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International forum on advanced high-power lasers and applications (AHPLA '99)

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Abstract. A review of reports made on the International Forum on Advanced High-Power Lasers and Applications, which was held at the beginning of November 1999 in Osaka (Japan), is presented. Five conferences were held during the forum on High-Power Laser Ablation, High-Power Lasers in Energy Engineering, High-Power Lasers in Civil Engineering and Architecture, High-Power Lasers in Manufacturing, and Advanced High-Power Lasers. The following trends in the field of high-power lasers and their applications were presented: laser fusion, laser applications in space, laser-triggered lightning, laser ablation of materials by short and ultrashort pulses, application of high-power lasers in manufacturing, application of high-power lasers in mining, laser decommissioning and decontamination of nuclear reactors, high-power solid-state and gas lasers, x-ray and free-electron lasers. One can find complete information on the forum in SPIE, vols. 3885-3889.

1. Introduction

The International Forum on Advanced High-Power Lasers and Applications (AHPLA '99) was held at the Institute of Laser Engineering, Osaka University (Japan), from November 1 to 5, 1999. Its co-chairmen were C H Townes (Univ. of California, Berkeley, USA), Nobel Prize winner, and Prof. H Oka (Mitsubishi Electric Corp., Japan). The forum was directed by Prof. S Nakai, former Director of the Japanese Program of laser fusion in Osaka. It was sponsored by the Laser Society of Japan and the International Society for Optical Engineering (SPIE). The following five conferences were held simultaneously during the forum:

— High-Power Laser Ablation;
— High-Power Lasers in Energy Engineering;
— High-Power Lasers in Civil Engineering and Architecture;
— High-Power Lasers in Manufacturing;
— Advanced High-Power Lasers.

The following major trends in the field of high-power lasers and their applications were discussed during the conferences: laser fusion; laser applications in space, mining, and architecture; laser-triggered lightning; laser decommissioning and decontamination of nuclear facilities; laser ablation of materials by short and ultrashort pulses; application of high-power lasers in manufacturing; laser isotope separation; laser acceleration of particles; laser deposition of films and optical coatings; frequency conversion and nonlinear optical materials; 3D structure formation; high-power solid-state lasers, including diode-pumped and fibre lasers; high-power gas lasers, including excimer, x-ray, and free-electron lasers.

There were 438 scientists from 30 countries who participated in the forum. In all 446 reports were presented from Japan (176 reports), Russia (89), USA (44), China (37), France (25), Germany (18), Great Britain (11), Belarus (3), Ukraine (2), Uzbekistan (1), and Armenia (1). The largest number of participants came from Japan (176), USA (36), Russia (31), France (18), Germany (18), China (16), and Great Britain (5).

2. Plenary session

In his report 'The Increasing Power of Lasers' presented during the plenary session, C Townes (Univ. of California, Berkeley, USA) touched upon the history of lasers. He noted that while the first ruby laser had a peak power ~ 1 kW, and its efficiency was $\sim 10^{-4}$ at the pulse duration ~ 1 ms, the average power of advanced lasers exceeds hundreds of kilowatts. He drew attention to the high-power Nd laser developed in Russia, which has a pulse energy of 1 – 2 kJ and a pulse repetition rate of 100 Hz. The brightness of advanced lasers is so high in comparison with the brightness of incoherent light sources that the radiation of a 1 W visible laser directed from Los Angeles to the Moon is well visualised on the Moon's surface, in contrast to the radiation emitted by the whole city.

Stellar masers (or radio-transmitting stars) emitting centimetre radiation with power exceeding the solar radiation power by a factor of ten are of considerable scientific interest. However, the speaker noted that it is unlikely that we shall ever obtain such radiation power on the Earth.

Prof. C Yamanaka (Osaka University, Japan) devoted his report 'Super High-Power Lasers and their Applications' to the development of high-power lasers and their applications in Japan. He paid much attention to the 12-channel multistage GEKKO XII laser facility intended for laser fusion. Using this facility, which was brought into use at the Institute of Laser Engineering in 1983, a neutron yield of 10^{13} was obtained in 1986, and target compression up to the density exceeding the solid-state density by a factor of 600 was obtained in 1986. Laser disks used in the system were $69.4 \times 38 \times 4.5$ cm in size. The radiation energy was 25 kJ at $\lambda = 1.05$ μm, 15 kJ at $\lambda = 0.53$ μm, and 12 kJ at $\lambda = 0.35$ μm, and laser pulses were 1 ns long. For 0.1 ns pulses ($\lambda = 1.05$ μm), the peak power was 55 TW. In 1996, a new pulsed ultrahigh-power laser beamline was constructed,

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which emits 1 ps pulses with energy of 100 J and peak power of 100 TW. It is intended to study the potentialities of a new ignition scheme for laser fusion (so-called fast ignition).

The experimental and theoretical studies on GEKKO XII aim to study hydrodynamics of a high-density plasma for laser fusion and the development of its mutidimensional numerical model, which can be also used for solving certain astrophysical problems, such as the formation and evolution of stars (the so-called laboratory astrophysics). At the Institute of Laser Engineering, Osaka University, a project to construct the Koyo reactor system for laser fusion was developed. Experiments on LEKKO VIII CO_2 laser system (10 kJ, 1 ns, 10 TW) were suspended, but a 2 kJ CO_2 laser is used advantageously to study laser-triggered lightning.

