ON PECULIAR FEATURES OF HARMONIC GENERATION OF THE COPPER VAPOR LASER RADIATION IN NONLINEAR CRYSTALS

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Three nonlinear processes responsible for frequency conversion of radiation of a copper vapor laser in KDP and BBO crystals are experimentally studied. For an average power of 2 W produced by a copper vapor laser at each of the two wavelengths (λ_1 = 510.6 nm and λ_2 = 578.2 nm) the efficiency of conversion into the second harmonics has been achieved up to 25%. The efficiency of conversion into the radiation with a sum frequency was about 14% Some features of the copper vapor laser unfavorable for the above-mentioned nonlinear processes are revealed. Possibilities of reaching better laser performance are demonstrated.

INTRODUCTION

The possibility of using a copper vapor laser (CVL) for production of ultraviolet (UV) radiation has attracted the attention of experimenters for rather a long period of time. Although the first attempt[1] was not encouraging, such studies were carried out newly and newly.[2–5] In those papers the case in point is the second harmonic generation of the green (λ = 510.6 nm) and yellow (λ = 578.2 nm) lines of the CVL and the summation of frequencies of both lines in various nonlinear crystals. Realization of these three processes makes the emission of UV radiation with wavelengths, 255, 289, and 271 nm respectively, possible.

The present state of the art of this problem incorporates a complete lack of theoretical and experimental analysis of the CVL features that show up in the generation of harmonics in a nonlinear medium. It remains elusive the issue about the CVL place among other laser sources used traditionally in nonlinear optics. It is also incomprehensible, what powers in the UV range one can get for a specific CVL, and what may be done to get them as high as possible.

A direct consequence of such an approach are the results obtained by now, which are of little interest for the practical use. It is true that some progress is noticeable but it relates only to extensive or direct (if I can say so) methods used for solution of the problem under consideration. We keep in mind that one applies more powerful CVL's[5] or recently appeared more effective nonlinear crystals, such as the crystals β–BaB$_2$0 (BBO) (see Ref. 4). The UV power ~ 1 W and the conversion efficiency 10% achieved in these works can be considered as rather good results, but without comparing them with the results obtained for other lasers.

It is clear that the pulsed radiation power on the main frequency and the nonlinear properties of the used crystals are the main factors determining high efficiencies of harmonic generation. Thus, it cannot be expected, presumably that typical CVL's (whose pulsed powers are about some tens of kilowatt) are able to compete with, for example, YAG lasers producing megawatts of output power with a typical efficiency of about 40–60%. However, it is quite a realistic goal to approach these values, and some possibilities for the solution of this problem are considered in the paper.

DESCRIPTION OF THE SETUP AND EXPERIMENTAL CONDITIONS

All results were obtained using the setup shown schematically in Fig. 1. The driving generator (DG) *1* was placed into the unstable resonator (UR) of the telescopic type being set up on the completely reflecting mirrors *2* (with the focal length f equal to 60 cm) and *3* (f = 100 cm). The radiation was extracted with the mirror *4* having a coupling hole 8 mm in diameter. The position of the common focus of the mirrors *2* and *3* coincided with the position of the hole. The Glan prism *5* was used to polarize the beam. A spatial mirror collimator filter (SMCF) was placed in front of the amplifier *9*. The spherical mirrors *6* and *7* of the SMCF had focus length of 60 cm and 150 cm, respectively. The round diaphragm *8* was placed at the common focus of the mirrors. The DG radiation, rejected and amplified, was focused by the spherical mirror *10* (f = 150 cm) into the center of the nonlinear crystal *11* anchored on a table having a mechanism for fine angle adjustment. To separate the main frequency beams from the harmonic frequency beam, the 30°–quartz prism *12* was used. The pumping power and the UV radiation power were measured using the calorimeter *13* of the IMO–2 type. The position of the light filters used in experiment is denoted by number *14*.

For the DG and amplifier the gas discharge tubes of the Kulon (having the length of an active zone 30 cm and diameter 12 cm) and GL–201 type (with the length 75 cm and diameter 2 cm) were applied, respectively. The start-up of the DG was performed using a cable delay line. When the pulse repetition frequency was 55 kHz, the total average power incident on the crystal was no more than 4.5 W.

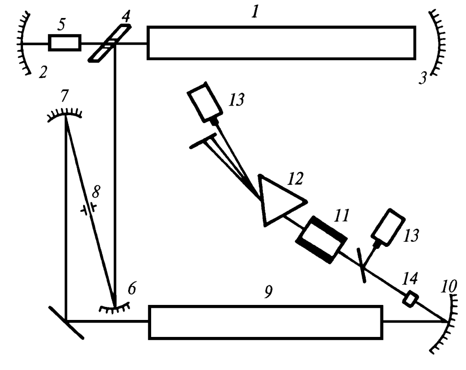

FIG. 1. Block diagram of the experimental setup.

