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UV radiation source based on a copper vapour laser with acousto-optically controlled spectral and temporal parameters

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***Abstract*. A modified version of the optical scheme for second harmonic generation in a copper vapour laser is proposed, in which mirror focusing optics mounted at an angle of 45° to the incident light beam is used instead of lens focusing optics. A mean radiation power 1.4 W at a wavelength of 255.3 nm is achieved with a conversion efficiency of 28 %. A high-speed system for controlling the spectral and temporal parameters of the UV radiation is developed and studied for the first time. The use of such a system in technological setups will considerably extend the range of their application.**

Keywords: *copper vapour laser, second harmonic generation, tunable acousto-optical filter.*

1. Introduction

An important direction in practical applications of lasers is the microprocessing of various materials, involving the use of radiation sources emitting in the UV spectral region. The requirements imposed on the energy, space and temporal parameters of the radiation sources are determined by the specific conditions. For example, a high productivity in the fabrication of microelectronic circuits, can be provided at a mean UV radiation power exceeding 1 W, a pulse repetition rate $\sim$10 kHz, and a beam divergence close to the diffraction-limited value. Because no UV lasers with such parameters are available commercially, nonlinear conversion of the radiation frequency from lasers in the visible and near IR range can be used as an alternative. Copper vapour lasers (CVLs) are among the most promising radiation sources for solving such a problem [1, 2]. The efficiency of using such lasers is determined by the following circumstances:

(i) Lasing in the visible spectral range at wavelengths 510.6 and 578.2 nm makes it possible to go over to the UV range by doubling ($\lambda = 255.3$ and 289.1 nm) and summing ($\lambda = 271.1$ nm) the fundamental radiation frequency. It is much easier to realise the second-harmonic generation (SHG) and sum-frequency generation (SFG) with a high efficiency than the higher-order regimes that are required for frequency conversion in longer-wavelength lasers, e.g., the widely used Nd : YAG laser.

(ii) The 10 – 20-ns pulses with a high repetition rate ($f = 5 - 30$ kHz) can be easily produced.

(iii) It is possible to obtain a high mean radiation power exceeding 30 W by using a simple scheme with one active element and 100 W in a scheme consisting of a master oscillator and an amplifier.

Despite the above advantages of CVLs and the availability of a number of high-quality nonlinear media, especially the BBO crystals, the highly efficient SHG and SFG could not be realised for a long time. This problem was solved after profound investigations of the CVL properties performed by various research groups. These properties lead to a complex nature of the formation of spatiotemporal parameters of the radiation emitted by such lasers. These studies made it possible to formulate the requirements to the laser resonator and the optical scheme of the beam formation in a nonlinear crystal [3].

Analysis of the published results of investigations shows that the efficiency $\sim$35 % of CVL radiation conversion into the UV region can be achieved by

(i) using unstable resonators with a magnification of 50 – 100;

(ii) employing active tubes with an optimal distribution of the gain over the cross section;

(iii) using BBO and *c*-LBO nonlinear crystals;

(iv) using anamorphic optical systems, enabling the formation of a beam with a divergence smaller than the phase-matching angle, in the plane of the principal cross section of the nonlinear crystal and the beam focusing in the orthogonal plane, thus making it possible to provide a high radiation density in this crystal and a high efficiency of nonlinear frequency conversion.

Under these conditions, the UV radiation of power $\sim$1.75 W at 255.3 nm was obtained in a scheme with one active element and $\sim$4.7 W in a scheme consisting of a master oscillator and an amplifier. In both cases, a high efficiency $\sim$35 % of nonlinear frequency conversion was achieved [4, 5].

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Note that the possibility of practical application of such lasers is determined to a considerable extent by the parameters of the beam controlling device. The aim of our study is to develop and test a high-speed device for controlling the spectral and temporal parameters of CVL radiation. Such a device is intended for use in technological facilities for various applications.

2. Experimental setup

The setup that we developed consists of two main components: a CVL and a radiation frequency converter, whose parameters are described below.

Figure 1 shows the scheme of the laser. The active element of the CVL is an LT-30 Cu sealed off gas-discharge tube [6] whose output windows are made of plane – parallel AR glass plates glued to the ends of the tube. This made it possible to minimise the optical aberrations in the cavity. The tube was mounted on an unstable 60-fold magnification telescopic resonator consisting of spherical concave mirrors (*1*) and (*2*) with radii of curvature $R_1 = 3$ m and $R_2 = 5$ cm, and plane mirror (*3*) with a hole of diameter 1 mm for beam coupling out. To control the laser radiation, a tunable acousto-optical filter (TAOF) made of a paratellurite (TeO_2) crystal was placed between mirrors (*2*) and (*3*) inside the cavity [7, 8]. Wide-angle noncollinear geometry of acousto-optical interaction was realised in the TAOF [9]. In such an interaction geometry, the TAOF need not be tuned to the Bragg angle upon tuning the radiation wavelength.

