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50TH ANNIVERSARY OF LASER TECHNOLOGY DEVELOPMENT

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50-РІЧЧЯ РОЗВИТКУ ЛАЗЕРНИХ ТЕХНОЛОГІЙ
У статті приводиться історичний аналіз розвитку лазерних технологій у світі. Проаналізовано вплив видатних учених на становлення й розвиток даної галузі науки. Наведено основні наукові з, нові технологіїі, тенденції розвитку освітніх програм, а також увага світової наукової громадськості в масштабах міжнародних проектів. Закладено принципи подальшого розвитку галузі науки.

В статье приводится исторический анализ развитияи лазерных технологий в мире. Проанализировано влияние выдающихся ученых на становление и развитие данной отрасли науки. Приведены основные научные достижения, новые технологии, тенденции развития образовательных программ, а также внимание мировой научной общественности в масштабах международных проектов. Заложены принципы дальнейшего развития области науки.

In article the historical analysis of laser technologies development in the world is resulted. Influence of outstanding scientists on becoming and development of the given branch of a science is analysed. The basic scientific achievements, new technologies, tendencies of development of educational programs, and also attention of world scientific community in scales of the international projects are resulted. Principles of the further development of area of a science are incorporated.

I. INTRODUCTION

50 years has passed since first laser appeared thus starting the new laser era in science and technology development. The achievements gained in this field for five decades prove that laser technology may be considered as the most significant discovery of the XX century.

The mankind is paying tribute first of all to fundamental theoretical studies in quantum physics, electronics, optics of the greatest scientist of the past century – Albert Einstein, Alexander Prokhorov, Nikolay Basov, Charles Towns, Theodore Meiman, Arthur Shawlow, Gordon Gould and to many others. First laser radiation with its unique characteristics was considered as prospective weaponry to destroy the armed forces and armament. The huge resources had been directed to the development of this field by highly industrialized countries, which promoted the disclosure of other prospective applications for lasers.

II. A BIT OF HISTORY

First research in the development of lasers and laser systems had been initiated almost in parallel in the former USSR and USA at the end of 50^{th} and beginning of 60^{th} of the last century. With time the all industrial countries of the world had been involved in such R&D programs and in implementation of lasers in different fields of human activities.

In Ukraine such research had been started at the Physics Institute, Institute of Semiconductor Physics, Paton Welding Institute and other institutions of the Academy of Science of Ukraine. First studies of laser use for material processing (industrial laser applications) had been initiated under the supervision of Prof. S. Kartavov at Kiev Polytechnic Institute (KPI) - now the National Technical University of Ukraine "KPI" - in 1964 and the first book in the world in this field had been published back in 1967 [1] – "The use of Optical Quantum Generators (OQG) for technological purposes", "Technika", Kiev. The great impact on interest development from researchers to other different applications had been promoted by John Ready's book [2], published in USA in 1971.

At first the focused laser radiation was considered as unique means to pierce small holes in different components of precision engineering. At the same time the manufacturer's attitude to new technology had been quite skeptical, some of them even had been afraid of being dangerously irradiated by laser light…But then fields of applications had become much wider and the focused laser beam was even named as the new type of universal tool, able to perform the vast variety of material processing. There were even arguing at first from some classic experts in mechanical engineering that such terminology is impossible to use in that case because such kind of "universal tool" can't be stored in typical shop instrumental bank of manufacturing enterprises of that time…

Even the well-known authorities in lasers (Prof. Charles Towns and Prof. Alexander Prokhorov) at first had been quite skeptical about industrial laser applications and personally advised the author of this paper back in 1964-1966 to quit "the childish games with laser holes drilling" and better to switch my efforts as mechanical engineer by profession to the study the possibilities for laser application in astrophysics (for example, for measurement the distance between the planets in outer space)…

III. MAIN ACHIEVEMENTS

When we started our first research at KPI at the beginning of 1964 except of self made laser device (at that time we called it the "Optical Quantum Generator" - OQG) there were no means to control the process parameters or the beam interaction with material results. By our assessment the pulse energy was around 2J

To evaluate the beam energy we used to measure pump lamp charging voltage and made the corresponding curve or just counted the number of blades pierced through with laser pulse. The more blades were pierced the higher was the pulse energy.

The special energy meters and power meters had been developed later and much more sophisticated devices had been manufactured to evaluate the parameters of laser material processing.

Microholes in dies, watch stones, different nozzles, diaphragms etc. became the first field of prospective laser technology application.

Laser systems. At the beginning of laser era the main industrial application were based on the use of solid state (mainly pulsed) lasers – ruby, Nd- glass, Nd:YAG pumped with flash lamps.

