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Energy characteristics of radiation from a KULON-10 Cu-M self-heated technological laser

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***Abstract*. The energy characteristics of a KULON-10 Cu-M technological copper vapour laser operating in the regime of high-speed pulsed modulation produced by special current pulses are investigated. The range of time delays of an additional pulse with respect to the main pulse is determined in which the peak power of laser pulses, their energy and duration can be varied. The total all-line peak power of the laser within the total divergence angle achieves 120 kW for the nominal delay. The average and peak powers, energies, and durations of pulses are measured for the individual components of the laser beam with different divergence (down to diffraction-limited). It is shown for the first time that the fraction of the pulse energy corresponding to the weakly diverging component of the laser beam and the laser pulse duration decrease with decreasing the time delay (below the nominal value). The outlook for using KULON lasers for nonlinear radiation frequency conversion is estimated.**

Keywords: *copper vapour laser, radiation parameters, operative control, radiation divergence, peak power, radiation pulse duration.*

1. Introduction

Modern technological copper vapour lasers (CVLs) [1] emitting in the visible range are powerful precision tools for rapid micromachining a variety of materials providing a high quality of products. In addition, CVLs are promising for the development of UV radiation sources [2, 3], which can considerably extend the scope of their applications. The efficiency of practical applications of CVLs in various precision technological processes and the possibility of the development of UV radiation sources depend considerably on the energy, spatial, and temporal parameters of laser pulses. Therefore, it is very important to study the radiation parameters of technological CVLs such as the average and peak pulse power, the pulse energy and duration, the relative fraction of energy concentrated in weakly diverging (diffraction) components of the laser beam, and their absolute peak power.

At present, technological KULON CVLs have been developed [4] and certified [5] at the Development and Experimental Plant, V.I. Lenin All-Russian Electrical Engineering Institute (Istra). The lasers are based on sealed off self-heated active LT-10 Cu elements (Istok Research and Production Association, Fryazino) producing 10 W of average output power in the stationary regime. The principal difference of KULON-10 Cu-M lasers from other CVLs of this series is the possibility to control promptly the energy parameters of radiation, which is achieved in the regime of paired pulses by introducing the so-called channel of rapid pulsed modulation providing the phase-pulse controlled delay τ_{del} of the additional excitation pulse with respect to the main pump pulse [6 – 8].

It is known [9, 10] that, by introducing additional excitation pulses, one can promptly change the average and pulsed parameters of laser radiation and to stabilise the output parameters of CVLs. However, the control rate of radiation parameters is not high enough for a number of applications. Thus, for example, the pulse repletion rate was changed in [9] no faster than by 1 – 2 kHz min^{-1} with the error of the pulse energy stabilisation of 1.5 % – 3 %.

A KULON-10 Cu-M laser provides the inertialless (virtually at an arbitrary rate) control of radiation parameters. The operation of this laser and the features of using paired current pulses are described in detail in paper [7]. Note only that the method of high-speed pulsed modulation is based on the change of conditions of the efficient lasing by controlling the population of metastable laser levels with the help of the additional pump pulse with energy sufficient to populate the lower (metastable) laser levels and insufficient to populate the upper (resonance) levels. By varying the appearance time of the additional pulse with respect to the main excitation pulse, the lasing regime is achieved (when the additional pulse lags behind the main pulse) or lasing is quenched (when the additional pulse is ahead of the main pulse).

We assume hereafter that positive delays τ_{del} correspond to the delay of the additional pulse with respect to the main pump pulse, while the negative delays correspond to the advance of the additional pulse with respect to the main pulse. In addition, to provide the stationary temperature regime of a gas-discharge tube, the pump source of the laser

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maintains the invariable total energy supply from the main and additional excitation pulses over the entire control range.

This method of controlling radiation parameters allows one to perform high-speed pulsed modulation of laser radiation by any specified law with accuracy to a laser pulse for the pulse energy stabilised within $1\,\%-1.5\,\%$, to change the laser pulse repetition rate from its nominal value to the monopulse regime, to produce any pulse trains (at rates not exceeding the nominal rate), and to perform the pulse control of the radiation chromaticity. All this provides the possibility to select easily the most efficient operation regime of CVLs for one or other technological process.

