USE OF A COPPER-VAPOR LASER TO OBTAIN ULTRAVIOLET RADIATION

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We present some results of investigation into obtaining ultraviolet radiation (UVR) at $\lambda = 0.271$ μm, *by frequency summation of the copper-vapor laser radiation at* $\lambda = 0.51$ μm *and* $\lambda = 0.578$ μm *in a nonlinear DKDP crystal. Using an unstable optical resonator with the magnification factor* $M = 200$ *and spatial filter we have obtained the UVR of* 0.75 W *mean power at the conversion efficiency* η *of* 12%. *In a low divergency beam the amplitudes of pulses at yellow and green lines came close and a time lag between them disappeared, that strongly favored the process of the UVR generation at the summed frequency.*

INTRODUCTION

A possibility of using copper-vapor lasers (CVL) and nonlinear crystals to obtain ultraviolet radiation (UVR) was shown long ago.[1] Since that time the efforts of researchers have been focused on addressing a complex of questions on increasing the efficiency of the CVL radiation conversion in nonlinear crystals, and choosing a proper optical arrangement of the converter to make it competitive with other known sources of UVR.[2–7]

The efficiency of a nonlinear frequency conversion of radiation mainly depends on peak power density and divergency of the beam incident onto a nonlinear crystal. Therefore two schemes are used most often to perform the CVL radiation conversion. The first one is the master-oscillator-amplifier[2,4,5] scheme while the second one uses a laser tube placed in an unstable resonator with large magnification coefficient, $M \sim 100$, and spatial filter (collimator) to separate out the low diverging beam core.[1,3,6,7]

The first scheme allows one to obtain a laser beam with low divergency and very high density of the radiation power incident on the crystal. It is evident that in order to improve the results achieved it is necessary to increase the amplitude of the radiation pulse delivered from the amplifier and the amplification efficiency to make the entire system more efficient.

The second scheme allows one to obtain a beam with low divergency also. For $M \geq 100$ it is possible to form even a diffraction limited beam.[8,9] At large M only several passages of a beam through the resonator are needed that take correspondingly short time as compared with the inversion lifetime in the CVL, ~ 30 ns. The second scheme is considerably simpler for implementation in a hardware, but has a disadvantage that a fraction of power in the diffraction limited beam is too low (~ 10 – 50%),[8,9] and the CVL power essentially decreases at large M.[10] However, these difficulties can most likely be overcome. In Ref. 11 it is shown experimentally that the fraction of power in the diffraction limited beam can be increased approximately up to 90% by increasing the inversion lifetime and, correspondingly, the radiation pulse duration, τ. Such an effect may be achieved by only in a properly modified excitation mode and selecting the CVL parameters. It is realistic in this case to essentially increase the laser efficiency, up to ~ 10%.[11,12] If the mean output power of 10–20 W is achieved, the second scheme of frequency conversion of CVL radiation to the UVR seems to be more promising.

Since CVLs simultaneously emit at two wavelengths it seems to be reasonable to mix both these emissions in order to obtain UVR at the sum frequency for a complete use of the output emission energy. In that case the radiation at $\lambda_1 = 0.578$ μm (yellow line) and $\lambda_2 = 0.51$ μm (green line) produce, when mixed, the UV radiation at the sum frequency $\lambda_3 = 0.27$ μm. In the majority of experiments that were carried out using such crystals as KDP, DKDP, and BBO, the highest efficiency of the CVL radiation conversion were obtained for the second harmonic generation, and that for the frequency summing was lower by the factor of 1.5 to 2.[3,5] Therefore, it could be of certain interest to investigate the frequency summing mechanism for CVL radiation in the optical arrangement with an unstable resonator in a more detail in order to elucidate physical causes that limit the conversion efficiency.

