Peculiarities in the operation of a copper vapor laser and a "copper vapor laser–UV converter" system in the regime of laser monitor

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In this paper we consider a system consisting of a copper vapor laser (CVL) with an unstable resonator, Glan prism providing for linear polarization of the laser radiation, DKDP nonlinear crystal to convert visible laser radiation into the UV, and projection optical part of the laser monitor. The results of investigation into the operation of this system in the regime of laser monitor are presented. Radiation from the CVL and the UV converter was focused on a test target. A magnified image of the test target on the monitor screen was analyzed. The results obtained are indicative of the capability of the CVL and the "CVL +UV converter" system of operating in the regime of laser monitor. The main factors hampering the use of the CVL and the "CVL+UV converter" system as a laser monitor are revealed; the ways to eliminate some of them are proposed.

Repetitively pulsed lasers on the self-limited transitions of metal atoms[1] and, first of all, copper vapor lasers (CVL's) possess a unique combination of two properties. The first one is high peak power of radiation providing the possibility of obtaining the intensity of focused radiation at the level of 10^8 W/cm^2 and even higher, what is needed in applications to sublimate different materials. The second one is the high gain of the active medium. These properties of the CVLs allow them to be used as a basis for systems simultaneously executing two functions: the function of the source of a working laser beam acting on a test target and the function of laser monitor for testing the processed surface just during this action. For the first time the possibility of using the "copper vapor laser+amplifier" system (λ = 510.5 nm) in the devices for processing small objects and visually testing their surface was studied in Ref. 2. However, the results from Ref. 2, as well as more recent results from Refs. 3 and 4, showed that operation of such devices is still unclear and requires further investigation. "esides, the recently developed sources of UV radiation based on a copper vapor laser or the "copper vapor laser+amplifier" system and nonlinear crystals (see, for example, Refs. 5 and 6) make urgent the question on the capability of such sources to operate in the regime of laser monitor.

In this paper we consider the capabilities and peculiarities of operation of the copper vapor laser and the "CVL+UV converter" system in the regime of laser monitor.

The optical arrangement of the experiment on studying the capability of a CVL with an unstable resonator to be used as a laser monitor is shown in Fig. 1*a*. In the experiments we used a GL–201 commercial active element *1* with the discharge channel 2 cm in diameter and 80 cm in length. The repetition rate of pump pulses was 10 kHz. A telescopic unstable resonator with the magnification factor M = 200 consisted of mirrors *2* (28 mm in diameter) and *3* (1.5 mm in diameter) and Glan prism *4*. The cavity mirrors were separated by 1.5 m distance. The beam diameter at the CVL output was 20 mm. The CVL radiation was focused with the lens f_1 (of 150 mm focal length) at a test target *5*. As a target we used a metal ruler with a millimeter scale. The ruler was set near the focus of the lens f_1. The distance from the output mirror *3* of the CVL cavity to the target *5* was chosen to be as small as possible; so it was from 470 to 510 mm.

The projection part of the system shown in Fig. 1*a* consisted of a beam-turning mirror *6*, telescopic objective *7* (lenses f_3 and f_4), a diaphragm *8* limiting the image of the test target, and a screen *9* onto which the magnified image of the test target *5* was projected. The target image was recorded with a camera. Color pictures were processed on a personal computer to reveal image details and analyze color distribution. Graphical software like Ulead Credia Studio was used for this purpose.

The Glan prism *4* executed two functions. First, it polarized laser radiation, what is necessary for its further nonlinear conversion into the UV radiation in the "CVL+UV converter" system. Hereinafter the radiation with the electric field vector $\mathbf{E}_y$ lying in the horizontal plane (see Fig. 1*a*) is called $\mathbf{E}_y$-radiation, whereas the radiation with the vertical orientation of the electric field vector $\mathbf{E}_x$ (see Fig. 1*a*) is called $\mathbf{E}_x$-radiation. The mean power of radiation is respectively denoted as W_y and W_x. Second, due to its polarization properties the Glan prism separated the $\mathbf{E}_y$-radiation circulating inside the cavity and the $\mathbf{E}_x$-radiation reflected from the test target, gained in the active element, while bearing information on the target image.

