Quantum Electronics **39** (5) 405 – 409 (2009)

PACS numbers: 42.55.Lt; 42.60.Lh; 42.65.Ky
DOI: 10.1070/QE2009v039n05ABEH013954

Output energy parameters of a KULON-10Cu-UV laser

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Abstract. **The output energy parameters of an industrial KULON copper vapour laser equipped with a nonlinear frequency converter based on DKDP and BBO crystals are studied. The average and peak powers, as well as the energies and pulse durations of radiation at wavelengths of 510, 578, 255, 271, and 289 nm, are measured in the regime of high-speed pulse modulation, which is used in lasers of this series. The maximum average power was 420 mW at a wavelength of 271 nm (DKDP) and 350 and 110 mW at 255 and 289 nm, respectively (BBO). It is experimentally shown that the average energy characteristics of UV radiation can be controlled on-line by changing the pulse repetition rate of the laser.**

Keywords: *copper vapour lasers, nonlinear frequency conversion, ultraviolet radiation, energy characteristics, power control.*

1. Introduction

The copper vapour lasers (CVLs) with nonlinear frequency conversion can operate in a larger wavelength region than conventional CVLs, which significantly extends the range of their application. Conventional CVLs operating at wavelengths of 510 and 578 nm are successfully used in precision microprocessing of various materials, in medicine, and in various technologies [1]. Because the visible radiation of CVLs is weakly absorbed in water and some other liquids, they are used for formation of nanoparticles by laser ablation of solids in these liquids [2]. CVLs operating in the UV wavelength region can be of interest for laser ablation of materials in vacuum or gases. An analysis shows that CVLs with frequency conversion in nonlinear crystals have some advantages compared to other UV laser sources. For example, compared to excimer lasers, they have a higher pulse repetition rate (12 – 15 kHz), a larger coherence length (from units to tens of centimetres), and a small beam divergence (about 0.2 mrad), as well as a longer service life and a lower cost. CVLs lasers have a smaller beam divergence than solid-state lasers and a higher average peak power than, for example, argon gas-discharge lasers.

Industrial CVLs of the KULON series [3] with a high-speed pulse modulation channel have been developed and certified [4]. The principle of the high-speed pulse modulation consists in changing the lasing conditions by controlling the population of the lower (metastable) laser levels using an additional excitation pulse whose energy is sufficient to populate these levels and insufficient to populate the upper (resonance) levels. In this case, by changing the time of appearance of the additional pulse with respect to the main excitation pulse, one can obtain either lasing (when the additional pulse is delayed from the main pulse) or quenching of laser radiation (if the additional excitation pulse is ahead of the main one). This control method is studied in detail in experimental paper [5]. It allows one to dose the CVL radiation according to any given law with an accuracy up to one pulse, change the pulse repetition rate $f_{\rm p}$, achieve a single-pulse operation regime, and create any sequence of laser pulses. Note that the excitation of the CVL active medium in these cases remains unchanged, i.e. the laser is pumped by pulses with the nominal repetition rate and energy deposition. This allows one to maintain constant parameters (energy, peak power, and divergence) of individual radiation pulses independently of their repetition rate $f_{\rm p}$.

Based on this industrial CVL and a nonlinear frequency converter based on DKDP and BBO crystals, we developed a KULON-10Cu-UV laser operating in the visible and UV regions. Below we describe this laser and present the output energy parameters of this laser.

2. Optical scheme of the laser and its functional capabilities

The optical scheme of the laser (Fig. 1) consists of an unstable optical resonator with a polariser, an optical scheme for forming the beam geometry in the nonlinear crystal, and an optical scheme for separating beams with wavelengths of different spectral regions and forming their geometry at the laser exit.