DESCRIPTION OF THE EXPERIMENT

Optical arrangement of the experiments is depicted in Fig. 1. In our experiments we used a

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commercially available gas-discharge tube GL–201 as the active laser element (*1*) and a power source providing up to 4 kW output power. The tube was placed within a telescopic unstable resonator with $M = 200$ (mirrors *2* and *4*). To polarize the radiation we used a Glan prism (*3*). The beam diameter D at the CVL output is 20 mm. The CVL radiation beam was then directed by two plane mirrors (*5*, *6*) to the collimator composed of two lenses f_1 and f_2. This collimator compresses the wide beam into a beam with the diameter $d \approx 1$ mm in order to increase the radiation power density incident on the crystal (*7*). The focal length of the input lens, f_1, is 550 mm, and that of the output one, f_2, could be varied. To isolate the beam core of low divergency the diaphragm (*8*) was placed in the focal plane of the lens f_1 with the diameter $\phi = 0.6$ to 0.8 mm.

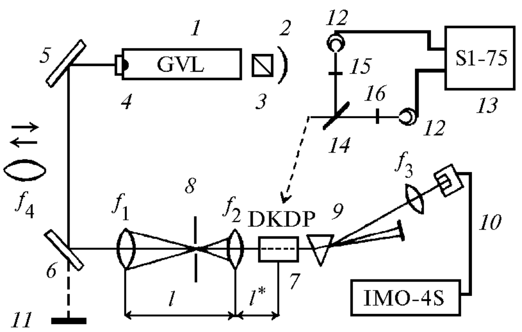

FIG. 1. The optical arrangement of the experiment: CVL (1), resonator mirrors (2, 4), Glan prism (3), beam folding mirrors (5, 6), input (f_1) and output (f_2) lenses of the collimator, crystal (7), diaphragm (8), quartz prism (9), CaF_2 *lens (f_3), power meter (10), screen (11), lens (f_4), photocells (12), oscilloscope (13), beam splitter (14), and optical filters (15, 16).*

In the experiment we used a DKDP crystal highly transparent for light at the wavelength λ_3, with high effective non-linearity $d_{\text{eff}}(\theta)$, and a small drift angle for the extraordinary ray. The calculated synchronism angle for the sum frequency generation at the temperature of 333 K in the OOE interaction mode was 78.8°. The EOE and OEE interaction modes could not occur under the particular conditions of this experiment. The crystal *7* of the length $L = 40$ mm was placed in a thermostat (with the electronic temperature stabilization), that was installed on a rotatable table, that allows one to make fine tuning at the synchronism angle. At the output from the crystal the beams with different wavelengths (λ_1, λ_2, and λ_3) were separated with a quartz prism (*9*). The UV beam was focused with a CaF_2 lens f_3 into an IMO–4S calorimetric power meter (*10*).

To determine the divergency and structure of the CVL radiation beam in the far zone we used a lens f_4 with the focal length of 10 m and a screen (*11*) placed in the focal plane (the mirror (*6*) was removed). The divergence of the beam converted with the collimator and its diameter in the crystal were determined using the calibrated diaphragm method. The distance l between the lenses f_1 and f_2 was selected such that the converted beam divergence be minimal while the distance to the crystal center being constant ($l^* = 80$ mm).

To investigate time parameters of laser pulses, at the wavelengths λ_1 and λ_2, that pass through the collimator and have different divergence we used a F–32 photocell (*12*) and an oscilloscope (*13*). The beam emerged from the collimator was divided into two beams with a beam splitting mirror (*14*), a yellow filter (*15*), and a green filter (*16*). Both paths had equal optical lengths. The oscilloscope was triggered by the leading edge of the CVL electric current pump pulse. In these experiments the collimator input lens with $f_1 = 1620$ mm was used. The same arrangement was used to measure the emission energy at yellow E_1 and green E_2 lines in beams with different divergence at the collimator output. In this case the photocells were replaced by the averaging power meter IMO–4S.

RESULTS

The mean output power of polarized radiation P delivered by the CVL used in our experiments was 10–11 W at the pulse repetition frequency $f = 10$ kHz.

On the screen (*11*), in the focal plane of the lens f_4 (see Fig. 1), four round spots could be seen, as formed by the beams with the divergence φ, in the far wave zone, of approximately 7.7, 2, 0.25, and 0.07 mrad.

The Table I gives the fraction ΔE of the total output energy E concentrated in the beam formed by different diaphragms ϕ, which were placed in the focal plane of the collimator input lens f_1 with the focal length of 1620 mm.

TABLE I.

