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REVIEW ARTICLE

Laser technology in Poland: 2013–2016

Adam CENIAN (✉)

Institute of Fluid-Flow Machinery Polish Academy of Sciences, Gdańsk, Poland

Abstract This paper presents the state of art of laser technologies in Poland. A list of primary laser technology development centers is included. The involvement of Polish scientists in the development of lasers and fourth generation synchrotron light sources as well as their applications is discussed. The development of laser applications in medical therapy and diagnostics, material micro- and macro-processing as well as environmental monitoring and protection, safety, and security is presented.

Keywords laser technologies, synchrotron light sources, laser micro-processing, laser diagnostics, laser medical applications

1 Introduction

The review is based on the research presented during the XIth National Symposium on Laser Technology (SLT2016) in Jastarnia, Poland (September 27–30, 2016), supported by newest publications. The symposium, which is organized every 3 years, provides a complete survey of the development of modern laser technology and laser applications in Poland [1].

The primary research activities in the period 2013–2016 were concentrated on issues related to novel laser development (optical fiber, quantum cascade and semiconductor lasers and light sources, solid-state lasers, and optical and photonic assemblies for lasers) and laser applications (in medical therapy and diagnostics, material micro- and macro-processing as well as environmental monitoring and protection, safety, and security).

The key academic and research centers that are active in laser technology development and applications in Poland include the following: Technical Universities from Wrocław (WUST), Kielce (KUT), Warsaw (WUT), Gdańsk (GUT), Białystok (BUT), Łódź (LUT), Warsaw (MUT/WAT), and Katowice/Gliwice (SUT), Universities from Toruń (NCU/UMK), Poznań (AMU/UAM), and research institutes: ITME Warsaw, ITE Warsaw, IPC PAS/IChF PAN Warsaw, IMMS PAS Kraków, AGH UST Kraków, IPPLM/IFPiLM Warsaw, IMP PAN Gdańsk, INTiBS PAN/ILTSR PAS Wrocław, and industry partners IPG-Poland, Solaris Laser, Solaris Optics, PCO, VIGO, Telesystem, etc.

2 Development of lasers and synchrotron light sources

Polish scientists are involved in the development of some recently constructed fourth generation synchrotron light sources (the X-ray free electron lasers), such as linac coherent light source (LCLS), Spring-8 angstrom compact free electron laser (SACLA), Switzerland's X-ray free-electron laser (SwissFEL), Sorgente Pulsata Auto-amplificata di Radiazione Coerente- frascati linac coherent light source (SPARC), free-electron laser in Hamburg (FLASH), and European X-ray free-electron laser (EuXFEL), as well as the fifth generation light sources (ultra-compact FELs that are driven by a beam derived from an advanced accelerator). Polish research teams are either participating in constructing some of the mentioned machines or conducting considerable experiments related to particle physics, atom optics, material engineering, biomedical engineering, etc., using the available light beams. The European X-Ray FEL, located in Hamburg region, will be partly open for first users in 2017. Polish teams participated in the design and construction stage of this considerably large machine, including cryo-systems and low-level radio frequency (LLRF) control, diagnostic, and measurement systems.

The investigations of low-temperature plasma created by photoionization of gases with intense radiation pulses from laser-produced plasma sources (PALS system) were performed at MUT and IPPLM in Warsaw. The achieved electron densities in low-temperature plasma conditions exceeded 10^{18} cm^{-3} [2]—see Fig. 1. The technology enables simultaneous EUV and plasma treatment of

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E-mail: cenian@imp.gda.pl

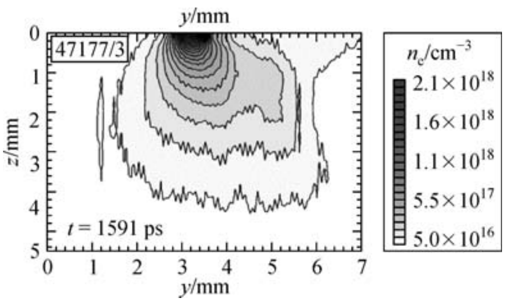

Fig. 1 Electron density distributions in Ne photoionized plasmas generated by PALS system, t = 1591 ps after arrival of laser pulse (after Ref. [1])

materials, for example, polymer surfaces where formation of functional groups containing nitrogen atoms was confirmed [3].

