SUM FREQUENCY GENERATION FROM COPPER VAPOR LASERS

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Some results of investigation of the UV ($\lambda = 0.271$ μm) *copper vapor laser sum frequency* ($\lambda_1 = 0.510$ μm, $\lambda_2 = 0.578$ μm) *generation in nonlinear DKDP crystal are presented. For OOE interaction type the mean UV power of* 0.2 W *and conversion efficiency* η *of* 3% *have been reached when the mean power of nonpolarized radiation at the crystal input equals to* 14 W. *The efficiency* η *is shown to be essentially influenced by the beam divergence, pulse amplitude at both yellow and green lines, and by the delay between those pulses.*

1. INTRODUCTION

Recently use of copper vapor laser (CVL) and nonlinear crystals to obtain the ultra violet radiation (UVR) is attracted much attention.[1,2] Visible range of the CVL emission provides a possibility of generating UVR simultaniously at the second harmonic and sum frequency in such nonlinear crystals as KDP, DKDP, BBO, and others. Extremely high CVL efficiency of 1–3% and mean power of 10–100 W make good basis for a considerable efficiency of the equipment in the whole and the higher UVR power in particlilar. Since CVL emits at two wavelengths the pulses close in amplitude and duration, it is expedient to realize a method of sum frequency generation (SFG) in order to use all power of the radiation. Green $\lambda_1 = 0.51$ μm and yellow $\lambda_2 = 0.578$ μm lines of CVL radiation are converted into UVR with $\lambda_3 = 0.271$ μm.

In our experiments we used a DKDP crystal which had a large effective nonlinearity coefficient $d_{\mathrm{eff}}(\theta)$, high transmittance, and small angle of drift of the extraordinary ray. In accordance with our calculations, for the specified wavelengths SFG is possible in DKDP when the synchronism angle is 78.8° (crystal temperature is $T = 333$ K) by OOE interaction type. There are no interactions of EOE and OEE types under these conditions.

Efficiency of the SFG is a function of peak power and beam quality. That is why we have studied the critical parameters of CVL radiation. It is known[3,4] that a CVL with a telescopic unstable resonator (TUR) emits a pulse consisting of three or four beams which have a different divergence and carry different fractions of the pulse power at two wavelengths. These beams are shifted in time relative to each other as they are formed at different passages of the beam in the resonator during the inversion time about 30 ns. Beam parameters depend on the resonator magnification factor M, discharge tube geometry, and CVL excitation regimes.

2. DESCRIPTION OF THE EXPERIMENT

Optical arrangement of the experiment is presented in Fig. 1. A CVL *1* with the mean power of 20 W and TUR with $M = 5$ are used. The pulse repetition frequency is 10 kHz. Beam diameter D at the output of the CVL is 20 mm. Radiation from the CVL is directed into a collimator by two plane mirrors *2*. The collimator consistes of two lenses *3* and *4* and transforms the broad beam to a beam with the diameter $d = 1$–3 mm to increase radiation power density within the crystal *5*. Focal length of the input lens *3* $f_1 = 533$ mm is constant, and focal length of the output lens *4* f_2 can be varied during the experiment.

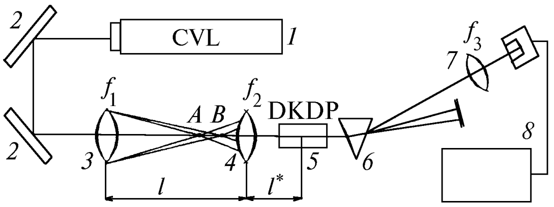

FIG. 1.

The DKDP crystal has the length $L = 40$ mm, and it is placed into a thermostat with the electronically stabilized temperature (accurate to 0.2°). The thermostat is mounted on a table that allowed it to be adjusted to the synchronism angle. At the output of the crystal the beams with the wavelengths λ_1, λ_2, and λ_3 are angular separated with a quartz prism *6*. The lens *7* ($f_3 = 280$ mm) made of CaF_2 focuses UV beam onto the power meter *8* of a calorimeter type. To study temporal characteristics of radiation pulses, the photocell and oscilloscope were used instead of the calorimeter *8*.

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3. RESULTS

Pulses of output power from the CVL, $U_1(t)$ and $U_2(t)$ at the wavelengths λ_1 and λ_2, are presented in Fig. 2*a*. Peak values of U_1 and U_2 are $1{\cdot}10^5$ and $1{\cdot}10^4$ W, peak values of the energy are $1.3{\cdot}10^{-3}$ and $0.7{\cdot}10^{-3}$ J, respectively. The delay τ between pulses at the green and yellow lines is 7–8 ns.

