, and experimental data from [1]

nique – PSD [13]. The role of PSD developed for the discrimination of nuclear radiation and particles could be expanded for optical phenomena, and especially when strong lasers interact with the material (induced gamma, neutron, proton beams).

The other scintillators on the front side of photocathode (pasted using a material with matched refraction index) are organic materials, polymers, *etc*. Some of them could be of interest as lasing materials, too. The application of fiber in detection of nuclear processes is also very successful [6, 14-17]. Those applications in medicine and power engineering are widely performed. From the ecological point of view, new detectors with improved sensitivity and efficiency are required.

The PMMA materials, as well known materials with additives, have today a new field of application. They intensively fluoresce when exposed to electrons or γ-ray beams. Different materials as PMMA dopants are of interest for waveguides (the fibers which, besides basic functions in signal transmission, have applications in optical powering of sensor, in optical computing, *etc.*) [18]. Besides the all optical computer concept there are couplings between the lasers and nuclear irradiations and components efficiency improvement [7-10]. Working environments are a matter of investigation in many sciences. Neutrons, α, β, γ, and electron irradiations of lasing and other materials are changing optical or mechanical characteristics [19, 20]. It holds for many devices and components linked to the energy conversion for lasers, solar cells, laser motors, and detectors in Earth and Space investigations [15, 21]. In Space investigations many radiations mix and their influence deserve attention. The hardness in general term and possible fluorescent processes are important for lidar (light or laser detection