The high-order harmonic generation (HHG effect) and its application in semiconductors and magnetic materials research, lens-less diffractive imaging with nanometer resolution, interferometric tracing of the intramolecular electron dynamics, FEL seeding, etc. are investigated by IO MUT Warsaw in cooperation with institutes from Czech Republic.

An important progress was achieved in the field of fiber lasers with femtosecond pulses. Researchers from Institute of Experimental Physics of Warsaw University and Institute of Physical Chemistry, Polish Academy of Science are working on the optimized construction of fiber optic amplifier of femtosecond pulses of high power. The pulse degradation effects were minimized by using two techniques: chirped pulse amplification with pulse broadening, amplification, and compression, and application of large modal area single mode fiber. This led to the following laser parameters: average power of 65 W, repetition frequency of 900 kHz, a pulse duration of 0.5 ps, and spatial beam quality M^2 at approximately 1.3 in iterbium-doped fiber amplifier. Researchers from WUST developed a 312-fs fiber laser mode-locked by graphene [4]. The laser starts to operate in the bound-soliton regime with the increase of pump power, when two identical pulses are generated.

A diode-pumped cw 37.4 W Tm^{3+}-doped fiber laser operating at a wavelength of 1940 nm was developed in MUT Warsaw. Currently, the laser system is being used for medical tests on animals. The clinical tests performed on pigs have shown possibility of precise incisions, which is particularly important when removing tumors from organs such as kidneys or pancreas.

There were also important achievements in the field of solid-state lasers including holmium-doped lasers (Ho:YAG, Ho:YLF, etc.), tunable Cr:ZnSe laser generating 2200 nm, Er:YAG laser with rotating mirror or Yb:KGW laser with hybrid passive mode locking [1]. The developed diode-pumped cw Tm:YAP laser generating 4.53 W in 1940 nm range (see beam quality in Fig. 2) can be used for various applications related to medicine, military, metrology, optical communication, and science.

Different structures of nitride, vertical-cavity surface emitting lasers (VCSELs), were developed in recent years, including structures with tunnel junctions as well as top and bottom dielectric-distributed Bragg reflectors (DBRs) — see, for example, Ref. [5].

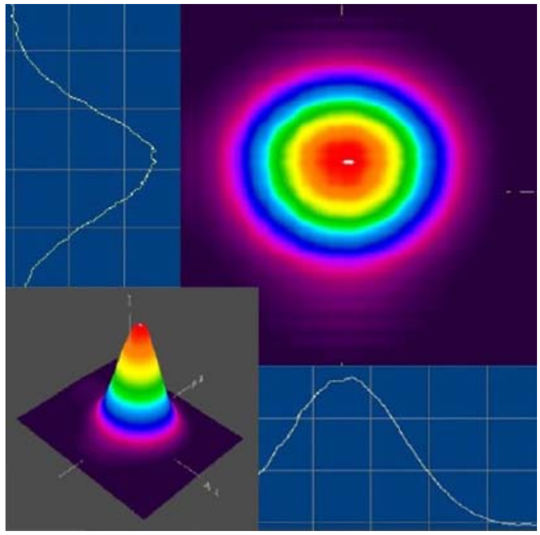

Fig. 2 Beam spatial distribution of diode-pumped Tm:YAP laser (after Ref. [1])

3 Laser applications

3.1 Micro-machining

In the field of laser application, significant results were achieved in micro-machining, including fabrication of micro-sieves for the separation of blood cells — see Fig. 3. A diode-pumped, picosecond Nd:YAG laser with a constant pulse repetition rate of 1 kHz was employed for emitting pulses with a constant energy of 3 mJ and a time duration of 70 ps [6]. Adjustment of energy of the system to approximately 10 μJ allowed drilling holes with a diameter of approximately 5 μm in a copper foil with a thickness of 25 μm, using 50 pulses per hole. The fabrication of a sieve with a diameter of 17 mm and holes distance of 50×50 μm^2 lasted for approximately 1 h. One of the possible applications is related to the isolation of circulating tumor cells (CTCs) from the blood. The enhancement of blood-cell survival depends on the roughness of a micro-sieve. Other interesting results of a laser interaction are periodic surface structures on pyrolytic carbon heart valve. Lasers with different pulse duration (15 ps, 450 fs) as well as different wavelengths (1064, 532, 355 nm) were applied. Ripples, with a period ranging from 90