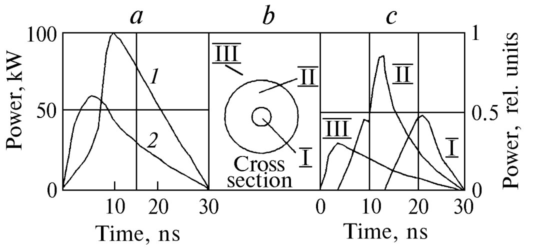

FIG. 2. Power pulses of CVL radiation: 1) U_1, $\lambda = 0.51$ μm; *2)* U_2, $\lambda = 0.578$ μm (*a*), *beam pattern in the far zone (b), pulses of radiation* ($\lambda_1 + \lambda_2$) *in relative units (c), divergence* φ *in rad*: I) $3{\cdot}10^{-4}$, II) $1.5{\cdot}10^{-3}$, III) $\geq 7{\cdot}10^{-3}$

Divergence of the CVL beam summed over wavelengths in the far zone is determined from the diameter of spots in the focal plane of a lens with $f = 9684$ mm. Three spots of different diameters are observed in this pattern (Fig. 2*b*). The beam I with the divergence of $3{\cdot}10^{-4}$ rad and power fraction of 30% corresponds to the spot I; the beam II with the divergence of $1.5{\cdot}10^{-3}$ rad and power fraction of 52% corresponds to the spot II; as to the spot III, the divergence of the beam III forming it is more than $7{\cdot}10^{-3}$ rad, and this beam is cut practically by the aperture of the lenses *3* and *4* (Fig. 1). The radiation pulses summed over wavelength for every beam I, II, and III are shifted in time (Fig. 2*c*) approximately by 10–12 ns.

According to calculations in the geometric optics approximation, the beam I must be focused by the lens *3* onto the point *A* at such a distance from the lens which is a little bit longer than f_1 (see Fig. 1), and the beam II must be focused 37 mm farther at the point *B*. Practically, in the zone *AB* the beam caustic 40–45 mm long with the diameter about 1 mm was observed. When matching the focus f_2 of the lens *4* with the point *A,* the beam I has a diameter, on this lens, on the order of Df_2/f_1 and divergence $\varphi_{\rm I}$ close to the diffraction one at the collimator output being determined by the beam diameter. In this case the beam II diverged essentially ($\varphi_{\rm II} > \varphi_{\rm I}$) at the output of the collimator. When matching the focus f_2 with the point *B*, $\varphi_{\rm I}$ increases, and $\varphi_{\rm II}$ falls off but remains considerably greater than the diffraction one. When f_2 is displaced from the point *B* at 10–15 mm both forward and backward, the value $\varphi_{\rm II}$ and the diameter of the spot II at the input of the crystal do not change essentially. This shows a bad quality of the wave front of the beam II. Note also that the CVL emission in our experiments had a random polarization.

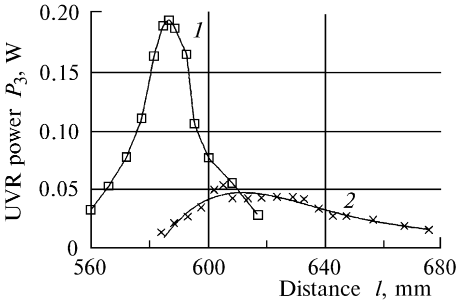

Fig. 3. UVR power $P_3(l)$; $l^* = 83$ mm, $f_2 = 30$ (*1*) and 62 mm (*2*).

Figure 3 presents the UVR mean power P_3 as a function of distance between the collimator lenses l (l^* is the distance from the output lens *4* to the middle point in the crystal *5*). The maximum value $P(l)$ was observed when the focus f_2 was disposed at the middle point of the interval *AB* (for any f_2). In this case the value P_3 reached 0.2 W ($l = 585$ mm, $l^* = 83$ mm, $f_2 = 30$ mm) (see curve *1* in Fig. 3).

The efficiency of SFG was determined as $\eta = P_3/P_{00}$, where P_{00} is a half of the mean power of the unpolarized CVL radiation at two wavelengths at the crystal input. It shoud be noted that P_3 and P_{00} are the average powers. Allowing for all losses along the optical path incurred by the beam I, we have $P_{00} = 2.2$ W, and for a sum of the beams I and II it is $P_{00} = 6$ W.