Laser emitter (*1*) (an LT-10Cu active element) was located in an unstable resonator formed by highly reflecting concave mirror (*2*), convex mirror (*3*), polarisation plate (*4*) with a special reflecting coating, and deflecting mirror

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Received 7 August 2008
Kvantovaya Elektronika **39** (5) 405 – 409 (2009)
Translated by M.N. Basieva

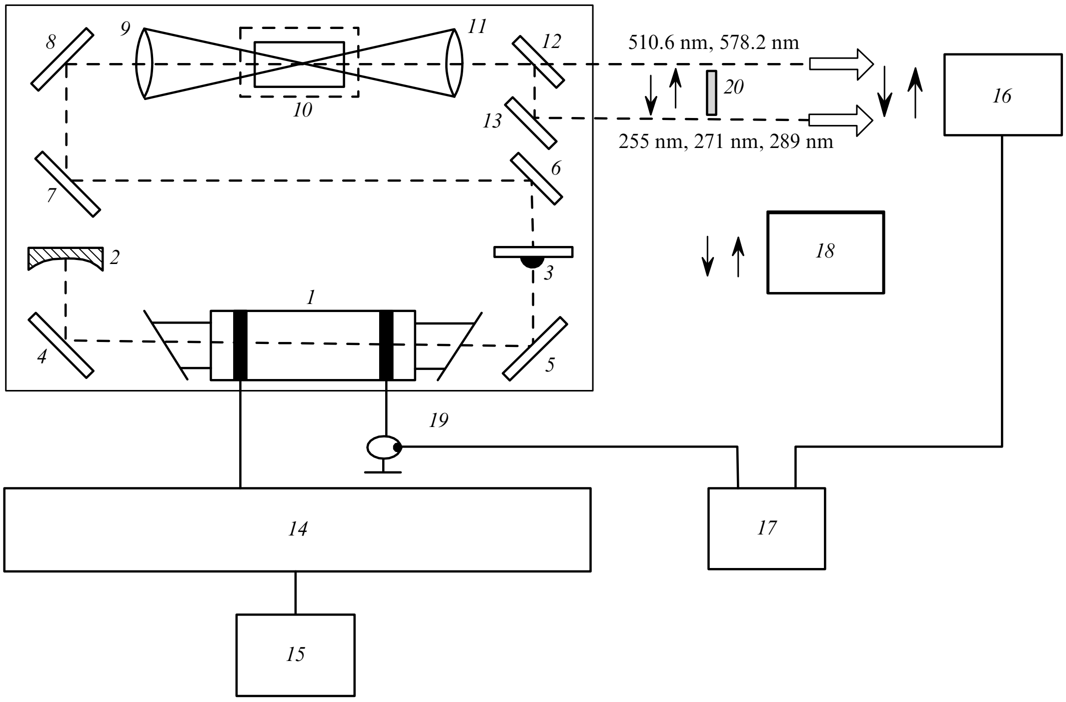

Figure 1. Optical scheme of the KULON-10Cu-UV laser.

(*5*). The radius of curvature of mirror (*2*) was ~ 2000 mm, and the radius of curvature of mirror (*3*) was about 10 or 100 mm, which corresponded to the cavity magnification factors M of ~ 200 and ~ 20. The beam diameter at the resonator exit was 14 mm.

The scheme for forming the beam geometry consists of plane deflecting mirrors (*6–8*) and objective (*9*) with an achromatic antireflection coating, which focuses laser radiation into nonlinear crystal (*10*) placed inside a thermostat. We used a 40-mm-long DKDP crystal 10 mm in diameter, which was cut at an angle corresponding to the sum-frequency generation (SFG) of the yellow and green lines of the CVL ($\lambda = 271$ nm), and a 7-mm-long BBO crystal with the transverse cross section of 7×6 mm and the cut angle of 48°. This crystal allowed us, in addition to SFG, to obtain the yellow and green radiation lines ($\lambda = 255$ and 289 nm) due to SHG achieved by rotating the BBO crystal within a range of ~ 10° using a micrometer rotary table. The focal distance of objective (*9*), which was optimised in [6, 7] for DKDP and similar laser radiation parameters, was 500 nm. The BBO crystal was used without optimisation.