Prof. A Kantrowitz (Dartmouth College, USA), who proposed the concept of a rocket with a laser engine 30 years ago, devoted the greater part of his report 'Then and Now' to philosophical problems. He noted that openness is a source of strength and that his hopes have not been realised, whereas his fears remain. The latter include the spread of different forms of cancer, the problem of food production, and global warming. He touched upon the problem of high-power lasers and their applications and noted that his idea of launching rockets with a laser engine is still alive and is successfully being developed.

Prof. W Krupke from the LLNL (Lawrence Livermore National Lab., USA) presented 'Advanced Diode-Pumped Solid-State Lasers: Near-Term Trends and Future Prospects'. He noted that, although the first report on diode pumping appeared in 1964 and a diode-pumped Nd laser was developed as early as 1968, high injection current densities ($j > 1$ kA cm^{-2}) and the necessity of cooling laser diodes down to cryogenic temperatures hampered the extensive use of laser diodes for pumping solid-state lasers. Advanced laser diodes operate at room temperature at pump current densities $j < 0.2$ kA cm^{-2}, and linear diode arrays with radiation power from 1 to 4 kW were developed.

In Japan, a diode-pumped Nd:YAG slab laser was developed, whose output power is 3.3 kW. At the LLNL, a project of a repetitively pulsed Mercury laser (100 J, 10 Hz, 10% efficiency, 2 ns) was developed. It represents a prototype of a diode-pumped laser driver and is the first one from the series of laser driver projects Mercury → Venus → Termini → Helios (with output energy up to 10^7 J). A 953 W Yb:YAG laser (Huges Co., USA) and a 100 W diode-pumped fibre laser were developed. The main obstacle to the extensive application of laser diodes is the high cost (100 USD/W) rather than the operating conditions. However, their cost is predicted to decrease to 10 USD/W by 2000 and 1.0 USD/W by 2005.

3. Laser fusion

More than 30 reports were presented by scientific centres in the USA, Japan, Russia, China that carry out studies on laser fusion. W Hogan and H Powell from the LLNL confirm the plan to develop at this scientific centre in several years the National Ignition Facility (NIF), which represents a laser system based on neodymium glass with an energy of ~ 1 MJ, for the experimental demonstration of laser ignition of a fusion burst in a target with the useful energy output.

Along with the development of megajoule laser facilities, such as NIF and LMJ (France), scientific centres in the USA and Japan carry out extensive studies on the development of repetitively pulsed laser drivers for target ignition in reactors of future thermonuclear plants. S Payne from the LLNL made a report on tests of the components of a prototype of a laser system of this kind (Mercury), which operates at a wavelength of about 1 μm on Yb^{3+}-doped crystals. Crystals are pumped by laser diode bars in the 900 nm spectral band, and the active medium is cooled by an inert gas flow.

At the Institute of Laser Engineering, Osaka University, an operating prototype of an amplifying module of a water-cooled repetitively pulsed laser driver on neodymium glass was developed (the report of T Kanabe, S Nakai, M Nakatsuka, et al.). The module is designed to produce 10 J laser pulses with a repetition rate of 10 Hz. An active slab $20 \times 523 \times 119$ mm in size, made of an HAP-4 glass (Hoya Corp.), is pumped by two 803-nm AlGaAs laser diode arrays of size 400×10 mm with a power density of 2.5 kW cm^{-2} (Hamamatsu Photonics). A laser beam travels in a slab along a zig-zag path and there undergoes more than 10 total internal reflections. At a 0.5 Hz pulse repetition rate, the following amplifier parameters were experimentally obtained: 8.5-J output power at 1053 nm, 20 ns pulse duration, output beam 20×10 mm in size, 10% efficiency, and the angular divergence exceeding the diffraction value only by a factor of two. The authors noted that water-cooled active elements of this type can be used to develop amplifying modules with output energy of 1 and 10 kJ.

Japanese scientists developed a conceptual project of a thermonuclear plant Koyo, which incorporates four 600-MW reactors. The project uses a 32-beam diode-pumped laser system operating at 351 nm. This laser driver has an energy of 4 MJ and a pulse repetition rate of 12 Hz, and its efficiency is 10%.

The possibility of using high-power explosion-pumped lasers for laser fusion was discussed in the report of G A Kirillov, V A Eroshenko, et al. (Institute of Experimental Physics, Russian Federal Nuclear Centre). In experiments with iodine explosion-pumped lasers, an energy of 5 kJ in 5 ns pulses was obtained, and the focusing of radiation (a 1-ns pulse with an energy of 100 J) on an area 2 μm in diameter was demonstrated.

About ten reports were devoted to studying the interaction of high-power laser ultra-short pulses with targets. These studies develop the fast ignition concept. The most interesting experiments were made on laser channels with power of 10^{14}– 10^{15} W on Nova (LLNL) and GEKKO XII (Osaka University) facilities and in the Rutherford Laboratory, Appleton (UK).