The value η reaches its maximum at the optimal ratio $f_2/f_1 = 0.06$-0.09 (Fig. 4) and it depends, besides, on the position of f_2 (i. e. on l). Curves *1* and *2* in Fig. 4 correspond to SFG when f_2 coincide with the point *A* ($P_3 \leq 0.08$ W, $\eta \leq 3.5\%$); curves *3* and *4* correspond to SFG when f_2 coincides with the center of the *AB* caustic ($P_3 \leq 0.2$ W, $\eta \leq 3.3\%$). In both cases the values of η are close to each other.

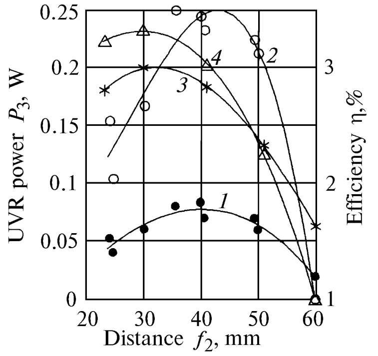

FIG. 4. SFG power and efficiency, $l^* = 83$ mm; *1)* P_3 *and 2)* η *with* f_2 *at the point A (see Fig. 1); 3)* P_3 *and 4)* η *with* f_2 *at the center of AB.*

The experiments described have been carried out with the DKDP crystal placed into the beams caustic

AB (without the lens *4*). The value P_{00} was 6.6 W, UVR power was 0.16 W, and η was 1.9%.

To estimate the influence of inhomogeneites in the temperature distribution caused by crystal heating with the laser beam on SFG efficiency, the experiments have been carried out where the mean CVL power was attenuated by a factor of 30 due to rotation of a disk with holes. In this case the pulse power of CVL radiation was the same, and the mean UVR power decreased by a factor of 30, but the efficiency η slightly increased by 1–2%.

4. DISCUSSION OF THE RESULTS AND EVALUATION OF THE PROSPECTS

The highest UVR power has been obtained in the experiments where the focus of the lens *4*, f_2, (see Fig. 1) is at the center of the caustic *AB*. In this case the values $\varphi_{\rm I}$ and $\varphi_{\rm II}$ are close in value, and it can be assumed that both beams take part in SFG. This circumstance explains the maximum value of P_3.

In the experiments where the focus f_2 coincides with the point *A*, as it was noted above, $\varphi_{\rm I}$ was small, and $\varphi_{\rm II}$ increased sharply. The spot II at the input of the crystal blurred and exceeded it in diameter. As a result, SFG has occurred for the beam I only. In spite of the lower P_{00} value for the beam I as compared with P_{00} for the sum of beams I and II, the efficiency η exceeded the values of η for UVR generation by sum of the two beams with f_2 at the center of the caustic *AB*. When the crystal is placed within the caustic zone, the value of η is still smaller. Probably, it is connected with the fact that when f_2 coincides with the point *A*, the value $\varphi_{\rm I}$ at the collimator output is essentially smaller then the values $\varphi_{\rm I}$ and $\varphi_{\rm II}$ when f_2 coincides with the center of the caustic *AB*, and, of course, it is smaller than the angle of beam convergence in the caustic of the lens *3*. A strong dependence of η on the beam divergence, in its turn, is connected with the fact that in our experiments the values $\varphi_{\rm I}$ and $\varphi_{\rm II}$ at the crystal input exceed the angle width of the SFG synchronism in DKDP.

Existence of an optimal ratio f_2/f_1 at which the value η is maximum can be explained qualitatively in the following way. For the ratios $f_2/f_1 \geq 0.1$, the beam diameter *d* at a fixed distance l^* is comparatively large (about 3 mm). This diameter is determined mainly by the beam transformation in accordance with the geometric optics, and diffraction does not make a marked contribution into the increase of the diameter. With a decrease in the ratio f_2/f_1 the value *d* falls, while the beam power density at the crystal input increases, and as a result the value η also increases. But as f_2/f_1 decreases, the diffraction beam divergence increases, and for a fixed l^* the value *d* passing a minimum begins to increase. This leads to subsequent decrease of the beam power density and decrease in the efficiency η too (for $f_2/f_1 \leq 0.06$; see Fig. 4). So the value η has a maximum that is observed in the experiment.

Practical invariability of η during the experiment with normal mean CVL power and that reduced by a factor of 30 points out that for the powers not exceeding 15–18 W a thermal blooming of the beam with the wavelengths used in DKDP is not large.