In this paper, we present the results of the study of the radiation parameters of a KULON-10 Cu-M technological laser. The influence of the delay of the additional current pulse on the output radiation parameters is investigated and the prompt control of the additional laser pulse is demonstrated. Unlike papers [6–8], the optical resonator of the technological laser in our study contained an element to polarise the output radiation, which is required for some applications, in particular, for nonlinear radiation frequency conversion.

2. Experimental

Figure 1 presents the scheme of the experiment. LT-10 Cu gas-discharge laser tube (*1*) was located in an unstable telescopic resonator formed by spherical concave mirror (*2*) of diameter 35 mm and convex mirror (*3*) of diameter 1.5 mm with the radii of curvature 2210 and 15 mm, respectively. The magnification factor of the resonator was 150. Radiation was coupled out through AR-coated plate (*4*) of diameter 35 mm with mirror (*3*) glued at the plate centre at an angle of 4° to the optical axis. Laser radiation was polarised with Glan prism (*5*). The resonator length was $L = 1105$ mm, the gas-discharge diameter was $D = 14$ mm, and the active volume length was $l = 495$ mm. The laser was pumped by power supply (*6*) with the channel of high-speed pulsed modulation (*7*) controlled by standard G5-56 pulse generator (*8*). The superradiance background at the laser output was cut off by aperture (*9*) of diameter 14 mm. A spatial filter consisted of lens (*10*) with the focal distance $f =$ 5300 mm and a set of apertures (*11*) located exactly at the focus of lens (*10*). The diameter d of apertures (*11*) was varied from 0.5 to 10 mm. In this case, the spatial filter selected from the laser beam the components with the divergence $\varphi \approx d/f$, which changed from $\varphi_{\rm d}$ to $20\varphi_{\rm d}$ (here, $\varphi_{\rm d} \approx 2.44\lambda/D$ is the limiting diffraction divergence of the laser beam).

The shape of radiation pulses was recorded with FEK-22SPU-M photodetector (*12*) and 500-MHz Tektronix TDS 3054B oscilloscope (*13*). The radiation power at the laser output averaged over the pulse repetition rate was measured with TI-5 thermoelectric transducer (*14*), and at the output of photodetector (*12*) by Moskit power meter (*15*). The average power and pulse shape of the 0.510-μm and 0.578-μm laser lines were measured and recorded by using green CZS20 or yellow OS11 glass filters (*16*) mounted in front of photodetector (*12*) and power meter (*15*). To provide the linear operation regime of photodetector (*12*), radiation was attenuated by using a set of neutral filters. Pump current pulses and their repetition rate