The beam separation scheme consists of lens (*11*) and plane dichroic mirrors (*12*) and (*13*) with a transmission coefficient of 97 % at 510 and 578 nm and a reflection coefficient of 0.97 % – 0.99 % at wavelengths of the UV region. Deflecting mirror (*13*) was used to couple out the UV radiation, while the residual visible radiation of the CVLs was coupled out via mirror (*12*). The output beam diameters were ~ 4 mm, and the electric vector polarisation was vertical for visible radiation and horizontal for UV radiation.

Laser emitter (*1*) operating in the high-speed pulse modulation regime was fed from power supply unit (*14*) constructed according to [3, 4] and controlled by PC (*15*). In these experiments, the electric power taken from power supply (*14*) in the dc circuit was ~ 2.0 kW. The CVL active medium was pumped with a constant nominal pulse repetition rate of 12.5 kHz. The repetition rate of radiation pulses was varied from 12.5 to 2.85 kHz.

The shape of laser pulses was recorded with FEK-22SPU-M photodetector (*16*) and Tektronix TDS3054B oscilloscope (*17*). The average power of radiation with different pulse repetition rates was measured with NOVA-II thermoelectric converter (*18*). The pump current pulses and their repetition rate were recorded with oscilloscope (*17*) using Rogowski loop (*19*). The output pulse energy was determined as the ratio of the average power to the pulse repetition rate. The power of laser pulses was determined from their oscillograms and measured energies. The measurements were performed under steady-state temperature conditions. To measure the average power and record the shape of laser pulses at different wavelengths, we used filters (*20*) (SZS20 for the green line, OS11 for the yellow line, and BS2 glass to cut off UV lines). The total (summed for 510.6- and 578.2-nm radiation) average power of the laser resonator $W_{\mathrm{g+y}}$ was measured behind mirror (*6*). The residual total average power at these wavelength at the exit of the entire laser system $W^*_{\mathrm{g+y}}$ was measured behind mirror (*12*). The average power for individual lines (W_{g} and W_{y} for the green and yellow lines, respectively) was measured at the same points of the optical scheme. The average output power at each of the UV lines (255, 271, or 289 nm) was measured behind mirror (*13*). The photodetectors for recording the oscillograms of visible (U) and UV (U_{UV}) pulses were placed at corresponding positions.

The KULON-10Cu-UV laser with a DKDP crystal operates simultaneously at wavelengths of 510.6, 578.2, and 271 nm. In the case of the BBO crystal, in addition to the CVL fundamental lines, one of the 271-, 255-, or 289-nm lines is generated. In the latter case, the UV wavelengths can be tuned on-line from one to another.

3. Experimental results and discussion

In our experiments, the maximum average output power $W_{\text{g+y}}$ at the exit of the CVL resonator was ~ 10 W, the ratio $W_{\text{g}}/W_{\text{y}}$ being 0.74–0.8 at the nominal pulse repetition rate ($f_{\text{p}} = 12.5$ kHz).

It is known [6, 7] that the efficiency of nonlinear frequency conversion of CVL radiation is determined mainly by the peak power density of radiation incident on the crystal, the beam divergence, and the fraction of the energy concentrated in the weakly diverging component of the laser beam. This fraction of the energy, in turn, strongly depends on the cavity magnification factor M. At $M \geqslant 100$, the beam can contain a component with a divergence close to diffraction-limited [8], but the fraction of the energy in the diffraction beam is small and does not exceed 25 % for CVLs of the KULON series [3].

To illustrate the effect of the magnification factor on the parameters of the KULON-10Cu-UV laser, we performed experiments at different M. Figure 2 shows the laser pulses at the resonator exit at $M = 200$ and 20. One can see that the maximum peak powers are approximately the same (~ 80 kW) in both cases, but the amplitude of the third peak of the third resonator beam at $M = 200$ (65 kW) is considerably higher than the corresponding amplitude at $M = 20$ (38 kW). This points to a decrease in the fraction of the energy in the diverging components of the output laser beam with decreasing M. Note that the power $W_{\text{g+y}}$ at the resonator exit in this experiment was almost independent of M.