To evaluate a prospects for UVR generation with the use of a CVL and a DKDP, the estimation calculations of η have been carried out. An approximation of plane waves and given fields of pump waves[5] is used. When duration of CVL radiation pulses is 20–30 ns and the beam diameter at the crystal input is 1–5 mm, the wave interaction regime can be considered as a quasistatic for the pulse and as a diffraction-free for the beam. Besides, the divergence and radial intensity distribution of the beam are assumed to be unchangeable during the pulse. In this approximation the pulse envelopes in Fig. 2*a* are approximated by a step function. For every step one can use known formulas.[5] Having summed the results, it is easy to obtain an expression for η in the form

$$\eta = \frac{\langle U_3 \rangle}{\langle U_1 + U_2 \rangle} =$$

$$= \gamma \frac{3.78 \cdot 10^4 \, d_{\rm eff}^2 \, L^2 \, \langle U_1 \rangle \, \langle U_2 \rangle \, {\rm sinc}^2 \, (|\Delta k| \, L/2)}{n_1^0 \, n_2^0 \, n_3^0 \, \lambda_3^2 \, d^2 \, \langle U_1 + U_2 \rangle} \cdot \qquad (1)$$

The parameter η in Eq. (1) is expressed in terms of $<U_1>$, $<U_2>$, and $<U_3>$ which are the powers averaged over the radiation pulses with the wavelengths λ_1, λ_2, and λ_3, respectively; γ is the coefficient allowing for a substitution of the instantaneous values of $U(t)$ by mean values in Eq. (1), this coefficient is calculated for the specific dependence $U(t)$ in Fig. 2*a*; $n_1^0(T)$ and $n_2^0(T)$ are the refractive indices for the ordinary ray for λ_1 and λ_2; $n_3^0(\theta, T)$ is the refractive index for the extraordinary ray at λ_3; $\Delta k(\theta, T)$ is the wave detuning; θ is the angle between the crystal optical axis and wave vector *k* incident on the crystal, ${\rm sinc}\,(x) = \sin\,(x)/x_0$. Assuming that the beam diameter is not changed essentially over the crystal length and the angular intensity distribution is uniform, the beam can be divided into separate partial beams propagating at different angles θ, and the expression (1) can be integrated over θ within the given divergence angle of the beam φ. This was calculated numerically.

The beam thermal blooming was taken into account in approximation of variance-free coefficients of radiation absorption in DKDP. In this case a radial temperature profile in the crystal was found from the heat equation. Specific θ and *T* were assigned to every partial beam. The synchronism condition $\Delta k = 0$ is fulfilled on the crystal axis (and full beam) at the given temperature $T = 333$°K.

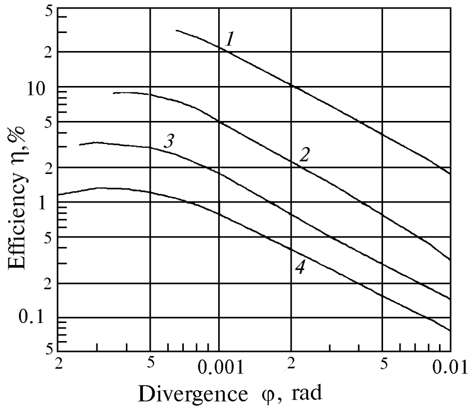

FIG. 5. Calculation of $\eta(\varphi, d)$ *for a* DKDP *crystal and a* CVL *of the mean power of* 25 W: d = 1 (*1*), 2 (*2*), 3 (*3*), *and* 5 mm (*4*).

The calculated dependence of η on the parameters φ and d is shown in Fig. 5 (P_{00} = 25 W for a completely polarized CVL radiation). At a sufficiently small $\varphi \le 8\cdot10^{-4}$ rad and $d \le 2$ mm $\eta \approx 10–30\%$ can be achieves in a single-beam and divergence CVL operation mode. The value of γ in Eq. (1) is maximum at zero delay τ between radiation pulses at yellow and green lines and equal amplitudes. It also follows from Eq. (1) that η rises with the increase on the peak power of CVL pulses. As the calculation shows, the increase in η is restriched by the beam thermal blooming when increasing in the mean power of a CVL radiation above 25–30 W.

5. CONCLUSIONS

Thus, it follows from the analysis of the above results that the CVL operation regime ought to be optimized and the laser radiation quality ought to be improved. This actions will allow a laser UV source with the radiation power of 5–10 W and total efficiency of 0.3–1% to be created. Such a laser may find a wide practical use.

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