The new step in laser technology development was the advent of the new generation of laser – CW lasers. Thanks to the invention of Dr. Kumar Patel the CO2 laser became for many years the very reliable source of CW infrared radiation

The latest success in laser systems development is the appearance of high power diode lasers with mean power ranging from few watts up to 10 kW. With development of broad variety of diode lasers it became possible to use more efficient pumping of solid state laser with the diode one.

The most recent achievement in manufacturing advanced laser systems is even more promising: the new type of laser has been developed – fiber optics laser. Small size and mass, high efficiency and shape flexibility are the most significant advantages of this new laser. Even at this quite early stage of development their mean power is reaching already 10 kW (Table 1.).

Table 1 – Some characteristics of industrial fiber optics lasers of IPG company.

Typical Specification

Optical Parameters	**Unit**	**YLR-1000**	**YLR-2000**	**YLR-4000**	**YLR-10000**
Mode of operation		CW	CW	CW	CW
Central emission wavelength [1]	nm	1070	1070	1070	1070
Nominal output power [2]	W	1000	2000	4000	10,000
Typical beam quality [3]	mm*mrad	6	18	20	25
Output power stability (long term)	%	+/-3	+/-3	+/-3	+/-3
Output fiber delivery diameter	μm	100-200	200-300	300-400	400
Electrical Parameters					
Typical electrical requirements	VAC	208-480	380-480V,3P+PE, 50 - 60Hz		
Maximum power consumption	kW	7	15	30	80
Max. cooling water consumption	m^3/h	0.6	1.2	3	5
Cooling water temperature	°C	5-30	5-30	5-30	5-30
General Parameters					
Dimensions (WxDxH)	cm	60x79x110	60x79x110	60x79x160	120x79x160
Weight	kg	150	300	450	1000
Ambient temperature	°C	0-45	0-45	0-45	0-45

The majority of industrial laser systems were designed to process different components. But in many cases the specialized equipment had been manufactured.

Thus for aerospace industry there had been developed the first highly special laser industrial system for hole drilling in long (0.5 - 3 m) stainless steel tubes 15-40 mm in diameter with wall thickness 0.8 mm. Such tubes were used as spraying collectors in the preventing fire systems and in the systems to prevent icing of Antonov’s Company aircrafts and some types of helicopters. The developed equipment had the focusing device moving along the long tube according to program and tube itself might be turned around its axis to the necessary angle providing the required hole diameter – 0.8 mm.

Analyzing the structure of today industrial laser systems it is obvious that the majority of lasers used for industrial applications belongs to CO_2 laser (68%). Then come the solid state lasers (21%). The niche of fiber lasers is still quite modest (11%) which may be explained by some natural inertia in implementation of those very efficient systems. At the same time the resent survey made by well known expert in laser technology David Belforte had demonstrated the very dynamic changes in laser system market for the last few years [3](Table 2-3).

<u>Surface treatment.</u> The ability to localize heat energy created the new possibility to control the properties of the components surface layers. The entirely new technologies had emerged -Transformation hardening, Surface alloying, Cladding,

Shock Hardening, Glazing.

Table 2 – Lasers for metal processing ($ million)

TYPE/YEAR	2009 REV.	2010 EST.	%	2011 PROJ.	%
CO_2	621	729	17	839	15
Solid State	208	224	8	244	9
Fiber	85	115	35	138	20
Total	914	1068	17	1221	14

Table 3 – Lasers for semiconductor and microprocessing ($ million)

TYPE/YEAR	2009 REV.	2010 EST.	%	2011 PROJ.	%
CO_2	10	18	80	20	11
Solid State	36	67	86	86	28
Fiber	10	18	80	22	20
Other	38	46	21	55	20
Total	94	149	59	183	23

Using the traditional laser hardening (transformation hardening) it is possible to increase material hardness in irradiated zone by factor 1.5-3. Our research had shown that laser surface alloying of aluminum alloys might change significantly the working characteristics of the treated components. Thus at laser surface alloying of technical aluminum *Al* 25 with *Mn*, *Ni* and *Fe* there is the large increase of hardness in comparison with untreated alloy and even with heat treated alloy.

Thanks to laser surface treatment the wear resistance of cutting tools, moulds, dies, and of different machines components had increased by factor 3-6.

Laser welding. This application immerged almost immediately with laser hole drilling. The ability to localize heat energy like at electron beam welding but in open air (not in deep vacuum) made this technology very attractive at once for different joining operations. Using at first stage the heat conduction mechanism for welding it was quite efficient technology for joining different thin sheet metals.