Experiments were carried out with two nonlinear crystals KDP ($2 \times 2 \times 4$ cm^3) and BBO ($4.5 \times 4.5 \times 7.5$ mm^3). The KDP crystal was cut out at an

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angle of 70° to the main optical axis and the angle y» was equal to 45°. In the BBO crystal these angles were 48° and 90°, respectively. The scalar OOE synchronism was used for the generation of harmonics in both crystals. The Glan prism polarized the main radiation in the direction normal to the stand plane. The crystals were rotated through the stand plane.

2. EXPERIMENTAL RESULTS

The best results for three nonlinear processes in the BBO and for two ones in the KDP are given in Table I. Here P_w is the power of the main radiation incident on the crystal, P_{2w} tne power of the UV radiation, and *if* is the conversion efficiency. The values of P_{2w} and η taking into account the 20% losses of the harmonic radiation in the quartz are given in parentheses.

TABLE I.

Parameters	BBO			KDP	
λ, nm	255	271	289	271	289
P_w, mW	2310	4100	1980	3700	1600
P_{2w}, mW	490 (588)	465 (558)	440 (528)	230 (276)	245 (294)
η, %	21,2 (25,5)	11,3 (13,6)	22,2 (26,7)	6,2 (7,5)	15,3 (18,3)

Figure 2 shows the variations of η (curve *1*), P_{2w} (2), and P_w (*3*) for the second harmonic generation of the yellow line of the copper vapor laser in the BBO as a function of the radius of the SMCF diaphragm (see position *8* in Fig. 1). The angular position of the crystal was adjusted every time as the diaphragm was changed.

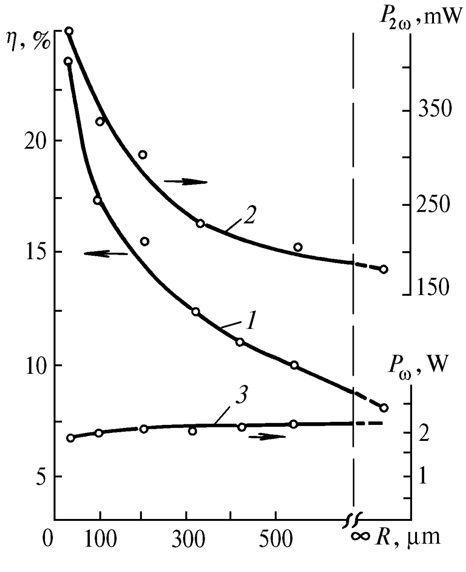

FIG. 2. Conversion efficiency η (curve 1), second harmonic average power P_{2w} (2), and main-frequency radiation average power P_w (3) as a function of the SMCF diaphragm radius for the yellow line of the second harmonic generation of the CVL.

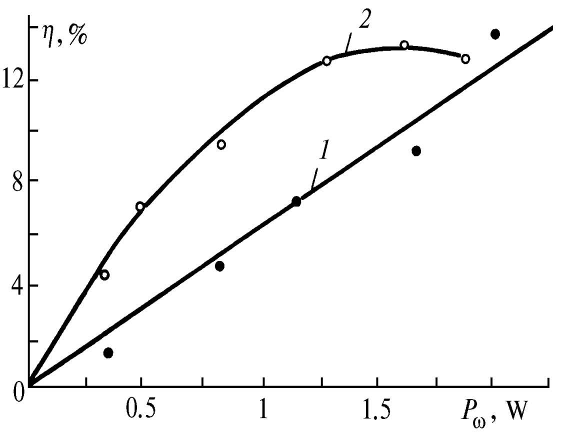

FIG. 3. Conversion efficiency as a function of average pump power for the green line of the second harmonic generation of the CVL: power is decreased with the help of the light filters (1) and vertical split diaphragm (2).

Figure 3 shows the dependence of the conversion efficiency for the second harmonic generation of the green line of the copper vapor laser in the BBO on the average pumping power. The pumping power varied with the help of a set of neutral light filters (curve *1*) or by gradually decreasing the horizontal beam size with a slit diaphragm (curve *2*). Because any light filter inevitably introduces some distortion, not only the angle orientation of the crystal was adjusted every time as the light filter was replaced, but also its position relative to the focal plane was done. When working with a split diaphragm, the original orientation of the crystal was unchanged.

3. DISCUSSION

The results presented in Table I allow some conclusions to be made. First, it is obvious that the BBO crystals are best suited for the CVL. They make it possible to generate all three UV lines (in the KDP at room temperature the green line is not doubled) and, to achieve noticeably higher conversion efficiency. We can add (using only visual observations) that the BBO crystals are much less subjected to thermal effects. This, in the main, is connected with the fact that they absorb the UV lines under consideration not so intensely as the KDP crystals. Second, the powers for all three UV lines are rather close to each other at equal proportions of the yellow and green lines in the CVL radiation. But the efficiency of the second harmonic generation for each line is about twice what is achieved with summation of frequencies. Here we come up against the first peculiarity of the CVL. The matter is that under ordinary conditions the pulse of the yellow line is de-excited later.[6] Thus, only part of the pump energy, which is accounted for the range of temporal overlapping pulses, is converted into the sum frequency. It is clear that in our case the efficiency of frequency summation also decreases due to spatial noncoincidence of beams of the yellow and green lines caused by dispersive phenomena, for instance, on the crystal surface.