Figure 3 shows the dependences of the average power of the UV radiation at the exit of the KULON-10Cu-UV laser with DKDP and BBO crystals on the laser pulse repetition rate f_{p}. The almost linear dependences of the average powers indicate that the parameters of the green and yellow pulses incident on the crystal and, hence, of UV pulses, as well as the nonlinear conversion efficiency, do not change with varying f_{p}. It is obvious that the UV radiation power depends on the factor M (Fig. 3a). The power W_{UV} at the wavelength 271 nm at $M = 200$ is almost twice as high as at $M = 20$, and, vice versa, the residual power $W^*_{\text{g+y}}$ at $M = 200$ is 10% lower than at $M = 20$. The latter relates to the fact that the fraction of the energy belonging to the superradiant component of the beam is higher at $M = 20$ than at $M = 200$. Due to the extremely large divergence of this component, a large part of it falls outside the crystal aperture, because of which the energy converted in the crystal at $M = 20$ is smaller than that at $M = 200$.

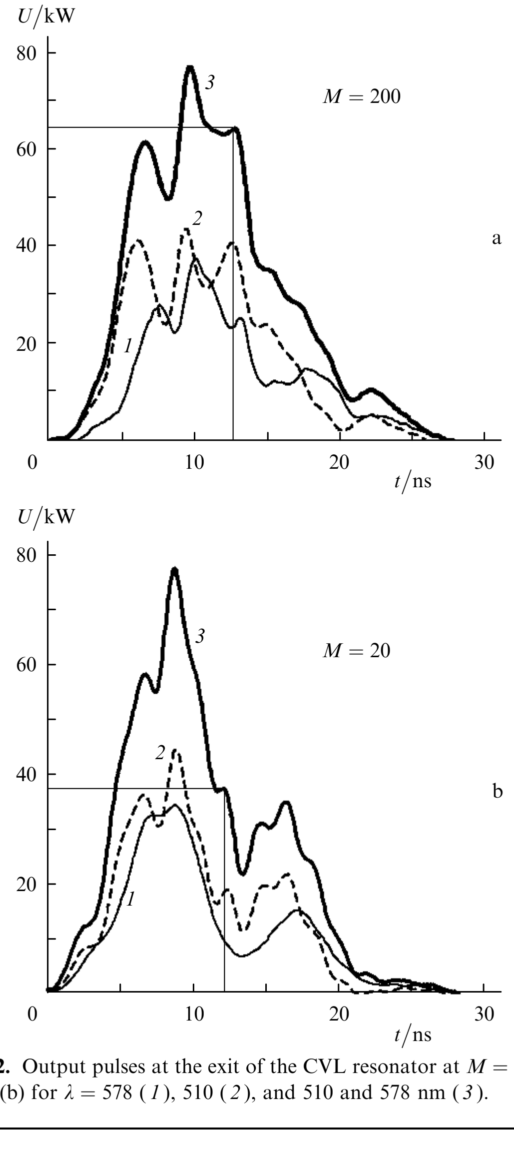

Figure 2. Output pulses at the exit of the CVL resonator at $M = 200$ (a) and 20 (b) for $\lambda = 578$ (*1*), 510 (*2*), and 510 and 578 nm (*3*).