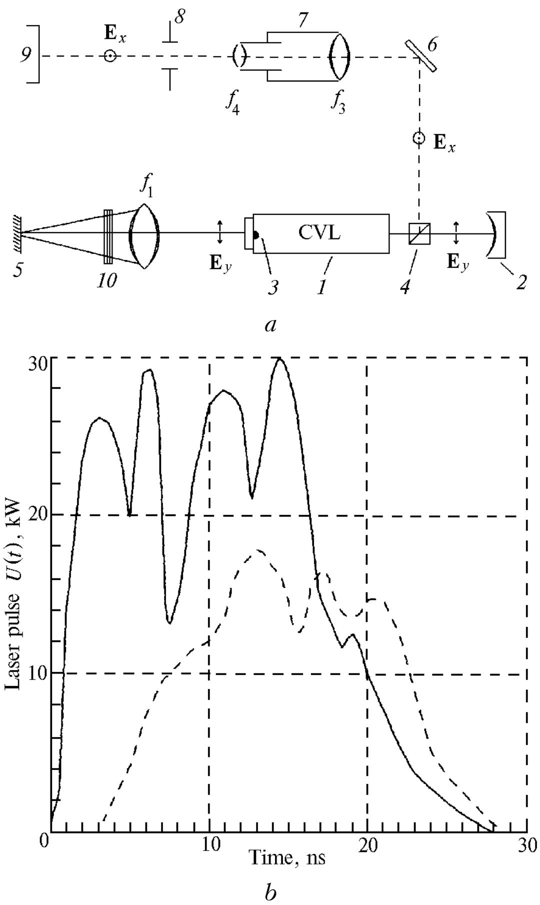


Fig. 1. Experiment on studying the capability of using a CVL as a monitor (*a*) and oscillograms of the laser pulses (*b*).

In the experiment it was assumed that the $\mathbf{E}_x$-radiation resulting from the partial depolarization of the laser $\mathbf{E}_y$-radiation incident on the target *5* is directed back to the Glan prism *4* through the optical elements and the active volume of the laser, is then separated by this prism and directed toward the mirror *6*, thus providing the capability of forming a magnified target image on the screen *9*. It was also assumed that another part of radiation, which kept the orientation $\mathbf{E}_y$ at reflection from the target, passed from the Glan prism toward the mirror *2* and upon reflection from it came back to the cavity, where it could affect, to a certain degree, the distribution of light field inside the cavity and at its mirrors.

The mean lasing power W at the CVL output (at both lines $\lambda_1 = 510.5$ nm and $\lambda_2 = 578.2$ nm and polarization) in the experiments was 12 to 14 W. The green-to-yellow ratio of W was equal to two. The mean power of radiation coming from the Glan prism toward the mirror *6* in the absence of the test target *5* was equal to 57 to 60 mW. In the presence of the test target this power increased by 2 to 3%. Figure 1*b* shows the oscillograms of pump pulses at the wavelengths λ_1 and λ_2 measured with coaxial photoelements when placed instead of the target *5* in the experiment, the arrangement of which is shown in Fig. 1*a*. In this case the lens f_1 collected the entire light flux from CVL including superluminescence with large divergence and sent it to a photoelement. It is of interest that, starting from the 17-th nanosecond from the beginning of lasing, the power of radiation at the yellow line λ_2 exceeded that at the green line λ_1 and the radiation pulse at the yellow line terminated later.

A film polarizer was used to measure the degree of polarization W_y/W_x and to separate the components W_y and W_x. In the zone of the target *5* the ratio W_x/W_y was about 0.01 at both the green and yellow lines of CVL emission. The value of the ratio of W_y at the green line to W_y at the yellow line was equal to two. The same value was also obtained for the ratio of W_x at the green line to W_x at the yellow line. The similar measurements showed that the radiation coming from the Glan prism toward the mirror *6* was mostly $\mathbf{E}_x$-radiation. The value of W_y proved to be lower than the level of electric noise of the power meter used, and we failed to find its correct value.

Figure 2 shows the experimentally obtained image of the test target (optical arrangement of the experiment is shown in Fig. 1*a*). In this figure we can see the following characteristic details (see Fig. 2): boundary *1* of the test target image formed because the diaphragm *8* limited the beam (see Fig. 1*a*), light area *2* caused by a sufficiently strong reflection of the laser radiation from the ruler surface; dark marks of the ruler *3*, light circle *4* without a segment in the top part (the segment was absent because the mount of the Glan prism intercepted the upper part of the laser beam propagating between the small and big mirrors of the cavity), hardly distinguishable light circle *5* (looking like the surface of the spherical mirror) inside the circle *4*, and bright spots *6* inside the circle *5*.

