Comparative analysis of parameters of pulsed copper vapour laser and known types of technological lasers

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ABSTRACT

In the present paper we present the results of a comparative analysis of pulsed copper vapour lasers with visible emission wavelengths of 510.6 and 578.2 nm and pulse duration of 10-30 ns and known types of technological lasers as well as the prospects for using the copper vapor laser for microprocessing of materials.

Copper vapour laser, visible spectral range, heat-affected zone, technological lasers, microprocessing of materials.

1. INTRODUCTION

The progress of electronic engineering industry with continued miniaturization of electronic components and employment of new materials places increasingly rigorous demands on the quality, reliability and competitive performance of the manufactured products. This fact, in turn, raises the requirements on the parameters of the components inspiring the development of new technologies and manufacturing procedures. Special emphasis is put on laser microprocessing technologies employing a focused light spot as a processing tool. To achieve high processing quality the instrument must meet particular parameter requirements such as several-micrometer cutting width (1-20 μm), minimum possible heat-affected zone (≤ 3…5 μm) and roughness (≤ 1…2 μm).

2. COPPER VAPOUR LASERS

Radiation sources in microprocessing instruments may involve (and they already do) short-pulsed, high-frequency UV-vis lasers with low pulse energy and low reflectivity, e.g. solid-state, excimer, nitrogen lasers and, in

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particular, copper vapour lasers and laser systems (CVLs and CVLSs). CVLs can be classified as gas lasers on self-terminated transitions of metal atoms utilizing the transition between the resonance and metastable levels[1].

To date the CVLs and CVLSs with emission wavelengths of $\lambda = 510.6$ and 578.2 nm, short pulse duration (τ_{pulse} = 20-40 ns) and high amplification of the active medium (AM) ($k = 10^1$-10^2 dB/m), average output of a single active element (AE) up to 750 W, high pulse repetition rates (f = 5-30 kHz) and low pulse energy (W = 0.1-10 mJ) are still the most powerful pulsed sources of coherent radiation in the visible range. For these parameters and provided that the output radiation reveals single-beam structure and has high diffractive quality, the peak power density in the focused spot (d = 5-20 μm) is as high as $P_{\text{pulse}} = 10^9$-10^{12} W/cm^2 even with relatively low values of the average radiation power (P_{rad} = 1-20 W). Such peak power is sufficient for microprocessing of metallic materials as well as a large number of dielectrics and semiconductors. The scope of the processed materials includes thermally-conductive ones, e.g. Cu, Al, Ag, Au; high-melting ones, e.g. W, Mo, Ta, Re, and other metals, e.g. Ni, Ti, Zr, Fe, and their alloys as well as steel, dielectrics and semiconductors, e.g. silicon, polycrystalline diamond, sapphire, graphite, carbides and nitrides, and transparent materials[2].

Lasing from a CVL was first demonstrated more than five decades ago and since then the efforts of a number of research teams, especially the scientists from Russia, the USA, the UK, Australia and Bulgaria, have led to establishment of the basic operational and design principles for these lasers; alongside with that, particular application areas in science, technology and medicine have been pointed out. The bulk of the research efforts is focused on "pure" CVLs operating with a mixture of a buffer gas (neon) and copper vapours at the discharge temperature of 1500-1600 °C. During the past 10-15 years increasing attention of researchers and developers was attracted to its modifications utilizing the same r-m transitions but operating at relatively low temperatures (300-600 °C) and with higher pulse repetition rates (up to a hundred of kilohertz), i.e. lasers based on copper chalcogenides (CuCl, CuBr and CuI) and "hybrid" modifications (with circulation of HBr, HCl, Br_2 or Cl_2 and Ne mixture) as well as the lasers with "enhanced kinetics" (with an addition of H_2 or its compounds)[1, 3]. However, the durability and stability of the output parameters of copper chalcogenide and "hybrid" CVLs are still relatively poor with no significant efficiency gain. This fact is due to time instability of the composition and properties of the AM gas mixture. Therefore, to date "pure" CVLs and the lasers with "enhanced kinetics" have the advantage over the considered modifications in the context of commercial production and practical use[1-3].