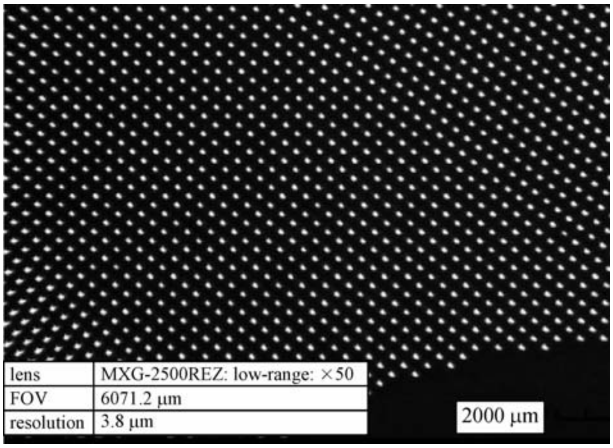

Fig. 3 Sieve manufactured with laser pulse of 75 μJ in 25 μm thick copper foil (after Ref. [1])

to 860 nm, are crucial for several biomedical applications: cell culture, culturing human embryonic kidney cells, and skeletal myoblasts or super-hydrophobic, self-cleaning surfaces. The group of Prof. Kusinski from AGH UST is investigating on novel gas sensors using thin films deposited by pulsed KrF laser (248 nm) on Si target [7].

3.2 Medical applications

In general, the medical applications of optical technologies stay in the focus of several research activities, for example, it was shown that 630 nm irradiation by LED lamps stimulates the proliferative potential of human mesen-/chymal stem cells. Irradiation under proper conditions may provide a novel and safe method for the *in vitro* simulation of human mesenchymal stem cells (hMSCs) before its therapeutic applications for tissue regeneration in medicine. The autofluorescence of human cells *in vitro* as a biomarker of their metabolic activity was investigated, as well.

The preliminary investigations of laser diode therapies (generating radiation with wavelength 975 nm) directed toward the treatment of distorted human cutaneous tissue indicated that the final outcomes for patients with dermal neurofibroma (Recklinghausen disease) are considerably positive and promising (see, e.g., Refs. [8,9]). The clinical studies were continued by investigating laser interactions with skin phantoms that are developed in GUT Gdansk [10,11]. The research team of Prof. A. Zając investigated the pros and cons for the application of semiconductor sources in the UV–VIS–NIR range, where the competition between the applications of semiconductor lasers and LEDs was observed in recent years [1].

3.3 Macrotechnologies

The investigations of macrotechnologies, including those related to welding, surface treatment, and coating [1], were continued. The filler-metal-free laser-beam welding of steel S700MC subjected to thermo-mechanical control process was accompanied by the increase in the content of alloying microagents (Ti and Nb), particularly near the fusion line. The objectives of other experiments were to establish the possibility of joining two dissimilar metals, including low alloy galvanized steel and aluminum sheet, by laser brazing by employing aluminum powder as the joint filler material. The results of Nd:YAG laser welding of iridium–platinum tips to spark plug electrodes have shown that endurance of spark plugs have increased by 100%.

The Co-based (Stellite 6) metal-matrix composite coatings reinforced by spherical-shaped tungsten carbide (WC) particles were produced using a laser cladding system that comprises a diode laser with a flat-top beam profile and an off-axis powder injection nozzle. Nonporous coatings with a WC fraction of approximately 50 vol.% and a low dissolution of WC particles in the matrix were obtained [12]. The results of laser modification of titanium surface using rhenium powder depend strongly on laser power and powder feed rate; the laser power increases the depth of laser penetration, while the increase in feed rate increases the width and height of face fusion. The valid layers with in-melted rhenium could be obtained by selecting the laser power in the range of 1300–1700 W and powder feed rate less than 5.75 g/min. The laser treatment of thin-film materials with hemocompatible coating was studied in IMMS PAS (see, e.g., Ref. [13]).