Joining of very delicate components like electronic device parts, different parts of medical instrumentation and other are gaining wide popularity in resent years.

Promising results had been achieved in joining parts made from plastic, ceramic and composite materials. Good example of high efficiency of such joining is laser welding of diamond composite cutting segments to the steel body of disk saw for cutting stones without water cooling. Besides the latter advantage the implementation of such joining process brings the significant saving of silver, used for traditional brazing of segments.

Cutting and material shearing. First cutting applications were mainly connected with manufacturing small slots in different parts, with sharing brittle materials (like diamond crystals) using scribing mechanism, with shearing silicon plates for solar elements using high frequency pulse lasers etc. Cutting speed had increased drastically with flying optics technique development.

With development of high power CO_2 lasers and optical fiber lasers the tailoring blank metal sheets became very efficient in automotive and aerospace industry.

For the last two decades the amount of components from ceramic materials used in car, aircrafts and missiles, different devices has increased drastically as well. The main advantage of such components - high heat, wear and corrosion resistance - is contradicting with the main technological characteristic – ability to be machined.. The quality of laser ceramic cutting with pulsed laser beam is improved significantly when processing is performed using the additional scanning (linear or circular) of the beam. Such combined technique of cutting (beam movement + additional scanning) appears to be effective for shearing thin silicon plates (0.4-0.6 mm thick) for solar elements. As it is known these elements are now in great demand as an alternative source of energy both in automotive and aerospace industries.

One more specific application of laser cutting technology had been proposed and developed at LTRI of the NTUU"KPI"- the use of laser radiation to dismantle the highly radioactive remnants of the Object "Shelter" of the Chernobyl Atomic Station. It had been demonstrated that with help of remote controlled laser robotized system it is possible to perform some demolishing operations in a highly complicated and dangerous conditions [4]. The experience gained at the development of that project may be especially very useful now when we have quite similar catastrophe at the nuclear reactor of the Fukushima Atomic Station (Japan), which had happened at the beginning of 2011.

Rapid prototyping. Thanks to information technology integration into laser processing it became possible to develop the new technology of 3D objects forming, based on the principle of biological growth taken from nature. Known as rapid prototyping this technology allows not using moulds, dies and other traditional expensive tools and techniques to manufacture components with complicated shape at very high productivity.

Started first from manufacturing components from polymer materials using stereo lithography this technology now came to the new stage – the possibility to create components from metal, ceramic or different composite materials.

The size of components formed by these methods may vary from very large (for example, engine body, steering wheel and other components of the car industry) down to micro and nano-components.

The first in Ukraine and in the countries of FSU universal rapid prototyping equipment had been developed at LTRI thanks to STCU financial support. It was based on use of two schemes of process realization – 1) laser sintering with robotized focusing beam system and powder injection system movements; 2) powder layer compressing with roller followed by laser sintering with programmed scanning of laser radiation [5].

Quite large variety of industrial systems for laser sintering and stereo lithography had been developed and manufactured in different countries (Switzerland, Germany, USA, France, etc.). One of such piece of equipment had been bought abroad and installed at the Kharkov National Technical University and now is use for manufacturing of different components for industry.

Two photon polymerization (2PP) as new stereo lithography technique [6] has demonstrated the unique possibilities to create micro and even nano objects and to open the way to bio processing in medical applications (tissue growing, implant forming, etc.).

One of the interesting technologies had been proposed at LTRI - the formation of the 3D image of the object using its black and white or color picture. In this case the flat picture was analyzed and lines of equal luminosity wee found to get the information on the changes of the 3d coordinate [7]. The obtained "map" was used to create the virtual 3D image of the flat object. Then based on such formalized description of the object it was possible to create the materialized 3D copy of it by means of Rapid Prototyping technique.

Micro and nano machining. The success in generating short and ultra short pulses (micro-, nano-, pico-, femto- and even atoseconds) made it possible to perform unique cutting operations especially with development of high frequency pulse lasers. At machining with super high power density pulses the very small amount of material is removed per pulse thus making possible achieving very high operation precision (up to few nanometers) [8]. In spite of rather low productivity there is no alternative technologies for manufacturing micro components like for example sapphire micro gear, different parts from ceramic, medical stents from stainless steel, tantalum or bio polymer for blood vessels restoration, etc. The later is especially important now day because cardio diseases are considered the #1 killer among other fatal health problems. The large amounts of stents are manufactured now with femtosecond laser systems. But the productivity of the process is low and thus the cost of the product is too high. To overcome this drawback the technology had been developed at LTRI of the NTUU, based on use of Q-switched laser which made it possible to get on the processed stent's surface the small "pockets" to store the special medicine to cure the blood vessel [9].