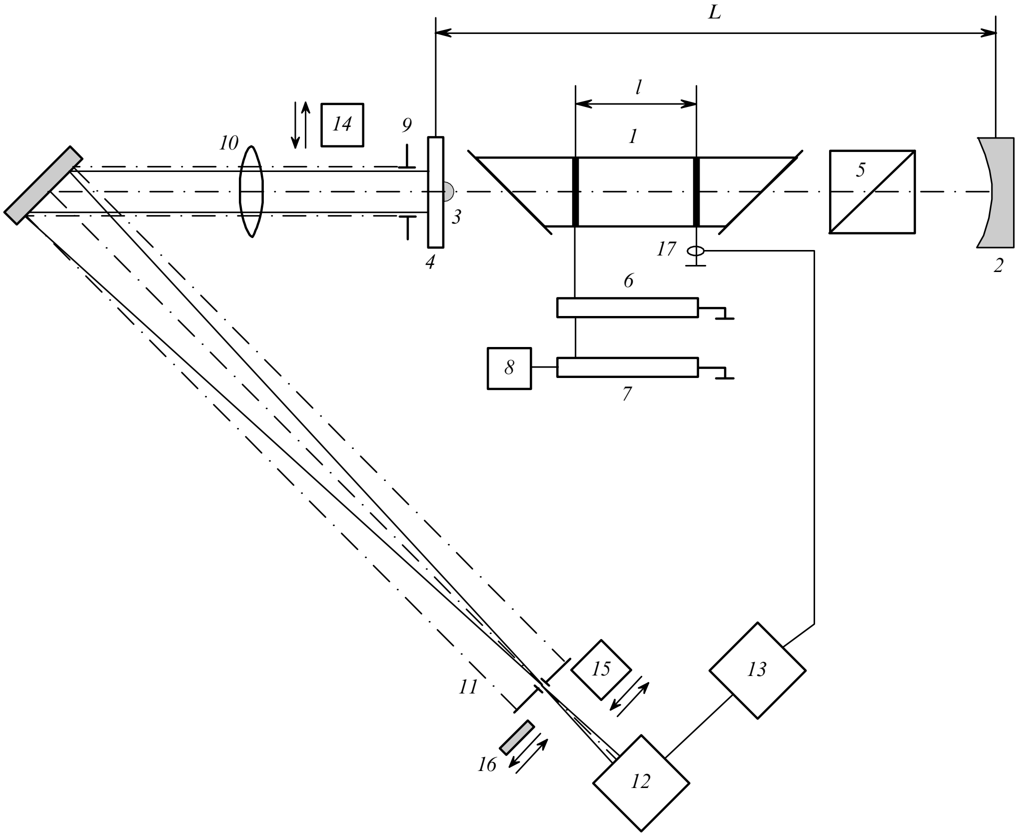

Figure 1. Experimental setup.

were recorded with oscilloscope (*13*) by using Rogowski loop (*17*). The pulse energy was determined as the ratio of the average power [measured with detectors (*14*) or (*15*)] to the laser pulse repetition rate. The peak pulse power was measured from oscillograms by calibrating oscilloscope signals by using the measured pulse energies.

Experiments were performed in the stationary temperature regime of the laser operation. Radiation losses in all optical elements were taken into account. The power of power supply (*6*) was ~ 1.9 kW and the pump pulse repetition rate was 12.8 kHz. The current amplitudes of the main and addition excitation pulses were ~ 380 A and ~ 70 A, respectively. The durations (in the base) of the main and additional pulses were ~ 120 ns and ~ 140 ns. The time delay τ_{del} was varied within 2 μs.

3. Experimental results and discussion

The power parameters of the laser changed weakly after the introduction of polariser (*5*). The average all-line output power W (within the entire divergence angle) decreased by 10% – 12% and was 9 – 10 W for the delay of the additional pulse $\tau_{\mathrm{del}} \approx +300$ ns, which we will call optimal.

The dependence of the average output power W on the delay time τ_{del} is presented in Fig. 2. One can see that in the region of delays from −700 to −200 ns the average power is low and changes insignificantly. For $\tau_{\mathrm{del}} \approx -200...100$ ns, the addition excitation pulse almost completely quenches the radiation pulse. In the delay interval from −100 to −50 ns, the output power drastically increases up to the rated value, and this interval can be used to control rapidly the average and peak pulse powers, the pulse duration and energy. The accuracy of pulse-to-pulse energy stabilisation in this interval is not determined at present. In the region of positive delays from 0 to 400 ns, the average radiation power is stable and achieves its maximum.

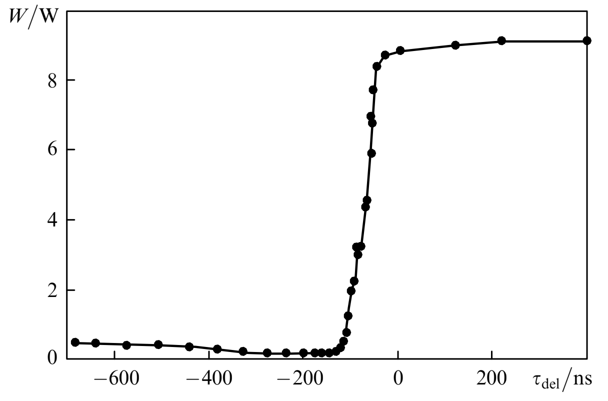

Figure 2. Dependence of the average output power of the laser on the delay time of the additional current pulse of the modulation channel.

Figure 3 shows the fractions $\delta = W_{\varphi}/W$ of the pulse energy contained in the components of the laser beam with different divergences (from diffraction to total). Here, W_{φ} is the average radiation power measured at the output of a spatial filter for different diameters of d of the output aperture, to which different relative divergences $\varphi/\varphi_{\mathrm{d}}$ correspond. The dependence was obtained for the optimal delay of the additional pulse and the scatter of the average output power of the laser, determined by the pump power, from 7.8 to 9.7 W. All the experimental points fall on one curve. For the negative values of τ_{del}, the energy fraction δ in the components of the laser beam with a low divergence was considerably smaller than that for the optimal delay. Thus, for example, for beams transmitted through an aperture with $d = 1.5$ mm ($\varphi/\varphi_{\mathrm{d}} \approx 3$), the value of δ decreased from 21 % to 8 % when τ_{del} was changed from +290 to −110 ns.

