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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Laser Precision Microprocessing of Materials
# Contents

Symbols and abbreviations  ix  
Introduction xi  

1. Overview of the present state and the development of copper vapour lasers and copper vapour laser systems 1  
   1.1. Discovery and first investigations and design of copper vapour lasers 1  
   1.2. The condition and development of CVL in Russia 3  
   1.3. The condition and development of CVL and CVLS in foreign countries 18  
   1.4. The current state and development of the CVL and CVLS in the Istok company 26  
   1.5. Conclusions and results for chapter 1 36  

2. Possibilities of pulsed copper vapour lasers and copper vapour laser systems for microprocessing of materials 41  
   2.1. The current state of the modern laser processing equipment for the processing of materials and the place in it of pulsed copper vapour lasers 41  
   2.2. Analysis of the capabilities of pulsed CVL for microprocessing of metallic and non-metallic materials 43  
   2.3. Equipment MP200X of Oxford Laser for microprocessing 51  
   2.4. The main results of the first domestic studies on microprocessing at the Kareliya CVLS and installations EM-5029 54  
   2.5. The first domestic experimental laser installation (ELI) Karavella 55  
   2.6. Conclusions and results for Chapter 2 66
## Contents

3. **A new generation of highly efficient and long-term industrial sealed-off active elements of pulsed copper vapour lasers of the Kulon series with a radiation power of 1–20 W and Kristall series with a power of 30–100 W**

   3.1. Analysis of the first designs of self-heating AE pulsed CVLs and the reasons for their low durability and efficiency  
   3.2. Investigation of ways to increase the efficiency, power and stability of the output radiation parameters of CVLs  
   3.3. Choice of directions for the development of a new generation of industrial sealed-off self-heating AE of the CVLs  
   3.4. Appearance and weight and dimensions of industrial sealed-off AEs of the pulsed CVL of the Kulon and Kristall series  
   3.5. Construction, manufacturing and training technology, basic parameters and characteristics of industrial sealed-off AEs of the Kulon and Kristall CVL series  
   3.6. Conclusions and results for chapter 3

4. **Highly selective optical systems for the formation of single-beam radiation of diffraction quality with stable parameters in copper vapour lasers and copper vapour laser systems**

   4.1. Distinctive properties and features of the formation of radiation in a pulsed CVL  
   4.2. Experimental settings and research methods  
   4.3. Structure and characteristics of radiation of CVL in single-mirror mode. Conditions for the formation of single-beam radiation with high quality  
   4.4. Structure and characteristics of the laser radiation in the regime with an unstable resonator with two convex mirrors  
      Conditions for the formation of single-beam radiation with diffraction divergence and stable parameters  
   4.5. Structure and characteristics of the radiation of CVL in the regime with telescopic UR. Conditions for the formation and separation of a radiation beam with diffraction divergence  
   4.6. Investigation of the conditions for the formation of a
## Contents

**powerful single-beam radiation with a diffraction divergence in a CVLS of the MO–PA type**  
4.7. Investigation of the properties of the active medium of a pulsed CVL using CVLS  
4.8. Conclusions and results for chapter 4  

**5. Industrial copper vapour lasers and copper vapour laser systems based on the new generation of sealed-off active elements and new optical systems**  
5.1. The first generation of industrial CVLs  
5.2. A new generation of industrial CVLs of the Kulon series  
5.3. Two-channel Karelia CVLS with high quality of radiation  
5.4. Two-channel lamp-pumped laser CVLS Kulon-15  
5.5. Three-channel CVLS Karelia-M  
5.6. Powerful CVLS  
5.7. Conclusions and results for chapter 5  

**6. Modern automated laser technological installation Karavella (ALTI)**  
6.1. Requirements for pulsed CVL and CVLS in modern technological equipment  
6.2. Industrial ALTI Karavella-1 and Karavella-1M on the basis of two-channel CVLS  
6.2.1. Composition, construction and principle of operation  
6.2.2. Principle of construction and structure of the motion and control system  
6.2.3. Main technical parameters and characteristics  
6.3. Industrial ALTIs Karavella-2 and Karavella-2M on the basis of single-channel CVL  
6.3.1. Basics of creating industrial ALTIs Karavella-2 and Karavella-2M  
6.3.2. Composition, design and operation principle of ALTI  
6.3.3. Main technical parameters and characteristics  
6.4. Conclusions and results for Chapter 6  

**7. Laser technologies of precision microprocessing of foil and thin sheet materials for components for electronic devices**  
7.1. The threshold densities of the peak and average radiation
Contents

Power of CVL for evaporation of heat-conducting and refractory materials, silicon and polycrystalline diamond 343

7.2. Effect of the thickness of the material on the speed and quality of the laser treatment 347

7.3. Development of the technology of chemical cleaning of metal parts from slag after laser micromachining 350

7.4. Investigation of the surface quality of laser cutting and the structure of the heat-affected zone 355

7.5. Development of microprocessing technology in the production of LTCC multi-layer ceramic boards for microwave electronics products 363

7.6. Conclusions and results for Chapter 7 371


8.1. The possibilities of application of ALTI Karavella for the manufacture of precision parts 373

8.2. Examples of the manufacture of precision parts for electronic components at ALTI Karavella 378

8.3. Advantages of the laser microprocessing of materials on ALTI Karavella in comparison with traditional processing methods 389

8.4. Perspective directions of application of ALTI Karavella 390

8.5. Conclusions and results for Chapter 8 395

Conclusion 397

References 401

Index 416
## Symbols and abbreviations

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

\[ P_{\text{ext}} \] – power consumed from the rectifier of the power source
\[ P_{\text{rad}} \] – average output power
\[ \lambda \] – wavelength of the radiation
\[ l_{\text{AM}} \] – length of the active medium
\[ l_{\text{chan}} \] – 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
\[ \tau \] – time of population inversion existence
\[ \tau_{\text{time}} \] – pulse duration
\[ \theta \] – radiation divergence
\[ \theta_{\text{dir}} \] – diffraction divergence of radiation
\[ \rho \] – peak radiation power density
\[ V_{\text{AM}} \] – 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/cm², sufficient for effective microprocessing of metallic materials.
Introduction

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, Br₂ or Cl₂ and Ne), and also with ‘enhanced kinetics’ (with the addition of H₂ 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 – $\lambda = 255.3, 289.1$ and 272.2 nm, i.e., into the ultraviolet region of the spectrum and titanium sapphire ($\text{Al}_2\text{O}_3$; 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 $\lambda = 10.6$ $\mu$m 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%.
Introduction

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 \( \lambda = 1064 \) nm and frequency doubling with \( \lambda = 532 \) 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 \( \lambda = 1030 \) 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 \( \lambda = 1530–1620 \) nm and \( \lambda = 1800–2100 \) 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 – $\lambda = 157; 193; 248; 282; 308; 351$ 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 – $\lambda = 800$–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 I.1 represents the global market for laser sales from 2007 to 2015, Fig. I.2 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