Laser micro and nanomachining are widely used now for manufacturing microelectronics elements. Widely implemented into electronic industry laser lithography provides the microchips manufacturing with ability of storage the huge volume of memory. To increase the memory volume the processing with short wavelength of 193 nm or even 157 nm are being used now.

Surface cleaning, marking, engraving. Modern sophisticated machines and devises need components with super clean surface. This is especially important for electronic device components, for optical elements, for modern printing devices etc. In some cases such technique may be used for radioactive contamination removal from the material surface. For that as well as for restoration of old paintings lasers canning processing is widely recommended. Marking and engraving became extremely popular for identification different components as well as for decoration treatment.

Shaping components from sheet materials. The possibility to control heating process and thus the resulting thermal deformation at sheet material laser irradiation brought to the development of the new technology for forming component of complicated shape from sheet metal, plastic or other materials [10].

Without any traditional mechanical deforming technique using only scanning laser beam it became possible to change the shape of the material according to the given program.

Combined and hybrid processing. Considering that laser itself is a very low efficient energy transformer different ways of additional energy supply into the working zone had been proposed. The most efficient was the direct electric energy addition to the concentrated laser energy. Depending on way of this additional energy supply different techniques had been developed:

- Electro-laser hole piercing;
- Arc-augmented laser welding;
- Laser cladding with electro-magnetic agitation;
- Laser alloying in electro-magnetic field;
- Laser-electrochemical processing;
- Plasma-laser processing;
- Laser ultra-sonic hardening;
- Laser-plastic deformation hardening etc.

The hybrid laser-plasma processing had attracted attention of many researchers in different countries [11]. This process has demonstrated very high efficiency and quality of welding and cutting.

Laser processing simulation. For the last two decades it became obvious that it is impossible to understand the very complicated multy factors processes of laser beam interaction with matters and to find the optimal working conditions without using modern techniques of process simulation.

Numerous physical models had been successfully developed based mainly on heat conduction theory and presenting “heat history” of the irradiated materials. Different limitations were considered making these models quite adequate for the simple cases of laser processing. For complicated cases when processing was connected with evaporation, explosion, plasma formation, ablation mechanism etc. such physical models didn’t “work” properly and could not be used at the industrial level.

Mathematical statistical models based on experimental results had been developed for industrial use but they are usually adequate only for some specific factor space and not always may be extrapolated for more complicated working conditions.

One of such models had been developed at joint research of LTRI with Laser Center of Zhejiang University of technology (China) [12].

IV. EVOLUTION OF THE EDUCATION PROGRAM.

Up to now not every highly industrialized country has education program in laser technology at its universities.

Germany is a good example of education in the advanced technology area. There are over 60 university level institutions actively teaching laser material processing.

Last decade China is paying great attention to the education and research in this field.

Since the first research in Ukraine on laser processing in 1964 at KPI students took part in this activity. Some of them had developed their engineer diploma projects on industrial laser applications in the framework of the wide specialty “Manufacturing Engineering”.

Based on research results the educational course «Electro physical and electrochemical methods of processing of materials» was initiated and delivered to Mech. Eng. students of KPI for almost four decades now.

In 1984 for the first time in Ukraine and FSU at KPI the new engineering specialty «Equipment and technology of laser processing» was opened which further was transformed into wider engineering specialty «Processing of materials with special technologies».

In 1990 on base of Department of Technology of Constructional Materials and R&D laboratory of Laser Technology the special Department of Laser Technology and Material Science (LTMSD) was created (later renamed into “Laser technologies and applied physics”).

Annually on a specialty "Processing of materials with special technologies" 50 new students –citizens of Ukraine are accepted until 2008. There were as well students from 32 different other countries. In total every year the Department was teaching around 300-350 students. Around 1000 Department graduates has got their Master’s or Engineer’s Diplomas.

The total amount of students has decreased last years. 30 Ph D thesis’s and 7 Doctors of technical Sciences thesis’s had been defended in laser technology at the Department.

V. ORGANIZATIONAL ACTIVITY

For the last more than 40years the great global consolidated activity of different researchers and industrialists in laser technology had been conducted by the Laser Institute of America (LIA). LIA is organizing regularly the International congresses – ICALEO, different regional conferences and seminars. Under its auspices few periodicals are being published (“Industrial Laser Solutions”, “Photonics Spectra”, etc) as well as some other special literature.