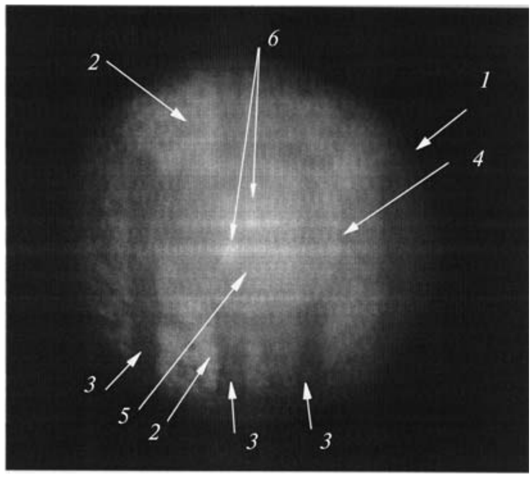


Fig. 2. Image of the test target obtained with a CVL in the experimental set up shown in Fig. 1*a*.

Taking into account that the mean lasing power at the green line exceeds that at the yellow line, we can assume that if the conditions of target illumination and reflection from the target surface are the same as for the green line, then the target image must be mostly green. However, the color of the test target image is different in different parts of the image. Moreover, the prevailing color is yellow. The green color prevails between the boundary *1* and the light area *2* (see Fig. 2) in the image of the test target. In Fig. 2 (in the gray scale) dark areas correspond to the green color. The light area *2* is yellow except for small dark inclusions, which are green in the color image. In the area *2* the marks on the ruler are clearly seen, and these marks are mostly green. The green ruler marks inside the yellow circle *3* are far less pronounced, and they are hardly distinguishable inside the circle *4* looking like the mirror surface and also colored in yellow.

Taking into account the shape of lasing pulses at the green and yellow lines (see Fig. 1*b*), the presence of $\mathbf{E}_x$-radiation in the CVL radiation, reflective and depolarization properties of the test target surface and the small mirror surface, and practically zero reflectance of the Glan prism for $\mathbf{E}_y$-radiation, we can draw some preliminary conclusions on the mechanisms of test target image formation as CVL operates in the regime of laser monitor. The green parts of the image near the boundaries are formed as lasing prevails at the green line. The light (yellow) area *2* in the test target image is formed due to reflection from the test target within low divergence beam and high degree of polarization. The polished surface of the ruler does not cause depolarization of the incident radiation at reflection. Taking into account that the Glan prism reflects $\mathbf{E}_x$-radiation in the direction toward the mirror *6* (see Fig. 1*a*), the yellow color of the test target specularly reflecting the laser radiation can be caused by the fact that the power of CVL output $\mathbf{E}_x$-radiation at the yellow line exceeds that at the green line. " y the same reason the specularly reflecting surface of the small mirror is also yellow. Within the dark ruler marks we can observe weak reflection and marked (possibly different for the green and yellow lines) depolarization of the reflected $\mathbf{E}_y$-radiation. As a result, the main contribution to the formation of the mark images comes from $\mathbf{E}_x$-radiation at the green line formed at reflection and amplified by the laser active medium. Even at the same coefficients of reflection and depolarization of the $\mathbf{E}_y$-radiation at the green and yellow lines, the green color must apparently dominate in the mark images, because the lasing power and the gain at the green line exceed those at the yellow line.

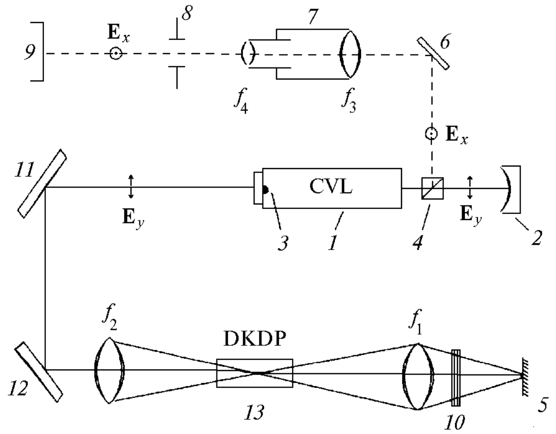
The peculiarities of the circles *4* and *5* indicate that they are not the circles existing at the surface of the test target. It is still unclear why do the circles *4* and *5* appear at all. These most likely result from reflection of the $\mathbf{E}_x$-radiation at the yellow line, which circulates inside the cavity, from the Glan prism. The circle *5* is likely the image of the small mirror surface. The point is that the position of the test target image formed by the lens f_1 roughly coincides with the position of the small mirror of the laser cavity, what results in the coincidence of the ruler image with the mirror image. " oth the circle *4* and circle *5* appear because a fraction of the $\mathbf{E}_x$-radiation, propagating inside the cavity from the small mirror to the big one, is reflected from the Glan prism in the direction of the screen *9* (see Fig. 1*a*). The image of the small mirror thus superimposes on the image of the test target. The yellow color of the circles *4* and *5* is caused by the same reasons as the yellow color of the polished surface of the ruler.