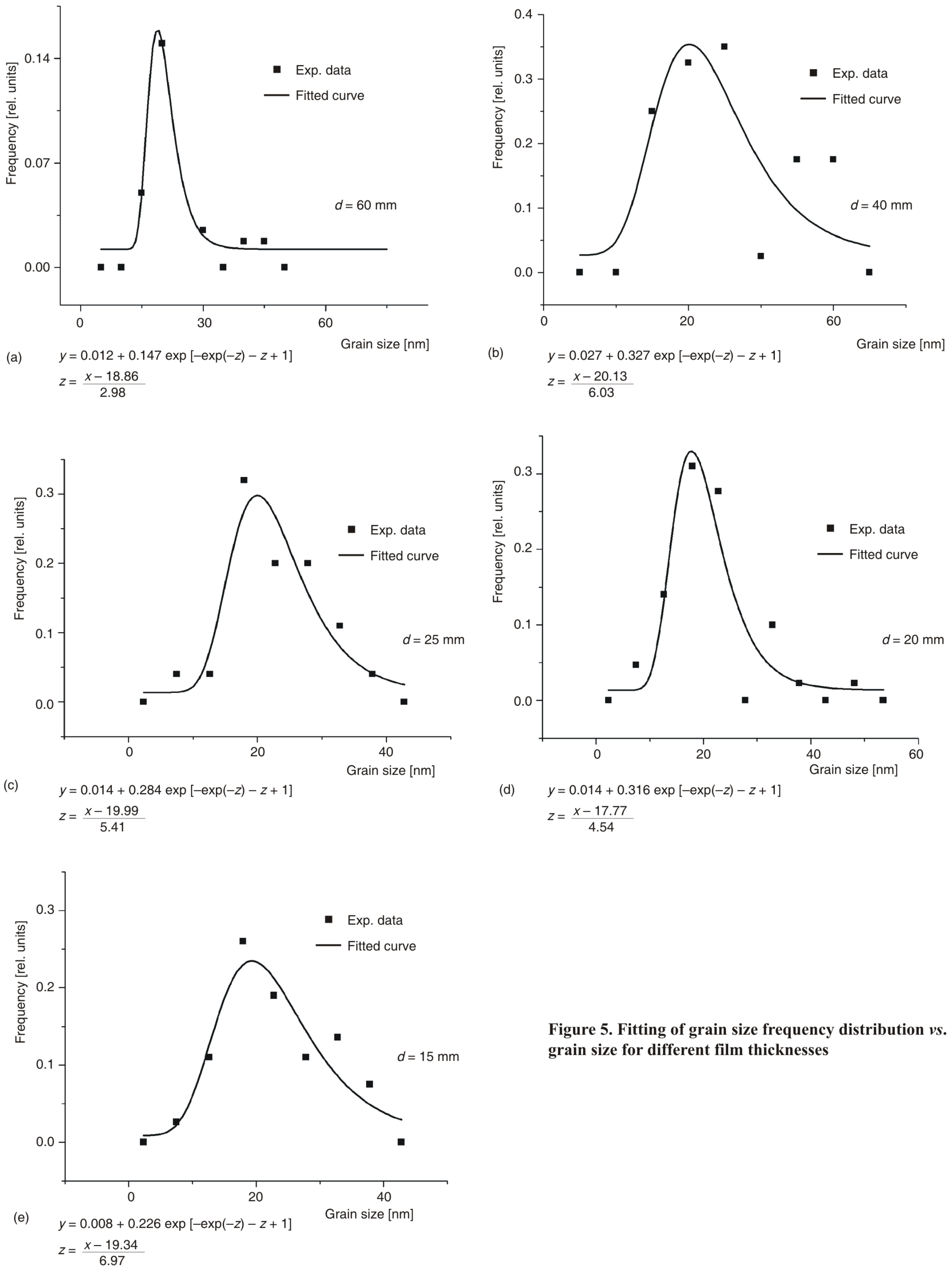

Figure 5. Fitting of grain size frequency distribution *vs.* grain size for different film thicknesses

and ranging) methods: more generally as the elion hardness. Laser beams provoke many processes but, the damages and the threshold represent useful data. Some damages analyzed here could be of interest in the area of scintillators which were in working conditions of nuclear detections, modern detection material and laser processing of scintillators and nuclear fuels.

Based on the data of crater profiling [12] using appropriate software packages, crater shapes in fig. 6, are obtained. The fittings are performed by using Digitizer (software). Some of the characteristic crater shapes could be fitted by appropriate mathematical functions as we have done. It is of interest for further comparisons and correlations. The analytical forms

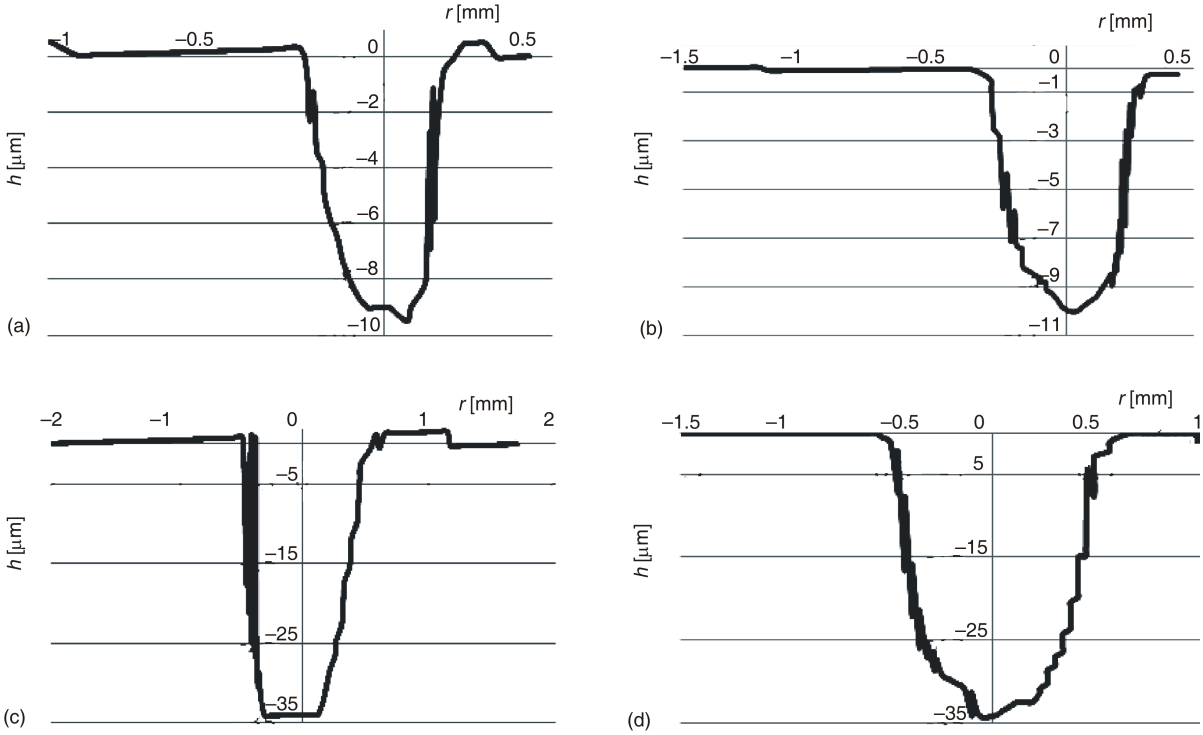

Figure 6. Craters provoked by laser beams of energies from tab. 2. Figure (a) and (b) correspond to the same damage but in two chosen perpendicular cross-sections, as well as (c) and (d). ***z*** **axis represents depth of craters (h). (a) and (b) are provoked by 15 100 mJ and (c) and (d) by 45 100 mJ**