In the report of M Key (USA), the results of experiments on a petawatt channel of the Nova laser were discussed. In a series of experiments on irradiation of plane polyethylene targets, 40–50% conversion of laser energy to relativistic electrons with energy of the order of 10 MeV was observed. The irradiation of a CD_2 plate by a 5 ps pulse with an energy of 180 J was found to give 2.45 MeV neutrons with a yield of 6×10^4, which were produced in thermonuclear DD reactions caused by heating the bulk of the plate with high-energy electrons. Moreover, approximately 7% of the laser pulse energy was found to be transformed into a collimated proton beam with energy of about 55 MeV, which travelled along the normal to the rear surface of the target. When the proton beam passed through Be and Ti plates, nuclear reactions $Be^9(p)B^{10}$, $Be^9(p,n)B^9$, $Ti^{48}(p,n)V^{48}$, and so on were observed. The authors proposed the use of proton beams obtained with a high-power laser for fast ignition of a preliminarily compressed core of a thermonuclear target.

In the experiments on irradiation of plane targets with high-power USP on the 100-TW laser channel of Osaka University (the report of K Mima et al.), 20% energy conversion of laser radiation to high-energy electrons was observed. In the report presented by a large group of scientists from the Rutherford Laboratory, the study of the angular distribution of quanta produced upon deceleration of relativistic electrons in a target was described. The angular distribution of quanta after the burst was determined by analysing the distribution of isotopes produced in photonuclear reactions in a reference copper plate placed behind the target. A similar diagnostics of the angular distribution and spectrum of gamma quanta using gold isotopes (from ^{197}Au to ^{191}Au) is employed on the petawatt laser channel at the LLNL.

The greatest number of reports (about 20) on thermonuclear studies were presented by the Japanese scientists who organized the forum. We note here the works from the Institute of Laser Engineering, Osaka University, devoted to the study of hybrid heating and compression of thermonuclear targets (the indirect/direct hybrid drive scheme, which uses indirect x-ray irradiation of a target), the technology of targets, new media for laser drivers (neodymium-doped silica glass), the system for laser radiation focusing onto a target, etc.

It is likely that the possibility of modelling astrophysical phenomena with the aid of high-power lasers, which was discussed in the literature, found one of the first confirmations in the work of the group of Japanese scientists (H Takabe, K Mima, M Nakatsuka, et al.) from the Institute of Laser Engineering. Using three channels of the GEKKO XII facility, they irradiated a high-density spherical target coated with a low-density foam (laser intensity of 2×10^4 W cm^{-2} at 0.53 μm). X-ray photographs obtained with a gated camera demonstrated the propagation of a shock wave and dense plasma flows in the foam layer and their collision. The photographs of a microburst of a target with typical size of 0.1 mm indeed resemble the photographs of consequences of the SN 1987A supernova explosion shown on the conference. On these photographs, the collision of explosion products with the substance of the gaseous cloud surrounding the supernova (on astronomical scales of $\sim 10^8$ km) is recorded.

4. Laser applications in space

One such application is the use of high-power lasers for space debris removal from circumterrestrial orbits by imparting the recoil momentum to a space object, which results in a change in its orbit and its subsequent burning in dense atmospheric layers. In particular, the Orion project (USA) was discussed, which aims to develop a high-power laser system, scanning and guidance systems.

Several reports from the USA on this problem were included in the program, but they were not presented.

One more application is the realisation of idea A Kantorowitz's published in 1972, which proposes the use of the recoil momentum produced in the interaction of high-intensity laser radiation with matter to obtain 'laser thrust'. In his report, W Bohn (Deutsche Forschungsanstalt für Luft und Raumfahrt (DLR), Germany) gave a brief review of studies on this problem. In particular, the works of L Myrabo (Air Force Research Lab., USA) were noted: the project of application of a 100-MW laser for carrying an object into a circumterrestrial orbit (1988) and the experiments made in 1997–98 on the - White Sands proving ground (New Mexico, USA). In these experiments, a specially designed vehicle, 25 g in weight, with a focusing specular reflector was launched at a height of $\sim$ 30 m by using a 30 Hz repetitively pulsed e-beam controlled discharge CO_2 laser with a pulse energy of $\sim$ 300 J. In the USA, the feasibility of launching a 1-kg object into an orbit 100 km in diameter is studied.

At the DLR, Germany, where a 5-kW repetitively pulsed e-beam controlled discharge CO_2 laser was used, $\sim 20 - 55$ g objects were raised by laser radiation (40 pulses with a repetition rate of 45 Hz) at a height of 6 m (the laboratory ceiling). However, it should be noted that the object was stabilised by a wire, which directed its motion, in contrast to Myrabo experiments, who used object rotation for this purpose. Estimates show that one needs a repetitively pulsed laser with an average power of 400 kW to launch a 10 kg object into a 150 km circumterrestrial orbit.

In the report of Y Tsujikawa (Osaka Prefecture University, Japan), the Japanese program of laser applications in space was discussed. One such application is the transfer of a space object from a low-lying orbit to a geostationary one by using a high-power airborne laser. It is supposed to carry on an An-225 aircraft a 200 Hz repetitively pulsed laser with pulse energy of 1 kJ, pulse duration of 0.1 ns, and efficiency of 10%. It is assumed that the laser system will consist of a 4-t laser, a 50-t power supply, and a 10-t cooling system.

This laser is scheduled for operation in 2015, whereas similar lasers with average power of 10 and 20 kW are scheduled for 2005 and 2010. The object transportation cost is assumed to be decreased by a factor of 25. Another project, which seems to be even more fantastic, is the LE-NET project (Lunar Energy NETwork system), which assumed energy transfer from space and the 'lunar energy park' to the Earth using high-power lasers. It is assumed to be designed in 2000 – 2010 within the framework of this program a Nd:YAG laser with an energy of 50 kW and arrange by 2050 in space 200 lasers, each with an average power of 100 MW.