ϕ, mm	φ, mrad	$\Delta E/E$, %	E_2/E_1
0.6	0.20	19	1.1
0.8	0.25	25	1.2
6.5	2.0	50	1.5
∞	7.7	100	2.0

The ratios of the energy at green line to that at the yellow one, in the beams of different divergency in the far wave zone, are also given in this table. Figure 2 presents the oscillograms of the laser pulses $U(t)$ at the collimator output with a diaphragm of the diameter $\phi = 0.6$ mm ($\varphi \approx 0.2$ mrad) in it and without the diaphragm ($\varphi \approx 7.7$ mrad) for both λ_1 and λ_2.

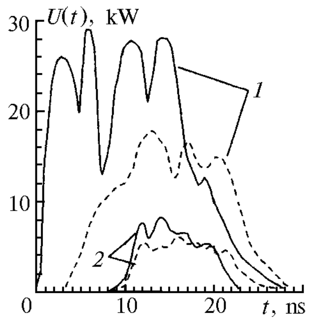

FIG. 2. The pulses $U(t)$ of the CVL radiation power: $\varphi = 7.7$ rad *(1),* $\varphi = 0.2$ rad *(2),* $\lambda = 0.51$ μm *(solid curve),* $\lambda = 0.578$ μm *(dashed curve).*

Other experiments have been carried out using the lens with $f_1 = 550$ mm and a diaphragm with the diameter $\phi = 0.8$ mm in the collimator. In this case the value $\varphi \approx 0.73$ mrad and energy fraction $\Delta E/E$ amounted approximately to 60%. Unfortunately, we could not isolate in this experiment the beams with lower divergency, because of instrumental limitations.

Figure 3 shows, as functions of the focal length of the lens f_2, the converted beam diameter d at the distance l^* from the collimator output, its divergency φ', and the SFG efficiency η, which was determined as $\eta = P_3/P_c$, where P_3 is the mean power of UVR, P_c is the mean power of CVL radiation at two wavelengths before it enters the crystal.

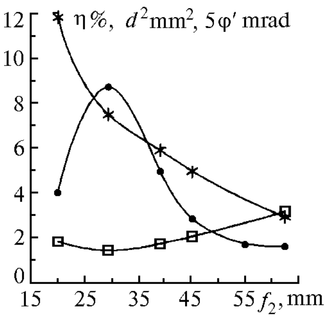

FIG. 3. Dependence of SFG efficiency and beam parameters on the focal length of the collimator output lens f_2: efficiency η (●——●); φ' (∗——∗); *the squared diameter* d^2 (□——□).

Figure 4 shows the average power of UVR, P_3, and the conversion efficiency, η, as functions of the beam power, P_c, incident onto the crystal. At the optimal alignment of the optical path and synchronism angle we have achieved the values of $P_3 = 0.75$ W and $\eta = 12\%$, with the maximum power $P_c = 6.4$ W.

To estimate the influence of inhomogeneous heating of the crystal by laser radiation on the SFG efficiency we have carried out the experiments when the CVL mean power was 30 times decreased with a rotating chopper disc. In this case the pulse power was the same. However, no changes in the efficiency η were recorded.

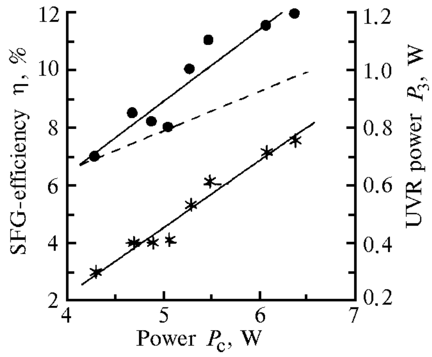

FIG. 4. SFG efficiency and UVR power as functions of the incident power P_c: UVR power P_3 (∗——∗), *efficiency* η (●——●), *theoretical calculation of* η *(dashed line).*

DISCUSSION OF THE RESULTS

It is known,[8,9,13] that a CVL with a telescopic unstable resonator emits a pulse consisting from three or four beams, which have different divergency and bear different fractions of the total pulse energy. These beams are shifted in the time relative each other because they are formed during different passes of radiation through the resonator, within the time interval of the population inversion. As a consequence the beam that is the last in time can have nearly diffraction limited divergency, as noted above. In our experiments two last beams with low divergency (0.25 mrad and 0.07 mrad) concentrate about 25% of the CVL radiation pulse energy (see Table I). The lowest φ value observed is approximately two times larger than the diffraction limited one, that is apparently caused by the aberration distortions.