give the possibility to obtain the volume of the ejected material, tab. 2, *vs*. incident energy. It could be the basis for relations between the d*E*/d*x* or the d*E*/d*m*.

The scintillator Ne 102 was broken during the exposition to cw CO_2 laser beams (50 W). The polycarbonates (plastics) which can be the substitutions for optical component were exposed to the laser, too. Powder materials (placed on top of disk-like samples) exposed to ruby laser in the range of 1-4 J are imprinted in. This can be of interest for one of coating methods. The results could be compared to lasing materials and generally optical transparent materials.

Laser induced dielectric breakdown threshold-LIDT experiments and calculations are often dispersive. We studied laser damages of various materials and lasers CO_2, Nd^{3+}:YAG, ruby, alexandrite, *etc*. PMMA elements (plates), and other plastic materials, cut by CO_2 lasers, have smooth surface.

The model of disintegration of material and laser processing

Contemporary models of disintegration of material in the area of laser interactions in various working regimes are considered. The technology requires multipurpose usage of laser beams. It is necessary to model provoked processes, to optimize: the beam parameters, optical systems and material itself. All models, besides analytical, include the empirical approach, too, involving both statistical and numerical approaches [22-26].

Thermal disintegration theory describes the interaction by conduction and evaporation processes and defined conditions of simplification of the problems. The questions of the transition time, the relationships of propagation front with sound velocity, the choice of co-ordinate system are coupled to acoustical

Table 2. Nd^{3+}:YAG laser damages, crater diameters, depths and evaluated volume V_e of ejected basic material for some sample damages

	Pulse energy [mJ]	Pulse number	Total energy [mJ]	Crater diameter [μm]	Crater depth [μm]	Evaluated V_e [mm^3]
1	100	1-15	100/1500	0.5, 0.65	9, 10	$1.23\ 10^{-3}$
2	100	45	4500	0.9	34	$10.8\ 10^{-3}$
3	350	1 + 9 = 10	3500	1.5 (non Gaussian)	12	
4	700	10	7000	2.25, 2.25	12, 13	

properties of material and crystal lattice. The transcendental equations are frequent solutions. The laser interaction could serve as a test of material loading or hardness [27]. The optimum interactions are also of interest for specific laser types. The interaction of the laser beam (working regime, power density) and the materials depends on the surface state but not for high intensity. If the phase transformations are obtained or, if the non-linear processes start, more complex systems must be used (in trimming, welding, cutting, *etc.*). A particular significance lies in security aspects which could give an advantage to a specific laser technique emphasizing the need to study the existing doses. The final formulas are not so valuable, their derivations and approximations are not discussed. They could serve as the first approximation if the history of the material is not well known and the limits of formulas applicability are not estimated.

Trimming aspects

Theoretical and commercial aspects of laser interactions with solid materials are always a topic, especially in microelectronics industry. We also investigated the details of analyses of obtained damages, *i. e.*, the trimming processes. Besides the integrated circuits, there are still macroscopic components in industry, electronics, microelectronics and mass media applications (resistance, capacitor, and inductive components). Laser applications in trimming processes have evolved through years including commercial devices for larger or more specific purposes (trimming of micro-motors - rotors, as well as printed circuits, *etc.*). Laser beams are used to eject the desired quantity of material. The characteristic forms are circular holes, or lines, depending on the desired resistance or breaking the connections formed through technological processes [28-30].

Some characteristics of laser damages are presented in fig. 7. The lengths of performed damages in the resistance material were 0.5 mm-1 mm. The thickness of the ejected material on the crater (0.5 mm diameter) edges was 0.004 mm. The tolerance after trimming processes was 10%; for 1% tolerance, so a better control has to be done. The resistance values of metal-strip resistors before and after laser beam exposition (9 J) varied from 0.53% to 1.8%. For damages obtained by the Nd^{3+}:YAG laser irradiation, crater diameters and depths are graphically presented in fig. 7.