In the case of low radiation power (1-20 W) a CVL usually is designed as a separate generator (single unit) with one low-duty AE and optical cavity. To achieve moderate (20-100 W) and, in particular, high (from few to tens of kW) radiation power the CVLSs implementing the following design are utilized: driving generator – power amplifier (DG – PA) with one or several high-output AEs acting as the PA and frequently with a preamplifier (preamp) at the input of the PA. Correspondingly, in a DG – PA-type CVLS higher efficiencies and quality of the output radiation beam are achieved as compared to a CVL operating as a single unit.

Additionally, CVLs remain the most efficient (with efficiencies of 30-50%) source for pumping organic dye solution lasers (ODSLs) with their emission wavelengths tunable over near-IR range as well as for pumping BBO-, KDP- and DKDP-type nonlinear crystals (NCs) (with 10-25% efficiencies) that convert CVL lasing into the second harmonic (λ = 255.3, 289.1 and 272.2 nm), i.e. into the UV wavelength range, and, finally, for pumping titan:sapphire ($Al_2O_3{:}Ti^{3+}$) laser with conversion of CVL lasing into near-IR radiation with subsequent transformation of the latter into blue radiation via the NC. Utilization of a CVL coupled to an ODSL and NC provides a means to almost entirely cover the wavelength range from near-UV to near-IR and, consequently, to extend the functionality of the laser. Such tunable pulsed laser systems are unique and they are advantageous for both practical use and scientific spectroscopic studies as well as for UV microprocessing.

An exclusive emphasis is laid on implementation of the CVLs combined with the ODSL with tunable emission wavelengths in high-power DG – PA-type laser systems. High power DG – PA-type CVLSs are chiefly involved into the setups for AVLIS-technology-based isotope separation which employs the difference between the absorption spectra for the atoms with different isotopic composition. This advanced optical technology provides a means to produce substances with the desired enrichment levels and high purity which are primarily used for the purposes of nuclear power industry and medicine[2].

Medicine is a promising area for the development of CVLs as well. For instance, state-of-the-art types of multifunctional medical complexes such as "Yachroma-Med" and "Kulon-Med" employing a CVL were designed for the purposes of oncotherapy, cold laser therapy, dermatology and cosmetology as well as for microsurgery and etc. The complexes of this class take the leading positions among the instruments for laser nonablating technologies. During operation of such complexes laser pulses selectively affect the defects of the body delivering no damage to the surrounding tissues and sensation of pain (consequently, anesthesia is not required)[4].

Moreover, CVLs serve as brightness amplifiers for microobjects and are employed in nanotechnology, high-speed photography as well as in compositional analysis. They are utilized in laser projection systems for large-screen and free-space image formation. They are used in lidar complexes for probing atmosphere and sea depths as well as in navigation systems; they are involved in processing in aqueous media, visualization of gas flows, laser acceleration of microparticles, holography, criminal investigation techniques, show industry and etc.[4-6]

3. OTHER TYPES OF TECHNOLOGICAL LASERS

Industrial CO_2-lasers with $\lambda = 10.6$ μm are widely used in the technology for microprocessing of materials. However, it is inefficient to process thermally-conductive metals, such as Cu, Al, Au and Ag, with the radiation of the CO_2-laser as well as with the radiation of the other IR lasers as the reflective index of these metals is rather high. High-power IR lasers are mainly used for high-speed cutting, slicing and welding of ferrous metals and steel with a thickness up to 20 mm.

Solid state lasers based on yttrium-aluminum garnet doped with neodymium (Nd:YAG-lasers) are close to the CVLs with regard to their spectra, output power and efficiency. These lasers emit at $\lambda = 1064$ nm and at a doubled-frequency with $\lambda = 532$ nm due to heat-induced distortions in the active element. However, they exhibit rather high divergence. Nd:YAG-lasers are widely used for part tagging and engraving, for metal (including aluminum) welding, for medical and location purposes[2].

