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各种材料的激光精密微加工

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Laser Precision Microprocessing of Materials

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Symbols and abbreviations

ALTI – automated laser technological installation
AM – active medium
AE – active element
MPG – master pulses generator
NPG – nanosecond pulse generator
MO – master oscillator
HAZ – heat-affected zone
PS – power supply
GVL – gold vapour laser
CVL – copper vapour laser
LPMET – metal vapour lasers
DSL – dye solution laser
CVLS – copper vapor laser system
NC – nonlinear crystal
UR – an unstable resonator
OE – optical element
SFC – spatial filter collimator
PA – power amplifier
PRF – pulse repetition frequency
ELTI – experimental laser technological installation
EOT – electroerosion treatment
c – speed of light
C_{cap} – capacity of the storage capacitor
C_{sc} – capacity of the sharpening condenser
D_{chan} – diameter of the discharge channel
n – number of double passes of radiation in the resonator
p_{Ne} – neon buffer gas pressure
P_{EA} – power input into the AE

P_{ext} – power consumed from the rectifier of the power source
P_{rad} – average output power
λ – wavelength of the radiation
l_{AM} – length of the active medium
l_{chan} – length of the discharge channel
L – length of the optical resonator
F – focal length of the lens
M – gain of the optical resonator
R – radius of curvature of the mirror
T_c – temperature of the discharge channel
τ – time of population inversion existence
τ_{time} – pulse duration
θ – radiation divergence
θ_{dif} – diffraction divergence of radiation
ρ – peak radiation power density
V_{AM} – volume of the active medium
U – voltage
W – energy in the radiation pulse

Introduction

The development of the electronic industry, with the further miniaturization of electronic components and the use of new materials, puts ever-increasing demands on the quality, reliability and competitiveness of manufactured products. That, in turn, makes higher demands on the parameters of the components, thus dictating the creation of new technologies and technological processes. A special recognition was given to laser technologies for microprocessing. In this case, the function of the processing tool is performed by a high-intensity focused light spot. To ensure high quality of machining, the tool should provide the following parameters – micron width of cut (1–20 μm), minimal heat-affected zone (≤3–5 μm) and roughness (≤1–2 μm). The radiation sources in the microprocessing equipment include short-pulsed, high-frequency lasers with a low energy in the pulse and a small reflection coefficient of the visible and ultraviolet radiation spectrum: solid-state, excimer, nitrogen and, in particular, lasers and laser systems on copper vapour (copper vapour lasers (CVL) and copper vapour laser systems (CVLS)). CVLs belong to the class of gas lasers on self-terminated transitions of metal atoms that generate on transitions from resonant to metastable levels [1–8].

CVL and CVLS with emission wavelengths λ = 510.6 and 578.2 nm, short pulses duration (τ_{pulse} = 20–40 ns), and high amplification of the active medium (AM) (k = 10^1–10^2 dB/m), the removal of medium power from one active element (AE) to 750 W, high pulse repetition rates (f = 5-30 kHz) and low pulse energy (W = 0.1–10 mJ) remain today the most powerful pulsed coherent radiation sources in the visible region of the spectrum. With these parameters and provided that the structure of the output radiation is single-beam and has a diffraction quality, the peak power density in the focused spot (d = 5–20 μm), even at relatively small values of the average power (P_{rad} = 1–20 W), reaches very high values – ρ = 10^9–10^{12} W/cm^2, sufficient for effective microprocessing of metallic materials and a large number of dielectrics and semiconductors [8–62]. The spectrum of processed materials includes: heat conducting – Cu, Al, Ag, Au; refractory – W, Mo, Ta, Re and other metals – Ni, Ti, Zr, Fe and their alloys, steel, dielectrics and semiconductors – silicon, polycrystalline diamond, sapphire, graphite, carbides and nitrides and transparent materials [15, 16, 20, 26].