5. Laser-triggered lightning

The development of an efficient lightning protection system is an urgent problem of contemporary industrial society. Such a system should protect electric-power transmission lines against lightning strikes and decrease the damage caused by instantaneous voltage jumps in the circuit and the failure of electrical equipment. The feasibility of using lasers for controlling lightning is of considerable scientific and practical interest. This problem attracts great attention of scientists and engineers in university laboratories and electrical engineering companies of Japan, USA, Canada, Russia, and other countries.

The problem is studied by artificial laser triggering of a lightning prior to its independent development and channeling of the electric discharge in the desired direction. The scientific investigations are concentrated mainly on laboratory studies of different factors that affect the development of spark discharges in air and on the construction of an adequate theoretical model on their basis.

It is common to use in such experiments submicrosecond CO_2 lasers with pulse energy up to a few kilojoules and excimer (XeCl or KrF) lasers with a relatively low energy from $\sim$ 10 mJ to $\sim$ 1 J, pulse duration from $\sim$ 100 fs to $\sim$ 10 ns, and a repetition rate up to 1 kHz. Using IR radiation of high-energy CO_2 lasers, which possess the lowest threshold of optical breakdown in air, plasma channels of up to several meters long are produced.

As a rule, a spark produced by an IR laser breakdown has a discrete structure, which consists of several areas of a strongly ionised plasma. Because of this, a certain amount of time is required to form a continuous conducting channel capable of closing the electric current. UV excimer lasers are predominantly used to produce very narrow and extended weakly ionised plasma channels due to high-efficiency multiphoton oxygen ionisation, increasing electron emission from high-voltage electrodes, and controlling electron detachment from electronegative O^- and O_2^- ions produced in weakly ionised air.

In hybrid schemes, which are generally agreed to offer the greatest promise for future lightning protection systems, a CO_2 laser is used as a trigger mechanism initiating a lightning bolt, and the excimer laser radiation guides the discharge. The longest weakly ionised channel ($\sim$ 200 m) was obtained in the experiments of B La Fontaine et al. (INRS Energie et Materiaux, Canada) owing to the nonlinear propagation and filamentation of femtosecond laser pulses. For UV laser radiation, the characteristic electron concentration in a channel 100 μm in diameter reached $\sim 10^{13}$ cm^{-3}, whereas this concentration in the case of IR radiation was an order of magnitude lower. The authors were able to direct sparks of length about 2 m by means of such weakly ionised channels, but no reduction in the breakdown voltage was observed in this case.

Focusing of the USP in the gap between two electrodes with the voltage 1.5 MV across them, which was accompanied by the formation of a strongly ionised plasma, initiated a discharge up to 5 m long, and the breakdown voltage was decreased by a factor of about two. One of the substantial restrictions imposed on the use of this technique in field experiments is the complexity and high cost of an excimer laser system for the production of USP. For example, the multistage system used by J C Diels et al. (University of New Mexico, USA), which emitted 500 fs UV pulses with an energy of 60 mJ and a repetition rate of 10 Hz, consisted of a master oscillator, a pulse stretcher for increasing the pulse length, a regenerative amplifier, a three-pass Ti:sapphire amplifier, a pulse compressor, a frequency multiplier, and several KrF amplifiers.

Laser-triggered discharges induced by the simultaneous action of laser radiation at different wavelengths was studied by the Japanese (M Uchiumi et al., Kyushi University and Kyushi Electric Power Co.) and Russian scientists (Yu Rezunkov et al., Research Institute for Complex Testing of Optoelectronic Devices). In the first work, the authors studied the optimum methods of focusing CO_2 (460 J, 50 ns) and XeCl (2 J, 40 ns) laser beams to decrease the breakdown voltage. In the second work, the delay between the main pulse of a CO_2 laser and a supplementary pulse of an Nd laser was varied.

Of most interest was the report of S Uchida et al. (Institute for Laser Technology, Osaka University, and Kansai Electric Power Co. Inc, Japan) devoted to the starting up of field experiments on the first-in-the world laser lightning protection system on the Japan Seashore (Dakeyama, Fukui prefecture). This place was chosen for the experiments because of frequent and strong winter thunderstorms caused by the collision of cold and warm atmospheric fronts. The test station is built at the top of a mountain. It includes a monitoring system, which indicates the approach of a thunderstorm front, and a 50-m tower. The CO_2 laser radiation (two beams with a pulse energy of 2 kJ and a pulse power of 20 GW) focused by a large-aperture (up to 1 m) optical system produced at the tower top a plasma filament directed toward a thundercloud.

Preparing the laser system for operation was terminated by a signal from a slow electrostatic detector, which responded to an increase in field strength. Another (fast) detector, which detected the so-called preliminary breakdown in thunderclouds, fired the laser system with a microsecond accuracy. At least two events of successful lightning connection to a 'plasma lightning rod' were recorded by video cameras and an electromagnetic wave interferometer. The development of a hybrid system on the basis of CO_2 and excimer lasers are included in future plans.