The yellow spots *6* inside the circle *5* may result due to at least two causes. First, the spots *6* may appear because of the existence of zones, specularly reflecting the laser radiation in the CVL cavity, on the test target surface. Another cause is that as the radiation is specularly reflected from the target surface, it is slightly depolarized and upon reentering the cavity it can lead to the spatial redistribution of the light field inside the cavity, that is, to appearance of the areas with the enhanced intensity of laser radiation on the mirror *3* (see Fig. 1*a*). Just these zones are then observed as the spots *6*.

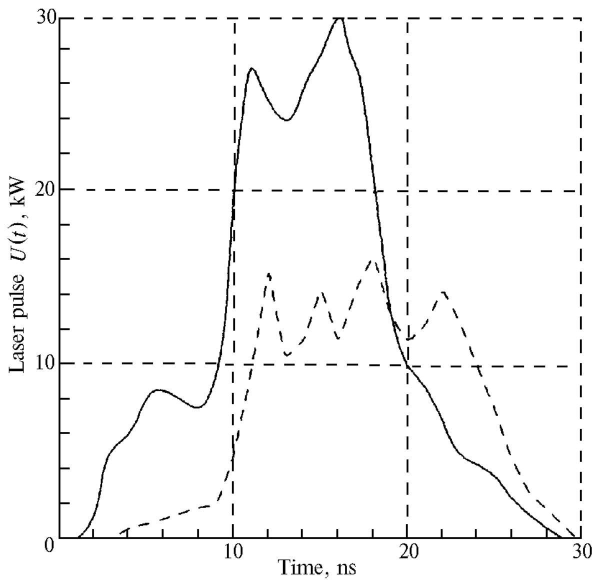
The optical arrangement of the experiment with the "CVL+UV converter" system is shown in Fig. 3*a*. In this experiment the plane mirrors *11* and *12* and the lens f_2 served to direct the CVL radiation and to focus it on the crystal *13*. The focal length of the lens f_2 was 550 mm. The CVL radiation was converted into the UV radiation at the wavelength $\lambda_3 = 271$ nm (sum-frequency conversion). For this purpose, we used the DKDP crystal (without antireflection coating at the faces) 40 mm in length and 10 mm in diameter. The crystal was placed at an adjusting table for fine adjustment to the matching angle. The rays λ_1, λ_2, and λ_3 leaving the crystal *13* were focused with the CaF_2 lens f_1 on the target *5*. The focal length of the lens f_1 (the distance between the lens f_1 and the target *5*) and the filter *10* were the same as in the previous experiment. The distance from the output mirror *3* to the target *5* was from 1630 to 1670 mm. The mean power of the CVL radiation passing through the crystal aperture of 10 mm was 6.4 W of the power at both lines together. The power of the UV radiation in the case of optimal adjustment of the crystal by the matching angle achieved 0.3 W.

Figure 3*b* shows the oscillograms of laser radiation pulses for the experimental scheme shown in Fig. 3*a*. To record these pulse, the crystal *13* was replaced with the diaphragm 10 mm in diameter which cut off the beam with high divergence (mostly, the beam of superluminescence) and transmitted the beams with lower divergence (~1 mrad in the far wave zone), which are formed in an unstable optical resonator at the beam passages following superluminescence. For this reason the radiation pulses shown in Fig. 3*b* were delayed. " esides, they were somewhat shorter than the pulses shown in Fig. 1*b*.