It has also been shown that, in a certain range of laser fluence, the amorphous TiO_2 can be transformed into anatase/rutile composite with a specific A/R ratio [14]. Sawczak et al. [15] showed that the phase transition (from anatase to rutile) occurs partially after thermal modification using a pulsed (6 ns) Nd:YAG laser (FHG 266 nm). The quasi-continuous and pulse interaction of strong laser radiation with military technical materials were investigated in MUT. Moreover, the high-power laser-beam interaction with target was investigated using hybrid FVM-FEM and digital image correlation methods.

The experimental investigations of the hybrid thermo-mechanical processing of thin plates with a laser beam proved the feasibility of laser assisted plate forming with high efficiency [16]. Large bending deformations of plates were achieved after passing a single laser beam. The absorption of the incident CO_2 laser-beam radiation increases with the application of a black paint as a coating layer, thereby providing 40% of energy coupling. It is found that the surface preparation can significantly influence the absorption coefficient of laser radiation. The highest absorption is characterized by the sample surface covered with black enamel. Contrary to expectations, the sandblasted surface shows a slight increase in capacity for absorbing radiation, as well. The waterglass covered surface shows wide discrepancies in absorption.

This may result from the imprecise method of applying a layer of waterglass onto the surface of the element. The team from MUT Warsaw was involved in development of laser technologies related to glass engraving and ceramics coloration.

3.4 Interaction of short and high energy pulses

An interaction of short laser pulses with intensities greater than 10^{20} to 10^{21} W/cm^2 with solid target results in the generation of plasma pulses and extremely strong electrical field gradients in the range of 10–100 GV/cm. The sub-picosecond ion pulses generated under these conditions are characterized by unique properties: extreme intensity 10^{20} W/cm^2, large current density 10^{12} A/cm^2, and considerably large fluency of the pulsed beam 10^{20} ions/cm^2. Such ion pulses enable novel research applications in science, medicine, and technology, including nuclear physics, experiments on new dynamic states of highly excited matter as well as small laser-based devices for hadron therapy of tumors. The research related to the influence of quasi-cw high-energy laser pulse and superimposed high-power pre-impulse on the heating process of the aluminum target was performed in MUT Warsaw. Furthermore, the effect of laser power and scanning speed on the laser penetration depth and track width and height during selective laser melting was studied. With an increase in the laser power, the penetration depth and track width will increase. The correlation between penetration depth and height of tracks was proven. It has been shown that for scanning speed over 300 mm/s, the width of the track is stabilized.

3.5 Laser diagnostic techniques

Significant progress was achieved in the field of laser diagnostics techniques. For example, a compact water-window, desktop microscope, based on nitrogen double stream gas puff target SXR source and Fresnel zone plate objective was developed in MUT Warsaw [17]. The microscope allows capturing magnified images of the objects, with a spatial resolution of a 60 nm half-pitch, exposure time as low as a few seconds, desktop footprint, easy accessibility, and simple operation. The system offers superior spatial resolution to the visible light microscopes, does not require sample preparation such as SEM microscopes, exploits natural, optical contrast in the water-window spectral range for biological imaging applications and may be considered as a complementary imaging tool to the already well-established techniques. One and two photon fluorescence spectroscopy were also developed to investigate normal and cancerous tissue.

Researchers from MUT Warsaw continued investigations of spectroscopic properties of second generation photosensitizers for photodiagnostics and photodynamic therapy [18]. Other MUT team developed a system of tuned quantum cascade lasers for detecting the trace amounts of gaseous atmospheric pollutants [19]. The operation and characteristics of the measuring system, in which an IR cascade laser is applied as the radiation source, were checked by measuring the levels of carbon monoxide, nitrous oxide, and ammonia in the atmospheric air. Moreover, a novel bio-aerosol detector allowing real time screening of ambient air was proposed. It was shown that the device allows effective classification of various biological and nonbiological aerosols including bacteria, fungi, and pollens.