The controlled output radiation beam is formed as follows. The initial superluminescence beam propagates through the coupling hole in mirror (*3*) and incident on the TAOF. An ultrasonic wave of frequency Ω_1 or Ω_2 corresponding to the Bragg diffraction at $\lambda_1 = 510.6$ nm or $\lambda_2 = 578.2$ nm, is excited in the TAOF with the help of a $LiNbO_3$ piezoelectric transducer. Light at each of these wavelengths experiences a first-order diffraction. Mirror (*2*) was adjusted in such a way that the light beams reflected from it and diffracted from ultrasound once again returned to the laser resonator, were reflected by mirror (*1*), amplified after double passage through the active medium, and coupled out with the help of mirror (*3*). Anisotropic diffraction of light from ultrasound is used in the TAOF, while the normal type of waves are linearly polarised. The adjusting of mirror (*2*) to any particular diffraction order makes the radiation in the output laser beam linearly polarised, and the radiation frequency is shifted by $2\Omega_1$ or $2\Omega_2$ after each round trip in the cavity. Radio pulses with a carrier frequency Ω_1 or Ω_2 fed (together or individually) to the piezoelectric transducer of the TAOF before the beginning of lasing produce a feedback in the laser cavity and output light pulses are generated at a specified wavelength. The frequencies Ω_1 and Ω_2 corresponding to λ_1 and λ_2 were 157 and 133 MHz, respectively. The time of generation of each pulse was controlled with a control unit, while the amplitude of the light pulses could be varied by varying the amplitudes of the output radio pulses of the TAOF.

To suppress superluminescence in the absence of control pulses and to perform angular selection, the output radiation propagates through a spatial filter in the form of aperture (*9*) placed at the focus of lens (*5*). In addition, the TAOF also plays the role of an effective polariser of laser radiation. A comparison of the output powers of a laser with a TAOF and a laser with a Glan prism instead of the TAOF showed that the mean output power of a CVL remained virtually the same for the same pump powers and for a diffraction efficiency of $\sim 80\,\%$ in the TAOF.

Thus, the use of a system of intracavity control of the radiation from a CVL with a TAOF makes it possible to control the wavelength and amplitude of each laser pulse without changing the regime of heating of the active element or direction of propagation of light. This considerably broadens the scope of technical application of the fundamental CVL radiation as well as radiation transformed to the UV spectral range. For example, it is possible to form a train of pulses at wavelengths 510.6, 578.2, 255.3, 289.1 and 271.1 nm, which are amplitude modulated according to a certain law.

The radiation propagated through the aperture was incident on the system of beam shaping. This system was chosen keeping in mind the results obtained in paper [4], where an anamorphic optical system [10] was used for the formation of a parallel light beam of diameter 3.75 mm in the principal plane of the crystal and a convergent beam focused inside a nonlinear BBO crystal in the orthogonal plane [11]. Figure 2 shows the first version of the optical system which we used for SHG in the CVL.

The output radiation from a laser in the form of a parallel beam of diameter 20 mm is polarised linearly in the

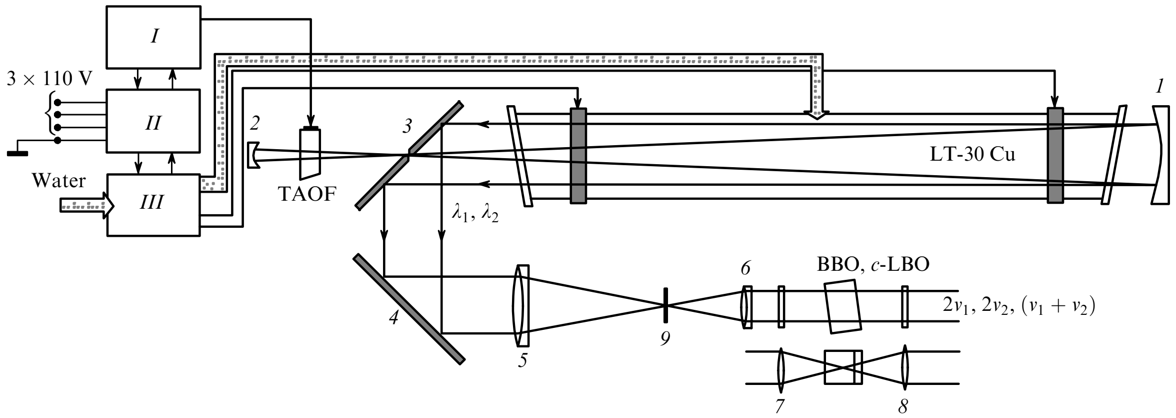

Figure 1. Functional scheme for SHG in a CVL: (*I*) control unit, (*II*) high-voltage transformer, (*III*) modulator block; (*1–4*) mirrors; (*5–8*) lenses; (*9*) aperture.