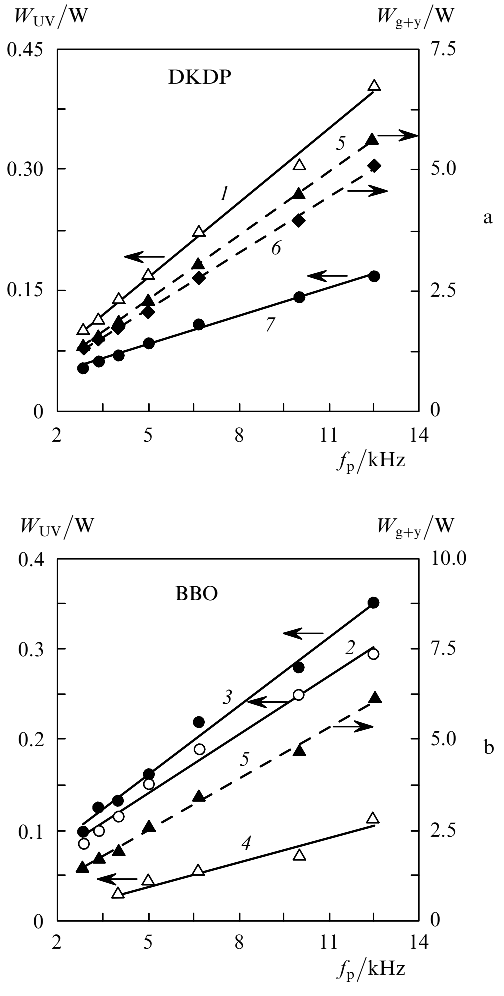

Figure 3. Dependences of the average power of UV laser radiation on the cavity magnification factor and the pulse repetition rate for $M = 200$ (*1–5*) and 20 (*6*, *7*); $\lambda = 271$ (*1*, *2*, *7*), 255 (*3*), 289 (*4*), and 510 and 578 nm (*5*, *6*).

Figure 4a presents the oscillograms of UV pulses (U_{UV}) of the KULON-10Cu-UV laser at the wavelength of 271 nm (DKDP crystal) for two M in the case of the nominal pulse repetition rate $f_{\mathrm{p}} = 12.5$ kHz. The decrease in M from 200 to 20 leads to an approximately twofold decrease in the peak power of the UV radiation, which agrees well with the effect of M on the average UV power (see Fig. 3a). The U_{UV} pulses at wavelengths of 289, 271, and 255 nm (BBO crystal) at the same pulse repetition rate f_{p} and $M = 200$ are shown in Fig. 4b. The best results are obtained at wavelengths of 271 and 255 nm (SFG and SHG of the green line).

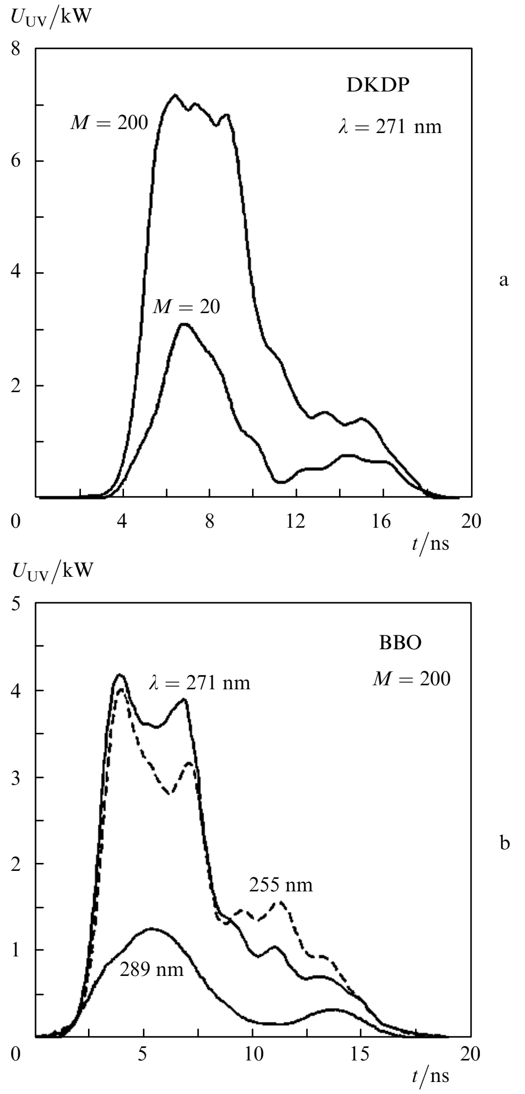

Figure 4. UV radiation pulses for (a) DKDP at $M = 20$ and 200 ($\lambda = 271$ nm) and (b) BBO at $M = 200$ ($\lambda = 271$, 255, and 289 nm).