Various optoelectronic methods (LIF, Raman scattering, and FTIR) were examined as the optimal tool for air allergens detection, in order to prevent allergic rhinitis (known as hay fever) — see Ref. [20]. An optoelectronic system based on cascade lasers for stand-off detection of alcohol vapors in moving cars was developed in MUT Warsaw. It was shown that the alcohol vapors inside a car can be successfully detected using 3.45 and 3.59 μm wavelengths even for cars with different windows [21]. Furthermore, a laser velocimeter was constructed by using at least 0.5 μJ laser pulse.

The measurements of optical surfaces and wavefronts with the use of interference techniques are necessary elements of optical components fabrication and system development. The Hilbert-Huang Transform method was used for measurements of optical surfaces quality for high-power laser applications. With the proposed preprocessing, the investigated object surface may be measured using single interferogram with sufficiently high accuracy. At IMP PAN Gdańsk, various nondestructive laser techniques were developed and used for the diagnostics of polimer structures [22], micro-electro-mechanical systems [23], or electrodes of storage systems [24]. Moreover, Dichroic Atomic-Vapor Laser-Lock signal-detection method was developed for laser frequency stabilization, which was enhanced by synchronous detection system based on surface-stabilized ferroelectric liquid crystals [25]. Laser frequency stabilization is crucial for many research areas, including gas spectroscopy, optical frequency references, atomic physics experiments, and interferometry or vibrometry measurements, etc.

3.6 Data transmission technologies

The laser applications in data transmission technology were investigated by researchers of MUT Warsaw [26]. A nonconventional asymmetric laser data transmission system and a unique method of data transmission based on pulsed laser radiation were developed.

4 Conclusions

Research on laser as well as its commercial applications are developing fast in Poland. The key academic and research centers that are active in laser-setup development and their applications include the following: Technical Universities from Wrocław (WUST), Kielce (KUT), Warsaw (WUT), Gdańsk (GUT), Białystok (BUT), Łódź (LUT), Warsaw (MUT/WAT), Katowice/Gliwice (SUT), Universities from Toruń (NCU/UMK), Poznań (AMU/UAM), and research institutes: ITME Warsaw, ITE Warsaw, IPC PAS/IChF PAN Warsaw, IMMS PAS Kraków, AGH UST Kraków, IPPLM/IFPiLM Warsaw, IMP PAN Gdańsk, INTiBS PAN/ILTSR PAS Wrocław, and industry partners IPG-Poland, Solaris Laser, Solaris Optics, PCO, VIGO, Telesystem, etc. A significant progress was achieved recently in the field of fiber lasers, particularly those with femtosecond pulses. Polish scientists are also involved in the development of fourth generation synchrotron light sources. Significant achievements have been made in the field of solid-state and diode lasers. In relation to laser applications, a significant progress is achieved in the fields of micro-processing, high energy pulses interaction with matter, and medical applications. The interesting results in the fields of laser macrotechnologies, diagnostics, and data transmission methods and systems are reported herein.

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Adam Cenian is a professor at the Institute of Fluid-Flow Machinery Polish Academy of Sciences (IFFM) in Gdańsk. In 1979, he earned his M.Sc. degree in applied physics from Gdańsk University of Technology (GUT). Later, he earned his Ph.D. degree in laser physics from IFFM (1984) and D.Sc. (habilitation) degree in plasma physics from GUT (2008). His primary scientific interests include laser technologies (CO_2 plasma physics, laser radiation—matter interaction, including laser ablation and laser techniques application), plasma-chemistry—kinetics and spectroscopy of plasma in electric discharges and flames, plasma–wall interactions, simulation techniques (Molecular Dynamics, Monte Carlo, PIC), plasma diagnostics—modeling of Langmuir probes and modeling of ion thrusters. Recently, he is involved in research related to medical laser development, nanotechnologies, and ecoenergetics.