6. Laser ablation of materials by short and ultrashort pulses

This is a new field of research in laser engineering. The quality of laser ablation processing of surfaces of different materials (metals, semiconductors, polymers), i.e., the formation of microstructures on these surfaces by femtosecond pulses, is found to be substantially higher than in the case of surface processing by longer pulses. The reports on laser ablation by short (nanosecond) and ultrashort (pico- and femtosecond) pulses presented at the conference encompassed the follows problems:

— experimental and numerical study of the mechanisms of ablation of metals and other materials (graphite, sapphire) by pulses of Nd and excimer lasers;
— experimental and numerical optimisation of the parameters of a crater formed upon metal ablation by a train of laser pulses;
— production of thin films with specific properties (including diamond-like films) by forming one or two interacting ablation plumes propagating towards a substrate where a film is formed;
— experimental study of a biological tissue ablation by excimer lasers for medical applications;
— comparison of ablation efficiencies for ultrashort (pico- and femtosecond) and short (nanosecond) pulses;
— experimental study of the possibility of using combined methods, in particular, the action of laser pulses on a target that is simultaneously blown off with a gas or a gas mixture;
— laser removal of oxide films from a metal surface;
— detection of nanoclusters formed by laser ablation;
— theoretical and numerical modelling of the dynamics of electron and phonon excitation and relaxation upon irradiation of a solid surface by subnanosecond laser pulses; and
— laser ablation of polymers by USP.

Note the most interesting and typical works in which these problems were studied. The greatest number of reports on laser ablation was presented by French scientists (CNRS University of Marseille). M Autric reported results of the experimental and numerical study of thin film formation. The experimental method consisted in generating two ablation plumes by KrF laser pulses that interact with each other and propagate towards a substrate. The use of two plumes substantially improves the quality of a film deposited on a substrate. The main advantage of this technique is the good homogeneity of the film, and the main drawback is the transfer of microparticles to the substrate.

The Japanese scientists from the National Institute of Materials and Chemical Research experimentally studied graphite ablation by 8 ns Nd:YAG laser pulses. They studied the distribution of ablation products (neutral atoms and carbon ions) depending on the energy density in a range of 0.4 – 4.5 J cm^{-2}. This work is related to the problem of diamond-like film formation.

In the joint work of the Max Born Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany) and the Chalmers University of Technology (Sweden), laser ablation of sapphire by USP pulses was studied. The aim of the work was to distinguish two ablation mechanisms, namely, the non-thermal process (Coulomb explosion) at low energy densities and the thermal process (phase transition) at energy densities exceeding the ablation threshold.

Myocard tissue ablation by Nd:YAG and excimer laser pulses was experimentally studied by Japanese scientists (Keio University, National Defence Medical College). They studied the ablation efficiency and histological characteristics of a tissue after ablation depending on the radiation wavelength. The ablation efficiency sharply increased at wavelengths shorter than 300 nm. The thermal effect was the weakest at $\lambda = 230$ nm. In the joint work of scientists from the Oakland University (USA) and the Institute of Mechanics (China), laser ablation of steel by Nd:YAG laser pulses with a high energy density and a high repetition rate was experimentally studied. The target surface was blown off with a mixture of nitrogen and oxygen. The crater parameters were studied as functions of the laser energy density and flow rate of a gas mixture.

In almost all theoretical works (France, Germany), the authors used the two-temperature model of a metal or the time-dependent kinetic Boltzmann equation for electron and phonon gases taking into account laser radiation absorption. Note, first of all, the works of French scientists, where the applicability of the two-temperature model to the study of metal ablation by femtosecond pulses was analysed. The numerical simulation of ablation by femtosecond pulses within the framework of the time-dependent kinetic Boltzmann equation was discussed in the report of scientists from the Institut für Theoretische Physik (TU Braunschweig, Germany). The approach developed in this work makes it possible to study collisional effects under conditions of a strong deviation of a metal from the equilibrium state caused by the action of pulsed laser radiation.

7. Application of high-power lasers in manufacturing

Within the framework of this problem, the following questions were discussed:
— foundations of laser material processing;
— technology of laser material removal (drilling, cutting, etc.);
— technology of laser surface modification;
— laser welding technology;
— control instrumentation;
— industrial applications;
— new lasers for laser material processing.

The majority of reports were devoted to deep-penetration melting of metals and alloys for welding and cutting, which characterises a worldwide increase of attention to these processes.

We note that the development of physical foundations and technologies of deep-penetration melting in metals and alloys are a priority for Russian scientists (see, e.g., the works of Bunkin, Grigor'yants, and Kayukov).

Of particular interest is the series of works of Japanese authors (A Matsunawa et al., Joining and Welding Research Institute, Osaka University; H Horisawa et al., Tokai University) on the dynamics of the development of a vapour-gas channel, the development of a plasma plume, and deep-penetration melting for cutting and welding. To study the dynamics of the development of the vapour-gas channel in steels and aluminium alloys under the action of cw CO_2 lasers with a power of 5 and 10 kW and a pulsed Nd:YAG laser (30 ms pulses with an energy of 180 J), the authors used a video camera.

For cw CO_2 laser powers exceeding 5 kW, the authors observed metastabilities in the development of the vapour-gas channel, which leads to the appearance of bubbles and pores in a weld at the bottom of the channel after cooling. Metastability is caused by intense metal evaporation at the vapour-gas channel walls. The best way to eliminate instability is to use a tailored pulse. [The idea of using a tailored pulse in laser welding belongs to Russian scientists (Kayukov et al.).] Plasma was shown to be formed simultaneously with a crater. Moreover, the effect of a shielding gas on the vapour-gas channel formation was analysed.