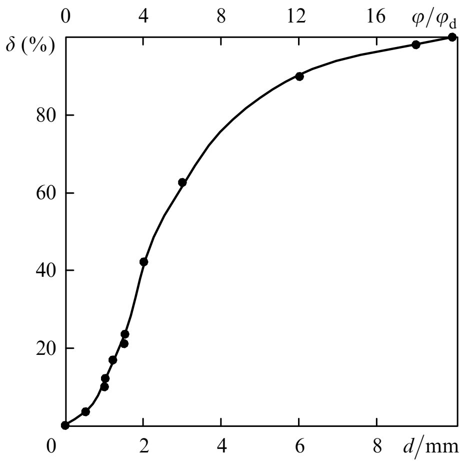

Figure 3. Fractions of the output pulse energy in the components of the laser beam with different divergences for the optimal delay of the additional current pulse.

Figure 4 shows the dependence of the peak power U_{p} of the components of the all-line laser beam with different divergences on d and $\varphi/\varphi_{\mathrm{d}}$ for the optimal delay and $W \approx 7.9$ W, and also the dependences of U_{p} on d for the 0.510-μm green line and 0.578-μm yellow line. Table 1 presents the values of U_{p} obtained for the higher pump power and the average output power $W \approx 9 - 10$ W. One can see that the maximum total peak intensity achieved 120 kW within the total divergence angle and 30 kW for the beam with the divergence $3\varphi_{\mathrm{d}}$.

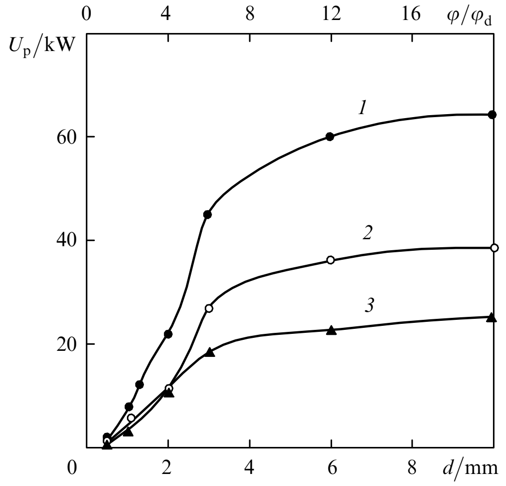

Figure 4. Peak radiation power of the components of the laser beam with different divergences: (*1*) all-line beam; (*2*) green 0.510-μm laser line; (*3*) yellow 0.578-μm laser line.

Table 1.

W/W	d/mm	$\varphi/\varphi_{\rm d}$	$U_{\rm p}$/kW		
			0.510 μm	0.578 μm	0.510 and 0.578 μm
9.3	1.5	3	13	10	23
	10	20	70	50	120
9.8	1.5	3	20	17	30
	10	20	–	–	–

The influence of the delay of the additional current pulse on the shape of radiation pulses within the total divergence angle of the laser beam is demonstrated in Fig. 5, and Fig. 6 demonstrates similar dependences for the spatial component of the laser beam with the divergence equal to $3\varphi_{\rm d}$.