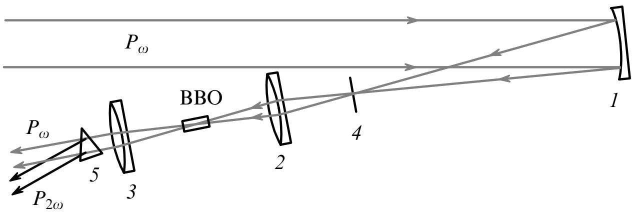

Figure 2. Optical scheme with anamorphic lenses: (*1*) spherical mirror; (*2*) bifocal lens; (*3*) cylindrical lens; (*4*) aperture; (*5*) prism.

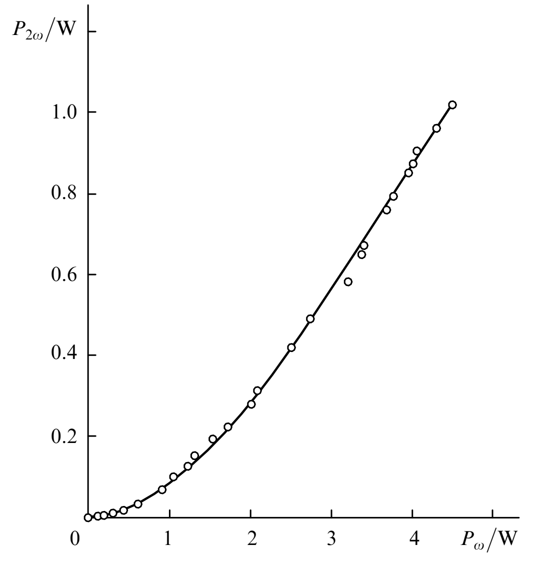

Figure 3. Dependence of the mean output power $P_{2\omega}$ of the second-harmonic radiation at $\lambda = 255.3$ nm on the mean power P_ω of CVL radiation at the fundamental wavelength $\lambda_1 = 510.6$ nm for the optical frequency-conversion scheme with anamorphic lenses.

plane of Fig. 2 was reflected at spherical mirror (*1*) with a radius of curvature 1 m mounted at an angle of ~3° to the incident beam. Aperture (*4*) of diameter 0.2 mm was placed at the focal plane of mirror (*1*). Measurement of the size of the light spot in the focal plane of the measuring lens of focal length 1 m showed that the main part of the energy of radiation in the beams passing through the aperture is concentrated within an angular divergence of 2.3×10^{-4} rad. Bifocal lens (*2*) with different focal lengths in mutually orthogonal planes ($F_1 = 36$ mm in the plane of the paper and $F_2 = 94$ mm in the orthogonal plane) was placed behind the aperture at a distance of 94 mm from it. A converging light beam with its focus at a distance of 60 mm from lens (*2*) was formed behind this lens in the plane of the paper, while a parallel beam of diameter 3.76 mm was formed in the orthogonal plane. The measured diameter of the light beam at the focus was 80 μm at half power.

A BBO crystal ($10 \times 6 \times 4$ mm) placed at the waist of the light beam was used for SHG. The crystal orientation ($\theta = 46.2°$, $\varphi = 90°$) was chosen so that phase-matching condition for obtaining sum-frequency radiation at 271.1 nm was satisfied for normal incidence of light on the front face of the crystal, while a rotation of the crystal from this position in one direction or the other in the principal plane created conditions for second-harmonic generation for the main wavelengths of the CVL: $\theta = 50.7°$ for $\lambda = 255.3$ nm and 42.5° for $\lambda = 289.1$ nm. The front face of the crystal had an AR coating for the CVL wavelength, while the rear face had an AR coating for the UV region (250–300 nm). To transform the diverging UV radiation to a parallel beam of diameter ~4 mm, cylindrical quartz lens (*3*) with the focal length 60 mm was placed behind the BBO crystal. Quartz prism (*5*) was used for angular selection of the UV radiation from the CVL radiation at the fundamental wavelengths. The mean output radiation power at the fundamental and harmonic wavelengths was measured simultaneously by IMO-2 calorimeters (not shown in Fig. 2) placed behind prism (*5*).