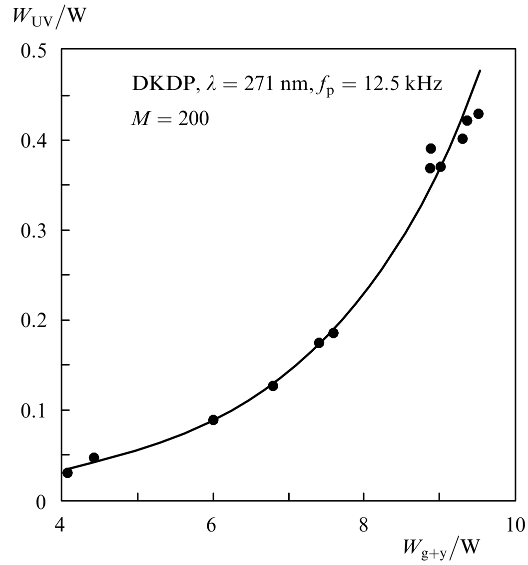

Figure 5. Dependence of the average power of UV radiation (DKDP, $\lambda = 271$ nm) on $W_{\mathrm{g+y}}$ at $M = 200$ and $f_{\mathrm{p}} = 12.5$ kHz.

All the experiments described above were performed at a steady-state pumping of the CVL, when the energy deposition in the active medium was constant and the average radiation power was varied by the method of high-speed pulse modulation. The effect of the pulsed energy deposition on the average power of the UV radiation is demonstrated in the DKDP crystal ($\lambda = 271$ nm) at a constant pulse repetition rate (12.5 kHz) of CVL excitation. The dependence of W_{UV} on $W_{\mathrm{g+y}}$ shown in Fig. 5 is nonlinear. This occurs because, when the average power $W_{\mathrm{g+y}}$ is changed due to changing the pulse energy deposition, the peak power of the CVL radiation and the relation between the energies of the yellow and green pulses also change, which significantly affects the UV generation efficiency. In addition, one can see that the highest UV radiation power was achieved at the maximum average power at the resonator exit.

The nonlinear frequency conversion efficiency η in crystals was determined as the ratio $W_{\mathrm{UV}}/\alpha W$. Here, W is $W_{\mathrm{g+y}}$ at $\lambda = 271$ nm, W_{g} at $\lambda = 255$ nm, and W_{y} at $\lambda = 289$ nm; W_{UV} is the average output power at the corresponding wavelength; and α is the coefficient corresponding to the ratio of powers at the entrance to the crystal and at the exit of the resonator, which takes into account the losses in the optical path and is ~ 0.9 at $M = 200$ and ~ 0.8 at $M = 20$. We also calculated the power conversion efficiency of CVL radiation into UV radiation in the considered optical scheme of the KULON-10Cu-UV laser, $\eta_{\mathrm{UV}} = W_{\mathrm{UV}}/W_{\mathrm{g+y}}$.

The output energy parameters of the KULON-10Cu-UV laser and the UV generation efficiencies obtained in this paper are listed in Table 1.

Table 1.

Crystal	λ/nm	M	W_{UV}/mW	U_{UV}/kW	$^*E$/μJ	η (%)	η_{UV} (%)
DKDP	271	200	420	7.3	34	4.9	4.4
		20	200	3.1	16	2.9	2.3
BBO	271	200	330	4.3	26	3.8	3.5
	255		350	4.4	28	7.1	3.7
	289		110	1.3	9	3.0	1.2

$^*E$ is the pulse energy.

4. Conclusions

The experimental study of the parameters of a prototype of the industrial KULON-10Cu-UV laser have shown that, using a CVL with an output power no higher than ten watts, it is possible to obtain UV radiation with an average power of about ~ 0.4 W and a nonlinear conversion efficiency of 3 % – 7 %, which is acceptable for practical applications.

It is shown that the pulse power incident on the nonlinear crystal and the output UV power, as well as the nonlinear conversion efficiency, do not change with changing the repetition rate of generated pulses. Thus, the regime of high-speed pulse modulation used in CVLs of the KULON series allows one to control the average power of UV radiation, which is very important for technological applications.

To achieve a further increase in the energy parameters of UV radiation, it is necessary to increase the peak power and improve the stability of initial CVL pulses, to increase the fraction of the energy in the weakly diverging components of the laser beam, and to optimise the nonlinear converter.

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