More than four decades after the first generation of the CVLs was by the efforts of a number of scientific teams, primarily Russia, the USA, England, Australia and Bulgaria, these lasers were established both with the basic physical principles of work and design, and specific applications in science, technology and medicine. The bulk of the research was devoted to the 'pure' CVL operating in a mixture of the neon buffer gas and copper vapour at a discharge temperature of 1500–1600°C. In the last 10–15 years, researchers and developers have increased interest in its varieties operating at the same *r–m* junctions, but at relatively low temperatures (300–600°C) and higher repetition rates (up to hundreds kilohertz) to lasers on copper halides (CuCl, CuBr, and CuI) and 'hybrid' (with the pumping of a mixture of HBr, HCl, Br_2 or Cl_2 and Ne), and also with 'enhanced kinetics' (with the addition of H_2 or its compounds) [19, 35]. But on copper halides and 'hybrid' CVLs, without appreciable performance, the service life and stability of the output parameters remain relatively low for today, which is due to the instability in time of the composition and properties of the multicomponent gas mixture of the active medium (AM). Therefore, today, from the point of view of industrial production and practical application, the advantage remains on the side of 'pure' CVLs and with 'enhanced kinetics'.

At low radiation power levels (1–20 W), the CVL is designed constructively as a separate generator (monoblock) with one low-power active element (AE) and an optical resonator. To obtain the average (20–100 W) and especially high (unit or tens of kW) radiation power levels, CVLSs operating according to the master oscillator–power amplifier (MO–PA) scheme with one or several powerful AEs as PAs are used with a preamplifier (PRA), located in front of the PA. In the CVL of the MO–PA type, in comparison with the CVL operating in the single-generator mode, higher efficiency and the quality of the output beam are achieved [16, 20].

The CVL remains the most efficient (30–50% efficiency) source for pumping lasers on solutions of organic dyes (DSL) tunable along wavelengths in the near infrared region of the spectrum, non-linear crystals of the BBO type, KDP, DKDP (efficiency 10–25 %), transforming the generation of CVL into the second harmonic – λ = 255.3, 289.1 and 272.2 nm, i.e., into the ultraviolet region of the spectrum and titanium sapphire (Al_2O_3: Ti^{3+}), which converts generation to the near-IR region spectrum, and then with the help of the non-linear crystal – from the IR region to blue. The use of CVL with DSL and the non-linear crystal allows us to practically cover the wavelength range from the near UV to the near IR spectral region and, accordingly, to expand the laser's functional capabilities. Such tunable pulsed laser systems are unique and preferable for both practical and scientific spectroscopic studies and microprocessing by UV radiation [15, 16, 20, 21, 31].

A special place is occupied by the use of CVLs in combination with DSL tunable in wavelengths in high-power laser systems of the MO–PA type. Powerful CVLs of the MO–PA type are used mainly in the isotope separation system according to AVLIS technology, which uses a difference in the absorption spectra of atoms of different isotopic composition. This progressive optical technology makes it possible to produce substances with the necessary level of enrichment and high purity for use, primarily in nuclear power engineering and medicine [15, 16, 20–23, 32, 37].

A promising area of development for CVL is also medicine. Multifunctional modern medical devices such as Yakhroma-Med and Kulon-Med for use in oncology, low-intensity therapy, dermatology and cosmetology, microsurgery, etc. are created on its basis. This class of equipment is the leader in laser non-ablative technologies. Laser pulses act on the body's defects selectively, without damaging the surrounding tissue and without causing pain (anesthesia is not required) [43–56].

In addition, CVL is used as an intensifier for the brightness of the image of microobjects, in nanotechnology, high-speed photography, for analyzing the composition of substances, in laser projection systems for imaging on large screens and in open space, in lidar installations for probing the atmosphere and sea depths, in navigation systems, water treatment, gas flow visualization, laser acceleration of microparticles, holography, forensics and entertainment industry, etc. [12, 15, 16, 20, 21, 24, 27–30, 38–42, 57].

In the technology of material processing, industrial CO_2 lasers with λ = 10.6 μm are widely used, but such heat-conducting metals as Cu, Al, Au, and Ag are not efficiently treated with CO_2 laser radiation and other infrared lasers as the reflection coefficient exceeds 95%.

Powerful IR lasers are mainly used for high-speed cutting, cutting and welding of ferrous metals and stainless steel up to 20 mm thick [21, 25].