Regarding the parameters needed for microprocessing one can consider solid state (SS) disc lasers based on yttrium-aluminum garnet doped with ytterbium (Yb:YAG-laser) emitting at $\lambda = 1030$ nm as the closest to the CVLs. Other SS lasers with pico- and femtosecond pulse duration can be considered as well. Take for instance the lasers produced in Germany by "Rofin-SinarLaser" and "TRUMPF". These devices are designed for micro-drilling of stainless steel sheets with thicknesses up to 1 mm for manufacturing engine fuel injectors. Ultrashort SS pulsed lasers are successfully developed in a number of leading Western countries (France, the UK, Latvia and others) as well. The key feature of ultrashort pulsed laser systems is that the highest microprocessing quality and high resolution are achieved due to mild thermal exposure of the base material without formation of a liquid melt. Such lasers are employed in the situations where high processing quality cannot be achieved with implementation of other lasers, e.g. drilling injection nozzles, manufacturing of medical facilities, display glasses and etc. However, to date these lasers have certain disadvantages, such as low average radiation power (1-10 W) and high cost.

Highly efficient ytterbium (Yb) fiber optic lasers emitting at wavelengths of 1060…1070 nm with average radiation power of 10-50000 W are now intensively developed. These lasers are designed and manufactured by the "IPG PhotonicsCorporation" international research and production association incorporating the IPG "ORE-Polus" domestic enterprise. However, pulsed single-mode operation of such lasers with nanosecond pulse duration does not provide the peak power density values as high as those achieved with the CVLs as nonlinear effects and material damage sites arise in the fiber. Continuous-wave fiber optic lasers doped with erbium and thulium with 5-50 W radiation power emitting at $\lambda = 1530…1620$ nm and $\lambda = 1800…2100$ nm, respectively, are available. Primary, fields of application for these lasers are high-precision cutting, slicing and welding of ferrous and nonferrous metals, metal heat hardening and surfacing, tagging and engraving, telecommunications and medicine.

Excimer gas lasers based on halogenides of noble gases (ArF, KrF, XeCl, XeF) and noble gas dimers (Ar, Kr) operate in pulsed mode with nanosecond pulse duration similarly to CVLs. However, these lasers exhibit shorter emission wavelengths $\lambda = 157$; 193; 248; 282; 308; 351 nm[2], i.e. near-UV lasing. Such properties are advantageous for their wide use in lithography processes in semiconductor industry, eye surgery, and in dermatology. However, due to relatively high radiation divergence and lower pulse repetition frequencies (not greater than 1…5 kHz) the quality and efficiency of material processing are reduced, and, consequently, this type of lasers is generally used for treatment of plastics, ceramics and biological tissues.

Diode (semiconductor) lasers have compact size and can be mass-produced at relatively low costs. Most of diode lasers provide near-IR radiation with λ = 800-1000 nm. These lasers are reliable and durable; however, they exhibit limited output power of a single unit as well as high divergence of the radiation. Diode lasers found applications in many fields of human activity, essentially in the spheres of telecommunication and optical memory[2]; additionally, these lasers are widely used for pumping solid-state and fiber optic lasers. The developed technology for assembling single diodes into diode arrays provides a means to increase the average output power of the laser up to 1-3 kW. For instance, these power values are sufficient for high-performance and high-quality laser welding of aluminum details.

4. CONCLUSION

The comparative analysis of the characteristics of CVLs and other known types of technological lasers carried out above confirms that with regard to the output parameters CVLs retain their potential as an advanced quantum device, especially for efficient processing of electronic device materials and selective isotope separation technologies, as well as for the purposes of spectroscopy, designing intensity amplifiers, medicine and other domains of science and technology.

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