At last decade the European Laser Institute (ELI) had been organized in Europe to promote laser technology activity in this part of the world. Under its auspices the journal “EuroPhotonics” is published. Together with China Academy of Science ELI is organizing 1st International Conference on Frontiers of Laser Processing (ICFL) in China on July 2011.

Great importance for promoting advanced laser systems for different application has the variety of specialized exhibitions the annual “Photonics” in Munich (Germany) being the most popular among the laser community experts.

At the global scale the significant activity is conducted by the International Academy of Production Engineering (CIRP) with headquarters in Paris. The deep surveys on different problems of laser technology developments are discussed at the annual General Assemblies, at the STC-E conferences “ISEM”, published in “Annals of the CIRP” and other sources.

In the former USSR the Laser Association (LAS) had been founded which is functioning until now in some countries of FSU. The “Bulletin of LAS” is the official publishing edition of that institution.

The similar activity had been initiated as well in different other industrialized countries last years.

Last decade two international conferences had been initiated at two countries of FSU – Ukraine and Russia:

1) Organized by Paton Welding Institute (PWI) of NASU and Laser Technology Research Institute (LTRI) of NTUU in Katsively, Crimea – Laser Technology in Welding and Material Processing (LTWMP). Five such conferences had been conducted until now (once in every two years).
2) Organized by State Polytechnic University - St. Petersburg, Russia – "Electron and beam machining" (six conferences had been conducted up to now).

Some papers on laser technologies are published in Paton Welding Journal (PWJ) at Paton Welding Institute of National Academy of Science of Ukraine.

VI. CONCLUSIONS

1. Laser became a real powerfull, higly efficient and universal tool for performing different processing operations.
2. 50 years activity in this field has proved that laser technology development is far from saturation.
3. The horizons of new prospective applications are widening and particularly with appearance of entirely new and unique niche – nano science, nanomaterials and nanotechnologies development.

References: 1. *S.A. Kartavov, V. S. Kovalenko,* The Application of the Optical Quantum Generators for Technology", 1967, "Technika", Kiev, 80 p.(in Russian). **2.** *John F.* Ready, Effects of High-Power Laser Radiation, Academic Press, NewYork – London, 1971, 467 p. **3.** *David Belforte,* 2010 Annual Economic review and forecast," Industrial laser solutions", PennWell Publishing, No. 1, Vol. 26, pp. 4-11. **4.** *V. Kovalenko, M. Anyakin, Yu. Karpachov,,* The Opportunities to Use Laser Technology in the Object "Shelter" of the Chernobyl Atomic Station, "Proceedings of International Congress "ICALEO'97", San Diego, USA, Nov. 1997, p.p. 21-26; 52-58. **5.** *V. Kovalenko, M.Anyakin, J..Meijer, A. W.Duley, , D.Roessler* "Laser 3D prototypes forming from metal and ceramic materials"//"Proceedings of International Congress "ICALEO'2003", Jacksonville, USA, Oct. 2003. **6.** *Boris N. Chichkov*, 3D-laser based nanofabrication for application in Photonics and Biomedicine, Proc. of the "6th International Symposium on Nanomanufacturing", Athens, Greece, Nov. 2008. **7**. *M. Anyakin, V. Anyakin, V. Kovalenko,* Laser 3D object prototyping using their flat images, Proceedings of International conference LTWMP-03, Paton EWI, NASU, Kiev, 2003, p.183-187. **8**. *J.Meijer,, K.Du, A. Gilbert, D. Hoffmann, T. Masuzawa, V. Kovalenko, A. Ostendorf, R. Poprawe, W. Schultz,* Laser machining by Short and Ultrashort Pulses: State of the Art, Keynote paper,, CIRP GA, Annals of the CIRP, Vol.51/2/2002. **9.** *V. Kovalenko, J. Meijer, M. Anyakin, R. Zhuk,* Some results of studying laser micromachining at medical stents manufacturing, International Journal of Nanomanufacturing, 2010, Vol.6, #11, p.253-263. **10.** *Namba Y.,* Laser forming in space, "Proceedings of International Conf. Laser'85, 1986, Las Vegas. **11.** *I. Krivtsun, V. Kovalenko,* Combined laser-arc methods of material machining, Part 2, "Science news of the National Technical University of Ukraine (KPI)", # 6, (2001) p.47-66 (in Russian). **12.** *J. Yao, V. Kovalenko, M. Anyakin, Q. Zhang, X. Hu, W. Wang,* Modeling of laser cladding with diode laser robotized system, "Electron material machining", #3, 2010, p.82-86.

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