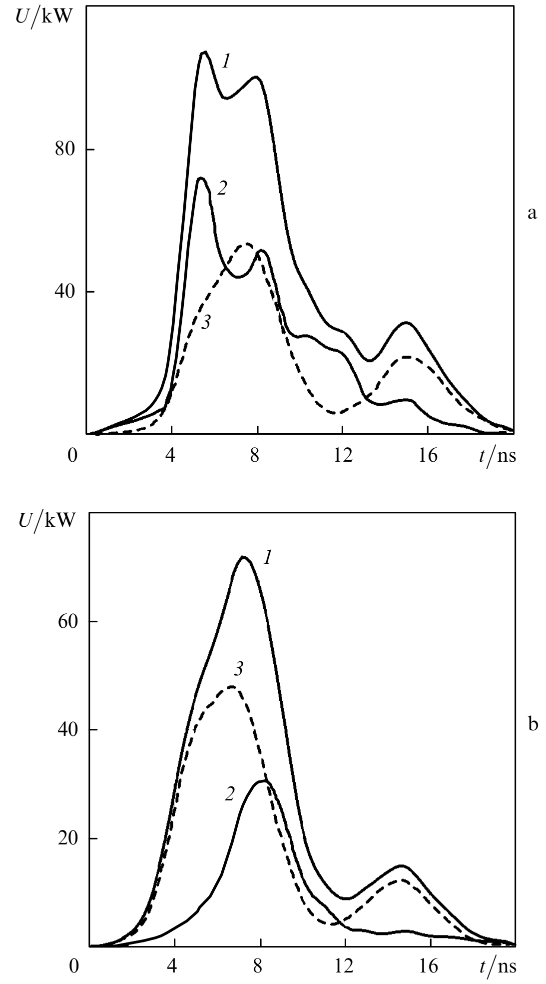

Figure 5. Radiation power U within the total divergence angle of the laser beam for $\tau_{\rm del} = +300$ ns, $W \approx 9.4$ W (a) and $\tau_{\rm del} = -66$ ns, $W \approx 5.3$ W (b): (*1*) all-line beam; (*2*) green 0.510-μm laser line; (*3*) yellow 0.578-μm laser line.

A comparison of Figs 5a and b shows that, as the time delay is decreased from its optimal value down to $\tau_{\rm del} \approx -66$ ns, the all-line peak power $U_{\rm p}$ decreases by $\sim 33\%$, whereas the total average power W decreases by $\sim 44\%$, from 9.4 to 5.3 W. While in the case of the optimal delay, the peak power of the 'green' pulse is higher than that of the 'yellow' pulse and the 'green' pulse appears earlier than the 'yellow' one, for $\tau_{\rm del} \approx -66$ ns, the situation is opposite: the peak power of the 'yellow' pulse is much higher than that of the 'green' pulse, and the 'yellow' pulse appears earlier. The fraction of the 'yellow' pulse energy in the total energy increases from 45 % to 70 %. The behaviour of the radiation pulses for the beam with the divergence $3\varphi_{\rm d}$ is similar (Figs 6a and b).

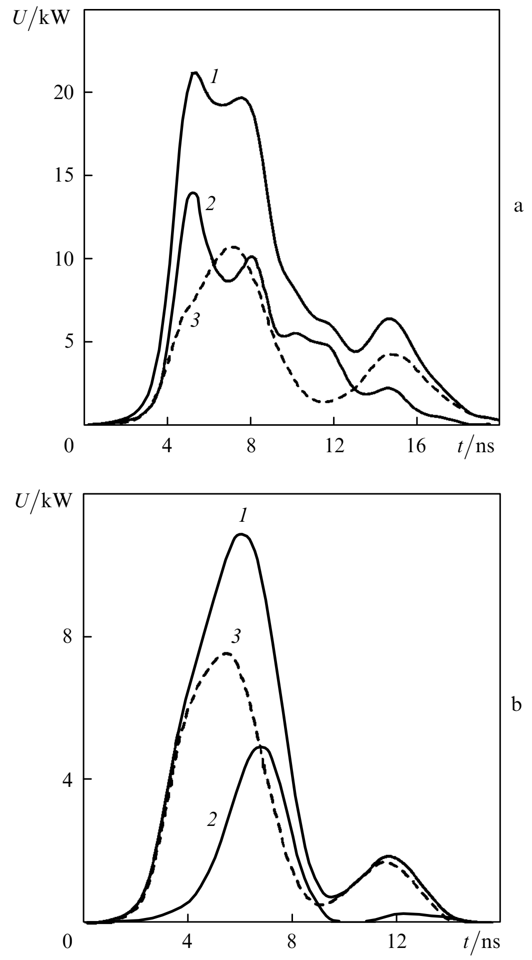

Figure 6. Radiation power U in the component with the divergence $3\varphi_{\rm d}$ for $\tau_{\rm del} = +300$ ns, $W_{\varphi} \approx 1.9$ W (a) and $\tau_{\rm del} = -66$ ns, $W_{\varphi} \approx 0.8$ W (b): (*1*) all-line beam; (*2*) green 0.510-μm laser line; (*3*) yellow 0.578-μm laser line.