It is worth noting that at a fivefold decrease in energy of the low diverging beam ($\varphi \approx 0.2$ mrad) the amplitude of the corresponding pulses decreased only by a factor of 3.5 at green line and by a factor of 3 at the yellow one (see Fig. 2). Moreover, it is clear that the delay between pulses at the green and yellow lines practically vanishes in this beam and their amplitudes are close. That means better temporal overlap between the pulses at the yellow and green lines for beams that are formed in the resonator during the last passes, as compared to the overlap in the total beam (compare the data shown in Fig. 2). These facts favor the SFG process because η is proportional to the product of instantaneous values of the pulse intensity at both lines.

The SFG efficiency η reaches its maximum (Fig. 3) at the optimal ratio f_1/f_2 (similar result has also been mentioned in Refs. 6 and 7). Such a behavior may be explained by the fact that, on the one hand, the diameter d of converted beam increases, while the power density decreases with increasing f_2 (see Fig. 3). On the other hand, the divergency of the converted beam, φ', in this case decreases. Both these facts influence the value of η in the opposite ways that leads to appearance of an optimum in f_2.

At the optimal value of f_2 the values of η and P_3, naturally, increase with increasing P_c (see Fig. 4).

Note that the value η reached in this experiment is about three times larger than the value η obtained in Refs. 6 and 7 because we used the resonator with $M = 200$ instead of $M = 5$ used there. Similar tendency of increasing η with the increasing M has been observed in other studies (see, for example, Ref. 3). This may be explained by the fact that at $M \geq 100$, by the time when the diffraction limited beam with a high-quality wave front appears, the divergency, φ′, of the beam converted by the collimator decreases and, hence, the power density on its axis grows.

Virtually, the invariability of η in the experiment with the nominal mean power of CVL and with the 30 times decreased one is indicative of the fact that thermal self-action of the beam in the DKDP crystal is small under conditions of this experiment. The problems of increasing the fraction of energy in the low diverging beam, improving the quality of optical components, and the CVL efficiency are still to be addressed.

To elucidate prospects of using the SFG of the CVL radiation we made calculations to estimate the η value. In these calculations we used the approximation of plane pump waves taking into account the depletion of their amplitudes in the crystal.[14,15] For the pulse duration, τ, of 20 to 30 ns and beam diameter at the crystal of 1 to 2 mm the mode of wave interaction can be considered as a quasi-static for a pulse, and non-diffraction for the ray. Moreover, we assumed that the divergency and Gaussian radial distribution of the beam intensity do not change during the pulse and the beam diameter is nearly constant along the crystal. In this case the spatial and temporal dependence of the radiation intensity in a pulse may be approximated by a step-wise function. To calculate each step of this function one may use expressions derived for the efficiency assuming the beam to be uniform and stationary. Then these results are to be summed (integrated). For the SFG such formulas may be found in Ref. 16

$$\frac{I_3(t, L)}{I_1(t, 0) + I_2(t, 0)} = \frac{2\pi c}{\lambda_3} X_1 \cdot \mathrm{sn}^2(a, b), \qquad (1)$$

where I_1, I_2, and I_3 are the radiation intensity on the wavelengths λ_1, λ_2, and λ_3, respectively; $\mathrm{sn}(a, b)$ is the Jacobi elliptic function, the arguments are $a = \xi \sqrt{X_1}$ and $b = \sqrt{X_1/X_2}$, X_1 and X_2 are the minimum and maximum roots of the equation

$$m_1 m_2 - (m_1 + m_2 + 0.25(\Delta kL/\xi)^2)X + X^2 = 0; \qquad (2)$$

$$m_1 = \frac{\lambda_2 I_2(t, 0)}{2\pi c(I_1(t, 0) + I_2(t, 0))};$$

$$m_2 = \frac{\lambda_1 I_1(t, 0)}{2\pi c(I_1(t, 0) + I_2(t, 0))};$$

$\Delta k(\theta, T) = |\mathbf{k}_3 - \mathbf{k}_2 - \mathbf{k}_1|$ is the wave detuning; ξ is the parameter which can be expressed by $d_{\mathrm{eff}}(\theta)$ (in SI)

$$\xi^2 = \frac{5.6 \cdot 10^{13}\, d_{\mathrm{eff}}^2\, L^2 (I_1(t, 0) + I_2(t, 0))}{n_1\, n_2\, n_3\, \lambda_1\, \lambda_2\, \lambda_3}. \qquad (3)$$