The same processes were discussed in the reports of K G Watkins (University of Liverpool, UK), A Kar (University of Central Florida, USA), and R Fabbro (Cooperation Laser Franco Allemande, France). In the latter report, results of the interaction of Nd:YAG laser radiation with a plume were also discussed. At a pulse repetition rate of $\sim$ 15 kHz, the pressure applied to the vapour-gas channel was described by a cyclic regime. At a low repetition rate ($\sim$ 2 kHz), the vapour-gas channel developed almost in a stationary regime.

The second active line of investigation in the field of laser material processing is the use of short and ultrashort laser pulses. It includes mechanical hardening, laser cleaning, precise drilling, precise mechanical processing, periodic surface structure formation, photopolymerisation, etc. The results on precise drilling and precise mechanical processing were of particular interest. F Dausinger (University of Stuttgart) reported that 25% of the annual financial support of laser research in Germany is spent on the development of laser precise processing technologies. Among the other items are innovation studies (15%), fundamental studies (35%), laser medicine (15%), and administration costs (10%).

It is known that the limiting diameters in mechanical drilling exceed 0.5 mm for ceramics and 0.1 mm for steel. The maximum depth of precise laser drilling correlates with the radiation intensity. The best results reported at the conference were obtained using a picosecond laser with pulses shorter than 20 ps, pulse repetition rate of $\sim$ 10 kHz, and pulse energy greater than 1 mJ. The hole diameters were $\sim$ 30 μm, and the aspect ratio was $\sim$ 10.

Scientists from the National Research Council (Canada) reported their study of the mechanism of precise processing of ceramics, composite materials, etc. by radiation of a diode-pumped Nd:YAG laser. They also studied the effect of laser radiation polarisation. Scientists from Panasonic Technologies, Inc. (USA) reported results of the use of Ti:sapphire laser pulses 100 – 200 fs long for metal processing. Channels 4 – 12 nm deep were obtained in silver. For polymer processing, 20 ps pulses of a 248 nm excimer laser were used. In the case of the so-called cold (dry) material ablation, holes with diameter less than 0.5 μm were obtained. In the Oxford Laser Ltd. (UK), diode-pumped solid-state lasers and copper vapour lasers were used. Holes with diameter from 50 to 100 μm in plates 1 mm thick were obtained. The best hole quality on both sides was observed for plate thicknesses not greater than 100 μm and hole diameters of the order of 60 μm.

The most prominent examples of laser applications in manufacturing, among the reports made at the conference, are the use of a 45 kW CO_2 laser at the Nippon Steel Corporation plant (Japan) for welding rolled sheets, cutting steel with a rate of 200 mm min^{-1} by 3.8 kW Nd:YAG laser radiation, and the use of a 20 kW CO_2 laser for welding 20 mm stainless steel sheets in a single pass (Cooperation Laser Franco Allemande, France and Fraunhofer Institute für Laser Lasertechnik, Germany).

8. Laser applications in mining

The interaction of laser radiation with rocks was extensively studied beginning from the late 1960s in the USA, USSR, and other countries. The majority of studies were made with 0.5 – 1.0 kW lasers. However, by the mid-1980s, interest in this problem vanished, most likely due to the unavailability of high-power lasers ($\sim$ 10 kW and higher) to the investigators, the absence of mobile laser systems, and the absence of financial support (in the USSR).

Studies of the interaction of radiation from the 0.5 – 1.2 MW MIRACL HF(DF) laser with rocks performed by American scientists (R Graves and D O'Brien from the Colorado School of Mines) on the White Sands proving ground (New Mexico, USA) showed that the rock excavation rate could be increased by an order of magnitude compared to conventional techniques, which rekindled interest in laser applications in mining.

This forum was the first one among laser conferences where a section on laser boring and destruction of rocks appeared. It predominantly presented the works of Japanese scientists. In their opinion, this is an urgent problem in Japan, where earthquakes produced a large number of rock slopes found in a critical condition, and because of this, they endanger public safety.

The use of lasers to drill holes for explosive and destroy rocks is of considerable importance because conventional rock destruction methods, which are accompanied by mechanical shocks and vibrations, are able to destroy a rock slope. D Sugimoto et al. (Tokai University, Japan) used a 13 kW cw CO_2 laser to drill granite and tuff.

In the case of granite drilling with lasers, the excavation rate decreased from 0.8 to 0.7 mm s^{-1} with increasing hole depth from 3 to 12 cm. The estimate of the average excavation rate in the case of boring a pit $\sim$ 8 m long with 50 kW CO_2 laser radiation gave 2.76 mm s^{-1} for tuff and 1.23 mm s^{-1} for granite. For tuff, the laser excavation rate was higher by a factor of two than the rate of mechanical drilling. The authors propose to develop a mobile 50 kW oxygen-iodine laser for applications in mining.

Experiments on laser cutting sandstone and granite by CO_2 laser radiation with power up to 10 kW were performed by K Nagai (Taisei Corp., Japan). The cutting rate reached 3 m min^{-1}, with a cut thickness as large as 10 mm. The maximum cut thickness of 63 mm was obtained for radiation power of 10 kW (the cutting rate was $\sim$ 100 mm min^{-1}). The author demonstrated the advantage of the combined granite drilling technique. Laser radiation acting on a material causes cracking and makes it more brittle, and subsequently mechanical drilling (with a drill up to 2 cm in diameter) is used. A two-beam Nd:YAG laser with a total radiation power of 6 kW was used in field experiments in the mountains (M Sato, Geoscience Research Laboratory, Japan). The 7 min laser irradiation of a rock produced there a hole 2 cm in diameter and 20 cm long.