Thus, as the delay of the additional excitation pulse is decreased, the relative contribution of the yellow line to the total output power increases and the total output power decreases. Note that this effect is consistent, for example, with results [11] and is not caused by the overheating of the active medium, which allows one to control promptly the average and peak powers of CVLs by varying simultaneously the chromaticity of output radiation.

It follows from Figs 5 and 6 that the delay $\tau_{\rm del}$ also noticeably affects the output pulse duration. The pulse duration decreases to a greater extent for the 'green' pulse than for the 'yellow' one. In addition, the pulse duration decreases stronger for the beam components with a low divergence than for radiation within the total divergence angle. A comparison of the output pulses for $\tau_{\rm del} \approx +300$ ns and -66 ns in the beam with the divergence $3\varphi_{\rm d}$ (Fig. 6) illustrates this: the 'green' pulse duration (in the base) decreased by half, from 16 to 8 ns, and the FWHM of the pulse decreased from 6 to 4 ns. The pulse amplitude decreased from ~ 13.5 to ~ 5 kW. The pulse duration

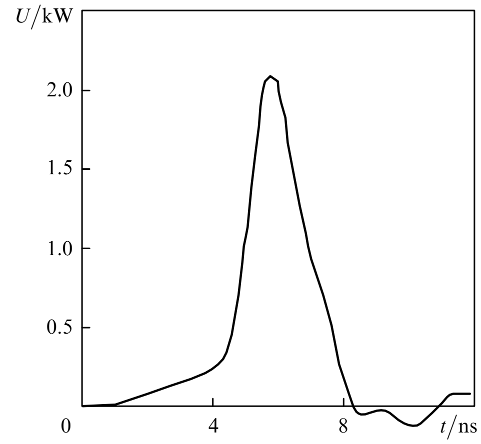

Figure 7. Radiation power U of the green 0.510-μm laser line for the component with the divergence $3\varphi_{\rm d}$ for $\tau_{\rm del} = -110$ ns, $W_\varphi \approx 0.05$ W.

decreases greater only for $\tau_{\rm del} < -100$ ns, as shown in Fig. 7. In this case, the 'green' pulse duration further decreased by a factor of ~ 1.5. However, the output power in this delay region is very low and the peak power does not exceed 2.2 kW.

These results demonstrate the possibility to control promptly the output pulse duration. Note that in this case, the rigid requirements on the stability and accuracy of specifying the value of $\tau_{\rm del}$ in a very narrow interval of width ~ 200 ns should be fulfilled.

4. Conclusions

Our experiments have shown that the inertialless method of high-speed pulsed modulation of radiation [7] realised in a KULON-10 Cu-M technological laser allows one not only to specify the number of radiation pulses and vary the average output power of the laser but also to control the parameters of individual pulses such as the peak pulse power, energy, and duration. The delay range of the additional current pulse in which such a control is possible is $\sim$100 ns. We have studied the influence of the additional current pulse on the pulsed and average parameters of laser radiation. Note that the pulse parameters change simultaneously with varying the additional pulse delay, but to different extents.

The influence of the additional pulse delay on the parameters of laser pulses in weakly diverging components of the laser beam has been studied for the first time. It has been shown that the decrease of the pulse delay below its rated value reduces the fraction of energy contained in the weakly diverging components of the beam. However, their peak power decreases to a lesser extent than the energy.

The results of the paper together with results [8] give quite complete information on the radiation parameters of KULON-10 Cu-M technological lasers, which is required for selecting the operation regime of lasers in various technological processes.

The peak powers and distributions of the pulse energy among the spatial components of the beam proved to be similar to those obtained in papers [2, 3] where nonlinear frequency conversion was studied in a CVL with a 20-W GL-201 active element. Therefore, there is reason to hope that a KULON-10 Cu-M technological laser can be used to obtain 0.1 – 0.3 W of UV radiation at wavelengths of 0.255, 0.271, and 0.289 μm, i.e. with parameters close to those obtained in [2, 3]. Note that in this case, the pulse repetition rate and average power of UV radiation can be also efficiently and simply performed by the method of high-speed pulsed modulation.

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