Thick film resistors

Trimming was performed in straight lines – *I* and *L* cuts. The length varied 0.5 mm-1 mm. The thickness of rejected material is in the zone 0.004 mm on both sides (the width of the kerf 0.002 mm-0.004 mm. Note that the scanning and power parameters have to

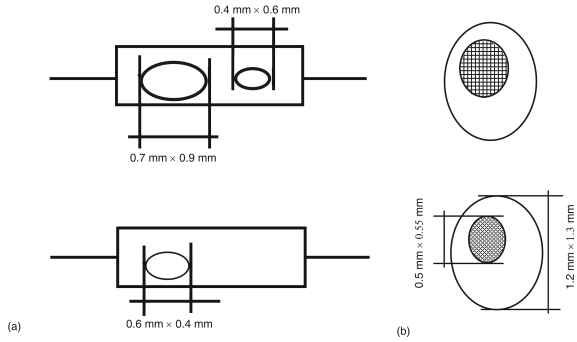

Figure 7. Characteristical details of trimming process (shape of damages); (a) resistors and (b) damage on high purity Al (the shape of concentric circle) front side (upper) and rear side (down); pulse energy 9 J

be optimized. The appearance of the boundary HAZ (heat affected zone) is similar to the material which was softened to melting. The HAZ directly affects the tolerance range and the temperature resistance coefficient. It is advisable to have a spot size of 5 μm so that the tolerance of higher trimming harmonics is 10%. As it is mentioned before, for the tolerances of 1%, resistance must be monitored. The typical problem is post-trim drift, and it should also be taken into account. By choosing the appropriate model for predicting of the processes, thermal imaging recording devices should be very useful as well as acousto-optic recording by irradiations. Trimming effects should be guided by introducing adequate models for crater depth control.

This approach we have performed for other materials and laser types. These techniques were used in various applications concerning medical therapy with nuclear radiation, diagnosis, but also in electrical circuits for hot points recovering. In many energy and environmental problems metals, PMMA, lasers, elion techniques, fibers, scintillators, could be useful [31]. The calculations have been made for the width and the depth of the crater for a range of energies and powers. The experiment shows a good agreement with the calculations for the diameter but not for the depth. The surface resembles to the mercury drops. It seems that the material is evaporated (sublimated).

Laser interaction with steel based samples and thin films

The micro-alloyed low carbon samples and other steel samples are exposed to various laser beam energy densities in visible and IR spectral portion in ns and ms regimes. They were various thermally processed and cold plastic deformed. The damages were analyzed by light microscope, SEM, IR spectroscopy, and mechanical testing. The damage diameter *vs.* the incident beam energy has been analyzed and the appropriate approximations with various polynomials (interpolation with second and third order) were performed. The main use of these materials is in electronics and mechanics and demands defining the thermo-mechanical processes as well as the technology of joining and separating, in order to maximize the preservation of material's magnetic characteristics (transformers) [30]. The interaction is connected to multiple problems (surface transformation, welding, indentation) through appropriate models. Laser and elion techniques have been applied to a variety of complex alloys, non-ferrous metals and micro-alloyed steels. In order to determine the effectiveness of laser usage in the metal treatment and damages at the microscopic level, the samples based on the steel were tested with several lasers. Between them were the Nd^{3+}: YAG, Q switch, with pulse energy 35 mJ (15 ns) in multi pulse regime and the Nd^{3+}:YAG, top hat, λ =1064 nm, 2 pulses of duration 2 ms, E_{tot} J t 10 J, beam diameter 2 mm , also [30]. The plasma screening is spotted for all laser beam energies higher than 4 J.

The provoked laser damages were divided into three groups. The cylindrical surface of the sample influenced the damage shape. Depending on the sample shapes (cylindric or flat) sharp edges, or only partially damaged surface had been found, fig. 8. The color of samples was changed from gray to dark gray. Clear grey contours were expressed while the central part of the damages was dark grey (almost black). The third group of weakest damages had the most irregular shape. The modular structure can be seen through the damages. In the damages without the sharp edges only partially dispersed droplets of melted and solidified materials of circular shape have been noticed. The IR spectra (fig. 9) could be useful for evaluation of reflection losses for basic material.