Considered as the second and, perhaps, distinguishing feature of the CVL, if the case in point is about harmonic generation, should be the spatial inhomogeneity of its radiation. During the output pulse the radius of coherence of the radiation beam produced by a CVL with an unstable resonator increases (hence, the divergence decreases) approximately M times (M is the coefficient of increase of the size of the unstable resonator) for each path around the resonator.[7] Consequently, towards the end of the pulse the power density in the crystal and, hence, the efficiency of nonlinear conversion becomes significantly higher than that early in the pulse. Thus, the CVL radiation can be represented arbitrarily consisting of two components: a nucleus being the coherent radiation part and a background being the beam part that is not converted into hannonic oscillations. Obviously the use of the SMCF permits the part of nuclei in the beam which gets the amplifier to be varied in rather a wide range (say, from 20% to 100%).

Figure 2 shows the variation of η and P_{2w} on when varying the filtering properties (the radius of the diaphragm *8* in Fig. 1) of the SMCF and, hence, the part of nuclei in the beam. The main advantage of the oscillator—amplifier system as compared to a unit CVL can be seen quite well in this figure. Actually, the case for $R = \infty$ on the plots of Fig. 2 is a somewhat improved display for the latter. It can be seen that both the efficiency and P_{2w} increase nearly three times for $R = R_{min} \sim 50$ μm. It is clear that depending on the CVL operating mode and the types of the unstable resonator this difference may be not so large. But one can argue with high confidence that the difference will always exist and count in favor of the oscillator—amplifier system.

We also need to say some words about the advantage of the oscillator—amplifier system. It is evident from the plots shown in Fig. 2 that the quantities $\partial n/dR$ and dR_{2w}/dR remain practically constant up to $R = R_C \sim 200–300$ μm, but as R is further decreased, they begin to monotonically increase. By now this phenomenon has defied a rigorous explanation, but we can hypothesize the mechanism as follows. For $R_c < R < \infty$ only the nucleus—background proportion changes, whereas for $R < R_c$ the coherence radius of the driving generator beam starts to increase. The density of radiation power in the crystal increases with the square of the coherence radius resulting in a fast rise of η and R_{2w}. Thus, the oscillator—amplifier system not only offers an improved nucleus—background proportiou, but also increases the coherence radius of the original radiation of the driving generator. To some limits, such a beam correction is carried on without an essential decrease in the output power of the oscillator—amplifier system (curve *3*).

One more specific feature of the CVL is associated with the necessity of precisely focusing its radiation into a nonlinear crystal, at least when we are not dealing with superpower lasers. We used the simplest variant of beam focusing — spherical focusing — and, obviously this is not optimum. This is evidenced, for instance, by the shape of a harmonic beam representing an ellipse extended in the vertical direction. This means that not the total input energy is converted into hannonic energy but only that part of this energy which falls within the angular width of synchronism of the nonlinear crystal (in our case it is much smaller than geometrical divergence of the beam downstream the mirror *10* (see Fig. 1). To avoid these losses it is necessary either to use cylindrical focusing or to specially shape the beam incident on the mirror *10*.

The validity of the preceding is confirmed by the plots given in Fig. 3. It can be seen that for the same pump power the vertical strip, which is cut out from the input radiation just upstream of the mirror *10* (curve *2*), is converted almost two times more efficiently in the crystal than it does a circular undiaphragmed beam (curve *1*). One more important practical conclusion follows from those plots. The dependence of η on P_w may be considered as linear at least up to the values $\eta \sim 20\%$. That gives promise that using a more powerful CVL will substantially increase the efficiency of harmonic generation as compared to those reported in this paper (in our case the sum P_w was ~ 4.5 W).

Note that the experiments whose results are presented in Fig. 3 were carried out with an ~ 400 μm diaphragm in the SMCF and ~ 7.5 kHz pulse repetition frequency of the CVL, i.e., pulse power was somewhat lower. Therefore the maximum efficiency turned out to be smaller than the values given in the table of the best results.

CONCLUSION

We need to say some words about the possibility of comparing results which are concerned with the generation of the CVL radiation harmonics and obtained by different authors under different experimental conditions. It seems reasonable to say that such a comparison is improper, if there is no information at least about the energy proportion between the nucleus and background signals and about the coherence radius of the nucleus. Because both of these quantities depend critically, for instance, on the mode of the CVL, construction and tuning quality of the unstable resonator and SMFC, the time delay of the driving generator start-up, i.e., they can substantially vary from experiment to experiment, the problem of prompt control of the quality of the CVL radiation arises. To solve this problem means in fact to find an optimum design for the oscillator—amplifier system and an optimum unstable resonator if we are dealing with a unit CVL. This, as follows from the above results, is just the simplest way for creating efficient frequency doublers for the CVL radiation.

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