9. Laser decommissioning and decontamination of nuclear reactors

S Saishu (Nuclear Power Engineering Corp., Japan) reported model experiments on cutting inner parts of a nuclear reactor (during its dismantling) $\sim$ 10 – 30 cm thick by 20 kW CO_2 laser radiation. Nd:YAG lasers were also considered as promising sources of high-power radiation for dismantling nuclear reactors. To clean decontaminated surfaces, a Q-switched Nd:YAG laser ($\tau = 12$ ns) was used. The ablation of a surface layer under the action of laser radiation, the radioactivity of a surface contaminated with ^{60}Co was decreased from 359 to 0.22 Bq/g. Remote cutting of technological elements of a nuclear reactor, removed from its active zone, by 5 kW CO_2 laser radiation was reported by B Ya Panchenko et al. (NICTL-Laser Research Centre, Shatura, Russia).

H Okado et al. (Kawasaki Heavy Industries, Ltd., Japan) reported results of underwater cutting by radiation of a 7 kW oxygen-iodine laser. Radiation was transported to an object by an optical fibre. To form a 10 mm gas-filled gap between the fibre end and a workpiece, the surface was blown off with an oxygen flow outgoing from a supersonic nozzle.

H Tanaka (Tokai University, Japan) reported that the use of a 30-kW oxygen-iodine laser for cutting concrete 1 m thick provided a cutting rate of 13 mm min^{-1}. These data are valuable for developing a conceptual design of a mobile oxygen-iodine laser for dismantling of nuclear facilities. The feasibility of using an oxygen-iodine laser for laser dismantling of nuclear reactors is also studied in the USA (W C Solomon, University of Illinois, Urbana).

10. High-power solid-state lasers

At the conference, the main attention was focused on high-power laser diodes and linear diode arrays, fibre lasers, and diode-pumped lasers. The main information on diode-pumped lasers is presented in the 'Plenary session' section. S Nakamura (Nichia Chemical Industries, Ltd., Japan) reported the achievement of an output power of $\sim$ 420 mW in a quantum-well InGaN laser diode (in the case of lasing on a single transverse mode, the power was 100 mW).

In Germany (F Dorsch et al., JENOPTIK Laserdiode GmbH), a cw 2-kW system on the basis of laser diodes was developed. Its radiation is transported to a workpiece by an optical fibre, and the radiation intensity on a sample is $\sim$ 200 kW cm^{-2}.

V Reichel (Institut für Physikalische Hochtechnologie e.V. Jena, Germany) described a very compact (shorter than 10 m) fibre laser (Yb-doped quarts) with an output power of 5 W and an efficiency of 65%. The efficiency of diode pumping of a 1 kW rod Nd:YAG laser was increased up to 46%, with electrical-to-optical efficiency being as high as 52% (A Takada, Corporate Engineering Centre, Toshiba Co., Japan). The authors also obtained radiation power of 3.3 kW using a multihead laser configuration.

11. High-power gas lasers

Japanese scientists are known by their developments of high-power CO lasers. K Shimizu (Institute of Research and Innovation, Japan) described a compact rf-pumped CO laser with output power as high as ~ 1 kW. The laser operates at room temperature, and the rate of axial circulation of a gas mixture is ~ 200 m s^{-1}. A laser tube is 300 mm long and 30 mm in diameter. An increase in the pump modulation frequency from 13.56 to 27.12 MHz increased the output power by 10 – 20%. When the $CO - N_2 - He - O_2$ mixture was used, the output power and the laser efficiency reached 830 W and 12.2%, respectively. The addition of a cheaper Kr gas to the laser mixture to increase the output power was more efficient than the addition of Xe. The output power and the efficiency were 910 W and 14.8% for Kr and 810 W and 16.2% for Xe. To obtain stable and high-power lasing, it is extremely important to decrease the H_2O concentration in a laser mixture down to 260 ppm or even lower.

As for excimer lasers, the majority of data was presented on repetitively pulsed electric-discharge XeCl lasers with x-ray preionisation and an average output power of up to 1 kW. They were studied in Nederlands Centrum voor Laser Research (Netherlands), Universites Aix-Marseille I&II and SOPRA company (France), and Frascati Research Ctr. / ENEA (Italy). The main goals of present-day studies in this area, after demonstrating a kilowatt average power some years ago, are the formation of a high-quality laser beam and the control of laser duration and high output power.

Combining homogeneous gas ionisation in a discharge gap with an improved circuit of a discharge power supply and using an unstable cavity, the Holland scientists managed to increase the laser pulse duration and obtain a nearly-diffraction divergence of laser radiation. A laser with such parameters is able to drill holes with diameter from 10 to 100 μm in different materials, such as metals (aluminium, steel, titanium, nickel), plastics, ceramics, and composites, with an average rate up to 1000 holes per second.

A high beam directivity was also demonstrated by the authors from the Frascati Research Ctr. In their experiments with a XeCl laser with two discharge chambers, the radiation divergence in the oscillator-amplifier system was held close to the diffraction limit with increasing pulse repetition rate up to 50 Hz.