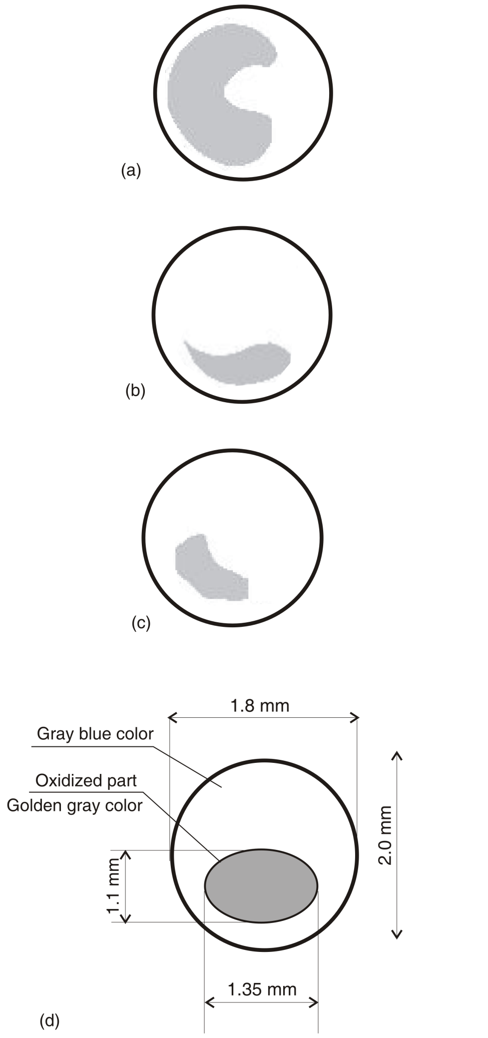

Figure 8. Microalloyed steel sample in the cylindric form with damages (a-d)

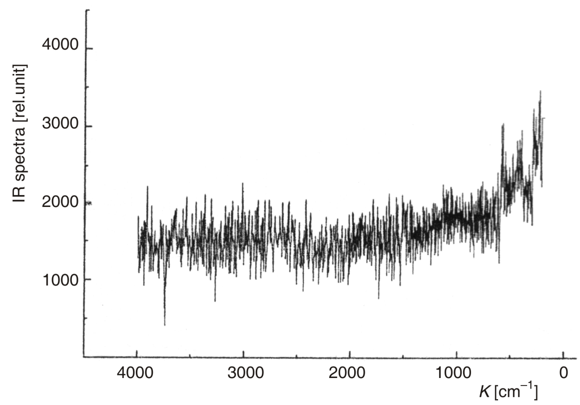

Figure 9. IR spectra of basic steel material

CONCLUSIONS

The laser processing (working conditions) in scintillator depends on the basic material type (organic, inorganic), and it is, in general, in correlation with the known data from commercial applications. The laser power, stability of polarizations, frequency, gas (inert, protective, auxiliary), jet type, lens focusing diameter and position, have to be monitored in order to obtain the smooth surfaces and regular damages. Comparing laser technique with other elion techniques show that previous does not require vacuum.

In the whole studding of laser processing methods; particularly in trimming methods, the conclusion is that the experiments and efforts should be continued to match the theoretical models and issues. Laser treatments of material coatings should be studied a bit differently. Coating treatment models on the other hand should broaden their perspective focusing on the width of the spot damages. If samples are used in areas were energy efficiency is of vital importance, a precise removing of coating could in dielectric areas lead to different electric field profiles (creating specific local fields).

The samples of micro-alloyed steel treated by laser beams of different wavelengths and power have shown various effects on different samples and the relationship is studied of obtained damage sizes versus energy. The plasma screening appeared by expositions of metals.

The damaged places and the pulse energy show that the saturation processes were present. The materials chosen for the photo-recordings served for establishing a theoretical-practical liaisons with the aim to reveal the mathematical expressions of the parameters change used for recordings (laser power, pulse energy, *etc*.). Since we have started from mathematically similar curves the work done might contribute to revealing the curve families corresponding to parameters change adequate for recordings on a given sample.

Some conclusions which follow from the fitting processes and chosen mathematical functions are:

Mathematical model presented in this paper proves the increase of diffraction efficiency with the increase of concentration of camphorquinone in polyacrilate, which had been shown experimentally. Through analytical formulation, we have found that there are indications that the value of exposition at inflection point as a function of concentration in solution is close to a parabolic function.