3. Experimental results

Figure 3 shows the dependence of the mean output power $P_{2\omega}$ of the second-harmonic radiation at 255.3 nm on the mean power P_ω of radiation at the fundamental wavelength $\lambda_1 = 510.6$ nm. Measurements were performed for a completely suppressed yellow lasing line and for a pulse repetition rate of 7 kHz. The mean output power of the radiation at 255.3 nm was 1 W for a conversion efficiency (the ratio of the mean pump and UV powers) of 22.6 %. When the laser was tuned to the fundamental wavelength $\lambda_2 = 578.2$ nm, the mean power of the second-harmonic radiation at 289.1 nm was 700 mW for a conversion efficiency of 21 %. The mean radiation power at 271.1 nm was 1.2 W for a mean power of laser radiation equal to 4.5 W and 3.3 W at $\lambda_1 = 510.6$ nm and $\lambda_2 = 578.2$ nm, respectively. The radiation power at the sum frequency was higher than at the second-harmonic frequency $2\nu_1$. In our opinion, this is due to higher absorption losses in the BBO crystal at 255.3 nm compared to losses at 271.1 nm.

The optical diagram of frequency conversion shown in Fig. 2 has some disadvantages. First, due to the complexities in its construction, the multicomponent anamorphic lens system of the beam formation may lead to aberrations of the fundamental harmonic beam and in the transformed UV radiation also. Second, harmonic aberrations can appear upon tuning second harmonic radiation. Moreover, the use of a quartz prism beamsplitter complicates beam coupling out from the laser and results in additional optical losses.

To achieve the maximum frequency conversion efficiency, a set of lenses with different focal lengths is required, as a rule, which complicates tuning and raises the cost of the optical system. These disadvantages can be eliminated by using mirror focusing optics instead of the lens optics while preserving the advantages inherent in a linear focusing system of the beam formation. In this connection, we developed a different version of the optical scheme for SHG in the CVL (Fig. 4).

Instead of bifocal lens (*2*) shown in Fig. 2, spherical mirror (*2*) with a radius of curvature R mounted at an angle α to the light beam incident on it was used in the system shown in Fig. 4. It is well known that for an oblique incidence of beams, the focal lengths of a mirror are different for two mutually orthogonal planes (the plane of incidence and a plane orthogonal to it) and are determined by the expressions $F_1 = (R/2)\cos\alpha$ and $F_2 = R/(2\cos\alpha)$ [12]. If mirror (*2*) is installed at a distance $\sim F_2$ from the focus of mirror (*1*), a converging beam is formed in one plane (plane of the paper) and a parallel beam is formed in the other plane. For the geometrical parameters (shape and size of the beam waist, beam convergence) of the

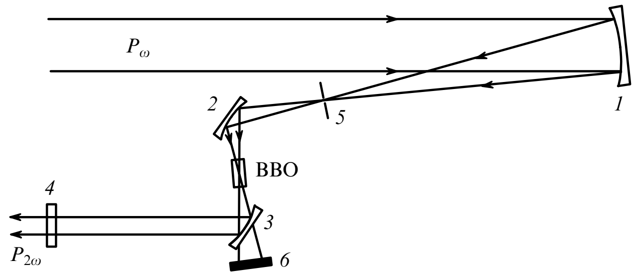

Figure 4. Optical scheme with mirrors: (*1*, *2*) spherical mirrors; (*3*) cylindrical mirror; (*4*) plane–parallel quartz plate; (*5*) aperture; (*6*) filter.

beam incident on a nonlinear crystal to remain the same as for the optical conversion scheme shown in Fig. 2, the values $R = 120$ mm and $\alpha \approx 45^\circ$ were chosen. BBO crystals with the same parameters as for Fig. 2 were placed at the beam waist. To recollimate the UV radiation diverging in one plane (in the plane of the paper), cylindrical mirror (*3*) (Fig. 4) with a radius of curvature equal to 180 mm was installed behind the crystal. Mirror (*3*) reflected the UV radiation and transmitted radiation at the fundamental CVL wavelengths, which was then absorbed by filter (*6*). Subsequent selection of the output UV radiation was carried out with the help of plane–parallel quartz plate (*4*) with an interference coating.