The oscillator-regenerative amplifier scheme was also used in the experiments of French scientists to obtain relatively short pulses (1 – 3 ns long) with energy of the order of 1 J, which give a peak intensity of $10^{11} - 10^{13}$ W cm^{-2} for radiation focused onto a target. This laser can be used to develop an efficient source of soft x-rays on the basis of laser-produced plasma for x-ray microscopy, microlithography, radiobiology, etc.

Powerful high-energy e-beam-pumped KrF lasers were only presented by the works of Japanese scientists from the Electrotechnical Laboratory. In the work devoted to the development of a laser pulse compression system for the ASHURA installation on the basis of SRS, the authors used direct amplification of a Stokes pulse at 268 nm, which was obtained in a cell with a methane-hydrogen mixture, in an SRS preamplifier and a five-pass amplifier. The pump energy was converted in the amplifier with an efficiency of 73%, and the amplification was accompanied by pulse shortening from 25 to 5 ns.

In another work, the development of a HV power supply for electron accelerators (300 kV, 80 ns) was reported. It is designed on the basis of pulse-forming lines with water isolation and magnetic switches for the repetitively pulsed laser developed in the laboratory. Moreover, the design of a cooled vacuum-tight window was discussed, which is used to outcouple an electron beam into a laser chamber, where the authors intend to use a foil made of HAVAR alloy instead of a commonly used titanium foil. This foil has a high strength, a good thermal conduction, and a high resistance against fluorine.

12. X-ray lasers

This area of study was presented by the works of American, French, Japanese, and Chinese scientists. Along with the search for new active media with the collisional excitation mechanism for emission of soft x-rays in the wavelength range from units to tens of nanometers, the optimisation of presently existing Ne- and Ni-like schemes in a laser plasma was carried out to improve the time and spatial coherence of radiation. Considerable attention was also devoted to applications of these lasers and efforts to make them a customary instrument for various studies in other areas of physics.

A group of French scientists (Univ. Paris-Sud / CNRS) obtained lasing on the transitions of Ne-like iron and zinc at 25.5 and 21.1 nm, respectively, and on the transitions of Ni-like silver at 13.9 nm in a laser plasma produced on the LULI high-power multibeam Nd laser system by several laser pulses with duration from 100 to 600 ps and energy as high as several hundreds of Joules. They used laser beam focusing into a line 2 cm long and x-ray mirrors on the basis of multilayer Mo / Si structures.

In joint experiments of Japenese, Chinese, and French scientists on the GEKKO XII laser facility, plasma was also produced by several high-power laser pulses, which were focused from two opposite sides on two plane targets positioned with a high accuracy with respect to one another. In this scheme, which is characterised by a weaker refraction of x-rays, they managed to obtain lasing in the running-wave regime at a number of transitions of Ni-like ions of different elements at wavelengths from 13.9 (silver) to 4.6 nm (hafnium). Moreover, for tantalum and tungsten, they observed lasing at transitions with shorter wavelengths of 4.5 and 4.3 nm. These studies are aimed at obtaining high-intensity x-ray laser emission in the so-called transparency window of water for various biological applications.

Whereas the two previous works were made on large-scale laser facilities, the scientists from the Advanced Photon Research Centre (Kansai est., Japan) and the Japan Atomic Energy Research Institute described the development of a table-top x-ray laser. It is pumped by a laser system consisting of a Ti:sapphire oscillator, which produces short pulses, and a Nd glass amplifier. The system produced in two beams prepulses 1 ns long with energy of 10 J and short pulses 1 ps long with energy of 15 J. The intensity of radiation focused into a line 2 cm long reached 10^{16} W cm^{-2}. Under these conditions, nonstationary lasing at the transitions of Ne-like titanium ($\lambda = 32.6$ nm) and Ni-like silver ($\lambda = 13.9$ nm) was studied.

Considerable interest was attracted by the work of scientists from the Colorado State University (USA), where the first x-ray laser excited in a capillary discharge (rather than in a laser-produced plasma) has been developed several years ago. The laser operates on Ne-like argon at 46.9 nm, i.e., in the spectral region where x-ray mirrors and other optical elements have been developed. The output energy of laser pulses following with a repetition rate of 4 Hz reaches 1 mJ. Because of the relative simplicity and the small size of this laser, it is a real laboratory instrument. The report demonstrated its applications for taking shadowgrams of a dense plasma of a capillary discharge and the interferometry of laser-produced plasma. In both cases, a small radiation wavelength enables one to probe plasma regions with a high electron density, which cannot be probed by conventional optical methods.

13. Free-electron lasers

A free-electron laser emitting ~ 0.7 ps pulses with a kilowatt average power and a repetition rate of ~ 75 MHz in the $2-8$ μm wavelength range was developed at the Thomas Jefferson National Acceleration Facility, USA (the report of G R Neil et al.). The authors are going to increase the output laser power above 10 kW in the near-IR range and up to kilowatt levels in the $0.3-60$ μm range. The free-electron laser developed at the Japan Atomic Energy Research Institute, works in the quasi-continuous regime with a power of ~ 0.1 kW (E J Minehara). The program goal is to increase the output power up to 1 kW. A conceptual design of an industrial 20 kW cw, 1.5 μm free-electron laser was discussed.

A more detailed information on the forum is presented in Proc. SPIE (vols. 3885 – 3889).