The experimental data was fitted with different mathematical functions for mentioned solid solutions after thermal developing. The height of the plateau rises with the increase of temperature as well as with the exposition density.

When the thickness of protection layer is greater than certain value, the dependences of the contrast coefficient *vs*. radiation power are explained by the same shape of mathematical functions, whereas for the thicknesses lower than that value, the mentioned dependence is explained by another shape of mathematical function.

Considering the grain sizes and optical film thicknesses, the same function is applied for fitting. For small and big grain sizes the functions tend to constant values.

ACKNOWLEDGEMENTS

The research in present paper is supported by the Ministry of Culture and Media of the Republic of Serbia project number 633-00-373 and the Ministry of Education, Science and Technological Development of the Republic of Serbia, project numbers: II45003, and TP 35046.

AUTHORS CONTRIBUTIONS

The theoretical analysis was carried out by M. Ž. Srećković, S. M. Ostojić, and J. T. Ilić; the experiments were carried out by M. Ž. Srećković, Z. A. Fidanovski, D. M. Knežević, and M. D. Obrenović. All authors analyzed and discussed the results. The manuscript was written by M. Ž. Srećković, S. D. Jevtić, and J. T. Ilić and the figures were prepared by S. M. Ostojić, Z. A. Fidanovski, S. D. Jevtić, and J. T. Ilić; Z. A. Fidanovski was responsible for the software packages.

REFERENCES

[1] Shvarts, K. K., *Physics of Optical Recording in Dielectrics and Semiconductors* (in Russian), Zinatie, Riga, 1986

[2] Shvarts, K. K., Radiation Damage in Crystalline and Amorphous Dielectrics, *Radiat. Eff., 74* (1983), 1, pp. 77-85

[3] Nosov, Yu., Tendency of Development of Optoelectronics Processing of the Delivering and Imaging of Information, *Zarubež. Electron., 9* (1984), 121, pp. 3-41

[4] Srećković, M., *et al*., Optical and Radiation Resistance of Some Optical Components and Fibers and Interactions with Some Laser Beams, *Proceedings*, Lasers 2001, Intern. Conference on Lasers, Tucson, Ariz., USA, December 3-7, 2002, pp. 367-372

[5] Srećković, M., *et al*., The Analysis of the Relation of Optical and Nonoptical Constants Applied to Materials of Interest in Quantum Electronics, *Proceedings*, Lasers 2001, Intern. Conference on Lasers, Tucson, Ariz., USA, 3-7 December, 2002, pp. 217-225

[6] ***, *Coherent Light* (Ed. A. F. Harvey), Wiley Intersc., London, 1970

[7] Timotijević, Lj., Vujisić, M., Stanković, K., Simulation of Radiation Effects in Ultra-Thin Insulating Layers, *Nucl Technol Radiat, 28* (2013), 3, pp. 308-315

[8] Nikolić, D., *et al*., Improvement Possibilities of the I-V Characteristics of Pin Photodiodes Damaged by Gamma Irradiation, *Nucl Technol Radiat, 28* (2013), 1, pp. 1-107

[9] Lazarević, Dj., *et al.*, Radiation Hardness of Indium Oxide Films in the Cooper-Pair Insulator State, *Nucl Technol Radiat, 27* (2012), 1, pp. 40-43

[10] Dolićanin, E., Gamma Ray Effects on Flash Memory Cell Arrays, *Nucl Technol Radiat, 27* (2012), 3, pp. 199-332

[11] Bartolini, R. A., Bloom, A., Weakliem, H. A., Volume Holographic Recording Characteristics of an Organic Medium, *Appl. Opt., 15* (1976), 5, pp. 1261-1265

[12] Srećković, M., *et al*., Some Laser Damages of Glass, Scintillator, and Optical Materials, *Opt. and Laser Techn, 23* (1991), 3, pp. 167-174

[13] Ueshima, K., *et al*., Scintillation/Only Based Pulse Shape Discrimination for Nuclear and Electron Recoils in Liquid Xenon, arXiV > 1106.2209v1 [physics.ins/det], 11 Jun, 2011, http://arxiv.org/pdf/1106.2209v1.pdf

[14] Pantelić, S., *et al*., Influence of Nuclear Radiation and Laser Beams on Optical Fibers and Components, *Nucl Technol Radiat, 26* (2011), 1, pp. 32-38