To reveal whether the crystal aperture diaphragming the laser radiation affects the quality of the test target image or not, we have obtained the image of the test target (Fig. 4*a*) in the experimental arrangement shown in Fig. 3*a*, but with the crystal replaced by the diaphragm of 10 mm diameter set at the place of the crystal face (Fig. 4*b*). The images of the test target shown in Fig. 4 are almost identical thus indicating that diaphragming of the laser radiation by the crystal aperture has no effect on the quality of the test target image. These images are mostly similar to those shown in Fig. 2, so let us note only the differences between them. First, the green area between the boundary *1* and the light area *2* is much wider than that in Fig. 2. This can likely be explained by much higher lasing power at the green line than at the yellow line during first 9 ns (see Fig. 3*b*), while under the conditions of the previous experiment this took place during first 5 ns.



a

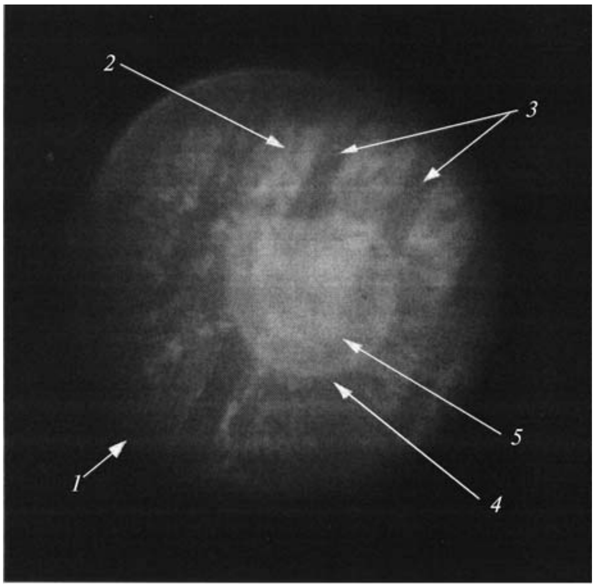


b

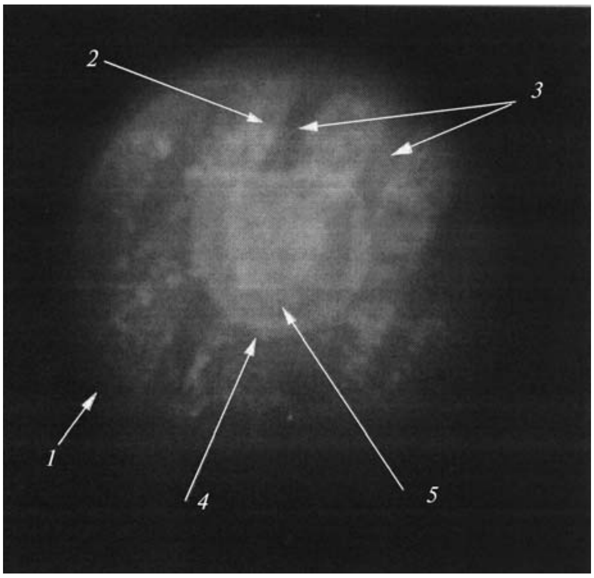
Fig. 3. Experiment on studying capabilities of the "CVL+UV converter" system operated in the regime of laser monitor (*a*) and oscillograms of laser pulses (*b*) at λ_1 (solid curve) and λ_2 (dashed curve).

Second, the light area *2* is less pronounced than in Fig. 2, it has a smaller size and is closer to the top right-hand side corner of the test target image.

Third, the light circle *5* does not look like the image of the small mirror surface. This is likely connected with the fact that in this experiment the position of the test target image formed by the lens f_1 did not coincide with the position of the small mirror of the cavity, what resulted in formation of the blurred mirror image against a sufficiently sharp image of the test target.