In (2) and (3) $n_1(T)$ and $n_2(T)$ are the refractive indices of the crystal for ordinary rays at λ_1 and λ_2, depending on crystal temperature; the refractive index of the crystal for the extraordinary ray at λ_3, $n_3(\theta, T)$, and $\Delta k(\theta, T)$ are also functions of θ, which is the angle between the optical axis of the crystal and wave vector $\mathbf{k}$ of radiation incident on the crystal.

The effect of thermal self-action of the beam was taken into account assuming that no dispersion exists in the DKDP absorption coefficient. Radial profile of temperature in the crystal was obtained from solution of the heat equation for the temperature at the crystal axis (and of the total beam as well) set to be $T_0 = 333$ K. In this case the temperature of crystal side T_c was calculated as a function of the mean power P_c.

The light beam incident on the crystal was divided into partial rays passing at different angles. The synchronism condition $\Delta k = 0$ was satisfied at the crystal axis. Every partial ray was characterized by its own θ, temperature T, and the detuning Δk. Then we calculated by formula (1) the values $I_3(t, L)$ for a preset moment in time. After that, the UVR pulse energy E_3 was obtained by integration of I_3 over the beam cross section within the beam divergency cone and the radiation pulse $U(t)$. The SFG efficiency was expressed as $\eta = e_3/(e_1 + e_2)$, that coincides with the efficiency definition as the ratio of the mean powers introduced above.

The calculated dependence of η on the parameters φ′ and P_c is presented in Fig. 5. The DKDP crystal length $L = 4$ cm, diameter 1 cm, and the beam diameter $d = 0.1$ cm. It was considered that the pulses at yellow and green lines are identical and coincide in time. The pulse power densities incident on the crystal are constant, $I_1 = I_2 = 0.65 \cdot 10^5$ W/cm^2, and do not depend on P_c, the radiation is completely polarized.

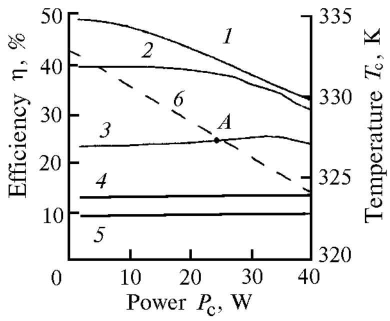

FIG. 5. The efficiency $\eta(\varphi', P_c)$ *calculated as a function of* P_c at $I_1 = I_2 = 0.65 \cdot 10^5$ W/cm^2: Curves *1, 2, 3, 4, and 5 correspond to* φ′ = 0.2, 0.35, 0.7, 1.4, 2.1 mrad, *respectively; 6 corresponds to temperature,* T_c*, at a crystal side.*

At a sufficiently small $\varphi' \le 5\cdot10^{-4}$ rad an essential drop of η is observed with increasing P_c that is connected with the beam thermal self-action. For the divergency $\varphi' \le 1\cdot10^{-3}$ rad the dependence η on P_c becomes negligible in the region of parameter values considered.

The point "AB on the curve *3* in Fig. 5 illustrates the possibility of obtaining high efficiency. This point corresponds to parameters of a CVL, that are quite realistic, namely $P_c = 25$ W, $f = 10$ kHz, and $\tau = 20$ ns. The divergency of the beam converted in the collimator is close to the diffraction limited one, $\varphi' = 7\cdot10^{-4}$ rad, at the diameter $d = 1$ mm. Given these parameters the value η equals 25% and can be essentially raised by increasing amplitudes of the pulses U while keeping the mean power P_c at the same unchanged level. This may be achieved by optimizing the CVL excitation and increasing the volume of the laser gas-discharge tube.

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