A widely distributed solid-state laser based on yttrium–aluminum garnet with neodymium (Nd:YAG laser) with λ = 1064 nm and frequency doubling with λ = 532 nm is close to the CVL in terms of spectrum, power, and efficiency, because of the appearance of thermal deformations in the active element, has relatively large divergences. Nd:YAG-lasers are widely used for marking and engraving parts and assemblies in the production process, for welding metals, including aluminum, in medicine and location [21, 25, 26, 58–61].

Lasers similar to the CVL are the solid state (SS) disk o the yttrium–aluminum garnet (Yb:YAG laser) at λ = 1030 nm and other SSs with pico- and femtosecond durations, for example, the German company Rofin-Sinar Laser and TRUMPF [21, 26], designed for drilling microholes in stainless steel up to 1 mm thick for injectors. Development of ultrashort pulse of the solid-state lasers was successfully conducted in a number of advanced countries (France, England, Latvia, etc.). The main distinguishing feature of laser systems with ultrashort pulses is that due to the low thermal impact on the base material and without the formation of a melt, the best microprocessing quality and high resolution are achieved. These lasers are used where it is impossible to achieve high quality of microprocessing by other lasers, for example, when drilling nozzles for injections, manufacturing medical stands and display glasses, etc. To their disadvantage today is a low average radiation power (1–10 W) and high cost.

At the stage of rapid development, highly efficient ytterbium (Yb) fiber lasers with wavelengths of 1060–1070 nm and an average radiation power of 10–50000 W continue to be developed and produced by the international research and production group IPG Photonics Corporation and IRE–Polyus [25, 62–64]. However, in these lasers, when operating in a single-mode pulsed regime with nanosecond duration, such high peak power densities as in CVL are not achieved, since non-linear effects and material destruction centres arise in the light-conducting fiber. Continuous fiber lasers activated by erbium and thulium with a power of 5–50 W at λ = 1530–1620 nm and λ = 1800–2100 nm, respectively, are produced. The main areas of application: precision cutting, cutting and welding of ferrous and non-ferrous metals, hardening and surfacing, marking and engraving, telecommunications and medicine.

Excimer gas lasers on halogen compounds on an inert gas (ArF, KrF, XeCl, XeF) and inert gas dimers (Ar, Kr) operate like a CVL in a pulsed mode with nanosecond duration, but have shorter radiation wavelengths – λ = 157; 193; 248; 282; 308; 351 nm [21, 25, 65, 66], i.e., they are generated in the near-UV range. This is their advantage for wide application in lithography processes in semiconductor manufacturing, in eye surgery, as well as in dermatology. However, due to the relatively large divergence and the smaller working pulse repetition frequencies (not more than 1–5 kHz), the quality and productivity of material processing is reduced, and this class of lasers is used mainly for the processing of plastics, ceramics, crystals, biological tissues.

Diode (semiconductor) lasers are small in size and can be produced in large batches at relatively low costs. Most diode lasers generate in the near-IR region – λ = 800–1000 nm. They are reliable and durable, but the output power of a single element is limited and have a high radiation divergence. The diode lasers are used in many spheres of human activity, mainly in the telecommunications and optical memory sectors [21, 25, 67, 68], and are also used in large quantities as pumping sources for solid-state and fiber lasers. The developed technology of adding single diodes to diode lines allows to increase the average laser power to 1–3 kW, which is enough for high-performance and high-quality welding, for example, aluminium parts.

The above comparative analysis of the characteristics of CVL with other known types of technological lasers confirms that the CVL remains a promising quantum device in terms of the set of radiation output parameters, primarily for the microprocessing of materials of electronic equipment and selective technologies for isotope separation, and also in spectroscopy, image brightness amplifiers, medicine and other fields of science and technology.

Figure I1 represents the global market for laser sales from 2007 to 2015, Fig. I2 shows structure of the world market of laser sources radiation for 2014 [69].

Figure I.3 presents the dynamics of the global sales volume of all types of lasers by years for the acquisition of technological equipment [69].

Technological equipment uses CO_2, solid-state, fiber, and excimer lasers. The use of CVL in specialized equipment, in spite of the unique combination of its output parameters, is extremely limited, due to the small number of commercial models on the market with

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