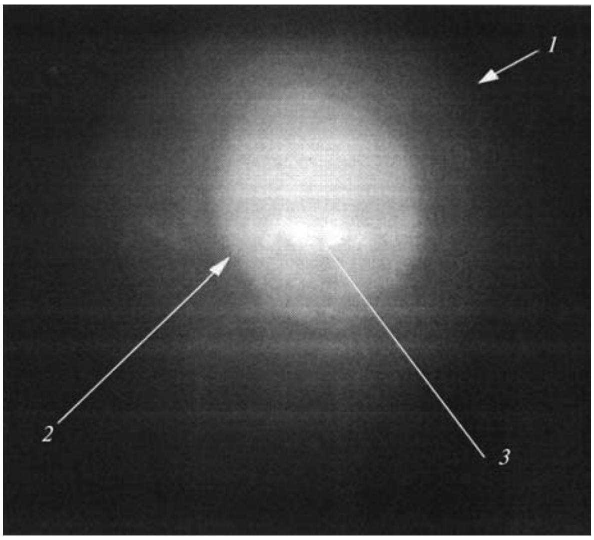
a



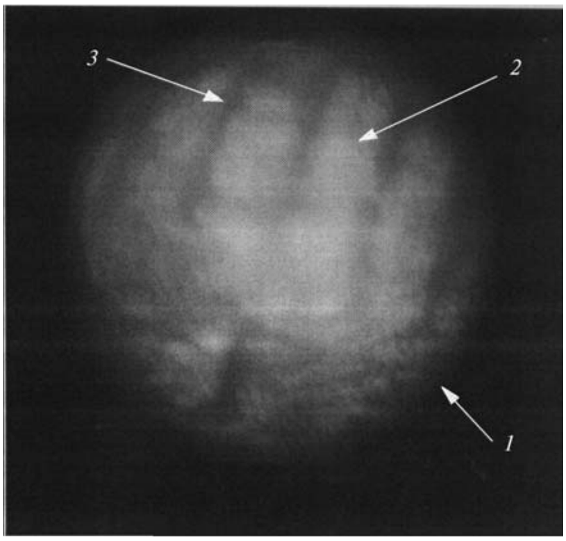
b

Fig. 4. Test target images obtained in the experiment in the scheme shown in Fig. 3*a* with no crystal (*a*) and with the diaphragm simulating its aperture (*b*).

Fourth, the bright spots *6* are absent in the image of the small mirror surface (see Fig. 2). This can be explained by the following causes: (a) the image of the small mirror surface in Fig. 4 is out of focus (blurred), (b) areas specularly reflecting the laser radiation back in the CVL cavity are absent on the observed ruler surface, (c) the test target is so far from CVL that the radiation reflected from it has no effect on the distribution of the light field inside the cavity.



a



b

Fig. 5. Test target images obtained in the “CVL+UV converter” system at the adjusted (*a*) and non-adjusted (*b*) crystal.

Figure 5 shows the images of the test target obtained in the experiment by the scheme shown in Fig. 3*a*. Figure 5*a* shows the results of the attempt to obtain the test target image in the case that the power of UV radiation was maximum (0.3 W) and the angle of incidence of the laser beam on the output face of the crystal was close to zero. One can see here a bright spot *2* of the light reflected from the crystal face instead of the test target image within the image boundary *1*. Inside this spot we can see even more bright yellow spots *3*. Most likely, this is indicative of the influence of the laser radiation reflected from the front face of the crystal on the CVL operation. As the crystal axis was slightly detuned by the angle thus keeping the reflected beam from reentering the cavity, the spot *2* was sharply decreased within the image boundary *1* (Fig. 5*b*) and the distorted image of ruler marks *3* appeared. In this case the mismatching and a sharp decrease in the power of UV radiation were observed. Note that the spot *2* can be removed (not changing the angle of the crystal axis and not decreasing the power of UV radiation) by making the faces antireflecting or cutting them at the ” rewster angle.

Conclusions

1. The Glan prism in the CVL cavity separates out the $\mathbf{E}_x$-radiation reflected from the surface of the test target thus providing the possibility of observing it.

2. The bright yellow spot of unclear origin and the yellow image of the small mirror of the cavity are imposed on the target image.

3. The color of the image of the target surface depends on the degree of specular reflection of the laser radiation from it, and this dependence indicates that CVL operating in the regime of a monitor allows one to judge on the degree of the target surface roughness based on the image color.

4. The “CVL+UV converter” system can operate in the regime of laser monitor. The image quality can be improved both due to improvement in the optical properties of different system elements and due to image correction with the corresponding computer software.

References

1. V.M. ” atenin, V.V. ” uchanov, M.A. Kazaryan, I.I. Klimovskii, and E.I. Molodykh, *Lasers at Self-Limited Transitions of Metal Atoms* (Nauchnaya Kniga, Moscow, 1988).
2. K.I. Zemskov, M.A. Kazaryan, V.M. Matveev, G.G. Petrash, M.P. Samsonova, and A.S. Skripnichenko, Kvant. Elektron. **11**, No. 2, 418–421 (1984).
3. I.I. Opachko and V.S. Shevera, in: *Processes of Elementary Interactions in Atoms* (Uzhgorod State University Publishing House, Uzhgorod, 1985), pp. 189–198.
4. I.I. Opachko, Teplofiz. Vysokikh Temperatur **27**, No. 5, 1020–1023 (1989).
5. J.A. Piper, in: *Pulsed Metal Vapor Lasers*, NATO ASI Series (Dordrecht, London, 1996), pp. 277–287.
6. V.T. Karpukhin, Yu.” . Konev, and M.M. Malikov, Kvant. Elektron. **25**, No. 9, 809–813 (1998).