Figure 5 shows the experimental dependences of the mean output power $P_{2\omega}$ of the second-harmonic radiation at 255.3 nm on the mean radiation power at the wavelength $\lambda_1 = 510.6$ nm for the conversion scheme shown in Fig. 4. Measurements were carried out for $f = 7.5$ kHz. The mean output power of the radiation at 255.3 nm was 1.4 W for a conversion efficiency of 28 %. For a laser tuned to the fundamental wavelength $\lambda_2 = 578.2$ nm, the mean power of the second-harmonic radiation at $\lambda = 289.1$ nm was 700 mW for a conversion efficiency of 23 %. The mean radiation power at $\lambda = 271.1$ nm was 1.4 W for a mean power of laser radiation equal to 5 W and 3 W at $\lambda_1 = 510.6$ nm and $\lambda_2 = 578.2$ nm, respectively.

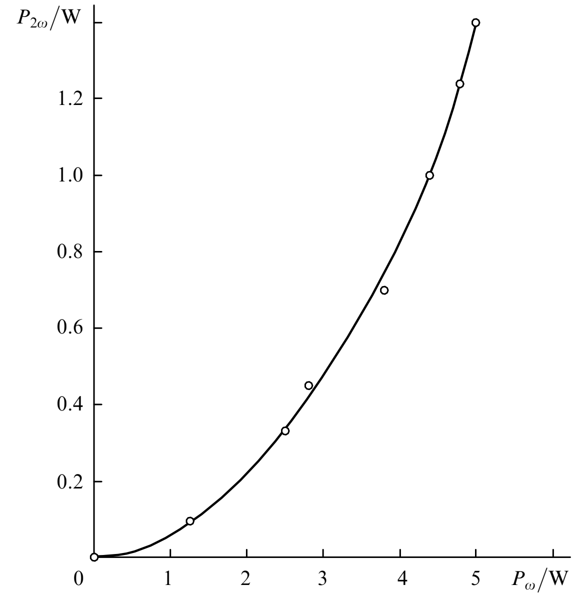

Figure 5. Dependence of the mean output power $P_{2\omega}$ of the second-harmonic radiation at 255.3 nm on the mean power P_ω of CVL radiation at the fundamental wavelength $\lambda_1 = 510.6$ nm for the optical frequency-conversion scheme with mirrors.

The possible applications of the UV system with CVL control developed by us include cutting, scribing, drilling and processing of materials like glass, sapphire, diamond, GaN, etc. The shape of the light spot and the divergence of the UV radiation have a considerable significance for these purposes. Figure 6 shows a photograph of the laser spot of radiation with 255.3 nm at the focal plane of a quartz lens of focal length 100 mm. The light spot was elliptical in shape with a ratio 3 : 1 of the axes. The minor axis had a length 25 μm which corresponds to the plane of phase synchronism of the nonlinear BBO crystal. The divergence 2.5×10^{-4} rad of radiation for this plane matches approximately with the synchronism angle (0.2–0.3 mrad cm^{-1}) for a 1-cm long BBO crystal.

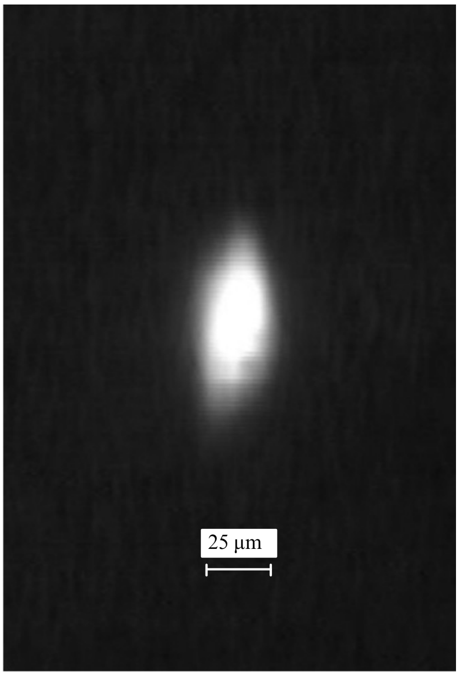

Figure 6. Photograph of a spot of laser radiation at 255.3 nm in the focal plane of a quartz lens of focal length 100 mm.

Thus, a nonlinear crystal plays the role of an angular filter of spatial frequencies for the fundamental radiation from a CVL, which is converted into the second harmonic. To obtain a circular spot, the divergence of the fundamental radiation must be decreased (by a factor of about 4–5) in the nonlinear frequency conversion scheme considered here. This can be done by using a combination of an oscillator and a copper vapour laser amplifier [5].

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