[15] Srećković, M., *et al*., Materials for Contemporary Quantum Generators and Components, *Proceedings*, Contemporary Materials, July 2010, Banja Luka, ANURS, 2011, pp.130-131

[16] Lazić, D., Centre de Recherches Nucleaires, Strasbourg, France, Ph. D. thesis, CRN 93-38, N. d'ordre 1534, 1993

[17] Pauwels, K., Ph. D. thesis, 5 February 2013 ,Univers. de Lyon, France

[18] Travica, S., Srećković, M., Analysis of Fiber Optical Systems in the System for Powering and Signal Transmission (in Serbian), *Nauka – Tehnika – Bezbednost*, (2003), pp. 79-82

[19] Nemtanu, M. R., Brasoveanu, M., Iovu, H., Degradation Rate of Some Electron Beam Irradiated Starches, *Scientific Buletin, 72* (2010) 2, pp. 69-74

[20] Marco, C. De., *et al*., Surface Properties of Femtosecond Laser Ablated PMMA, ACS, *Appl. Mater. Interfaces, 2* (2010), 8, pp. 2377-2384

[21] Srećković, M., Dinulović, M., Fotev, V., Constructions and Calculations Related to Nonconventional

Ecological Approaches for Earth and Space, *Mach. Des*., 2 (2010), 1, pp.193-198
[22] ***, *Laser Materials Processing* (Ed. M. Bass), North Holland, Amsterdam, 1983
[23] Srećković, M., *et al*., Laser Interaction with Material in Theory, Experiment and Reality, Regional Talent Center II, Belgrade, 2012
[24] Srećković, M., *et al*, Damages Induced by Laser Beams in Organic Materials, *Las. Phys., 11* (2001), 3, pp. 336-342
[25] Chmel, A. E., Cumulative Effect in Laser-Induced Damage of Optical Glasses: A Review, *Glass Physics and Chemistry, 26* (2000), 2, pp. 49-58
[26] Borna, N., *et al*., Laser Interactions with Bundle Fiber Structures, *J. Intens. Puls. Las. and Applic. in Adv. Phys., 1* (2011), 3, pp. 73-78
[27] Srećković, M., *et al*., Mechanisms of Laser Interaction with Materials (in Serbian), *Tehnika, 51* (2002), pp. 9-16
[28] Srećković, M., *et al*., Some Aspects of Laser Interaction with Solids, Trimming and Shape Damages, *Rev. Roum. Phys., 34* (1988), 7-9, pp.1081-1086
[29] Novicki, M., *Lasers in Electronic Technology and Material Processing*, Mašinostroenie, Moskow, 1981
[30] Srećković, M., *et al*., Laser Influence and Interaction on Microalloyed Steels, *Proceedings* (Eds.: V. J. Corcoran & T. A. Corcoran), Laser's 2000, December 2000, 2001, pp. 736-743
[31] ***, *Energy and Environment* (Ed. M. Andjelković), Serbian Academy of Sciences and Arts, Belgrade, 2013

Received on July 21, 2014
Accepted on March 2, 2015

Милеса Ж. СРЕЋКОВИЋ, Станко М. ОСТОЈИЋ, Јелена Т. ИЛИЋ, Зоран А. ФИДАНОВСКИ, Сања Д. ЈЕВТИЋ, Драган М. КНЕЖЕВИЋ, Марија Д. ОБРАДОВИЋ

ФОТОЈОНИЗАЦИОНИ ПРОЦЕСИ, ИНТЕРАКЦИЈА ЗРАЧЕЊА СА МАТЕРИЈАЛОМ И ОШТЕЋЕЊА – ОТПОРНОСТ МАТЕРИЈАЛА

Процеси индуковани оптичким и нуклеарним зрачењем разматрани су кроз интеракције зрачења са полупроводничким, металним и другим материјалима укључујући и материјале сцинтилатора. Анализирани су процеси повишења ефикасности компонената коришћењем квантних генератора, процеси тримовања и хибридних процеса са нуклеарним зрачењем. Проучавани процеси могу бити позитивни или негативни, зависно од примене. Поред експерименталног прилаза процесима и изабраним интеракцијама, обављен је аналитички опис наших експеримената као и експерименталних радова других аутора. Размотрена су савремена спрезања између нуклеарне физике, ласерске технике и одговарајућих дозиметрија.

Кључне речи: нуклеарна технологија, ласер, запис, оштећење, отпорност