Sum Frequency Mixing of Copper Vapor Laser Output in KDP and β-BBO

D. W. COUTTS, M. D. AINSWORTH, AND J. A. PIPER

Abstract—**Generation at 271 nm by frequency summing the two CVL output wavelengths (at 511 and 578 nm) in β-BBO and KDP is reported. A maximum sum frequency output of 100 mW was obtained for 6.8 W total pump power from a CVL operating with a fully unstable ($M = 16$) confocal cavity.**

THE technology of the copper vapor laser (CVL) has developed rapidly over the past few years to the point where high average power (up to 60 W), high pulse rate (10–20 kHz) devices are now widely available. Wavelength conversion of the green 510.6 and yellow 578.2 nm CVL outputs into the ultraviolet is now of considerable interest so as to extend the applicability of the CVL to photolithography, UV-induced fluorescence mapping, and other technologies requiring UV laser sources of moderate power. Obtaining high overall efficiency by nonlinear frequency generation based on the CVL is critically dependant on achieving high beam quality from the CVL. However such high beam quality is obtained only at the expense of significantly-reduced power output from the CVL [1]. To date there has been only one report [2] describing second harmonic generation (SHG) of a CVL output for which the crystal β-BBO was used. Average powers up to 40 mW at the second harmonic of the green were obtained for 1 W average power (in the green) in a low divergence (0.05 mrad) beam obtained with a high magnification ($M = 60$) confocal unstable cavity. The corresponding conversion efficiency is 4 percent, however, based on the total power (5 W) available from the CVL in a high divergence beam (flat–flat cavity) conversion efficiency is somewhat less than 1 percent.

An alternative to SHG which offers the potential for more efficient conversion into the UV is that of sum frequency mixing of the two CVL output wavelengths, since this process depends on the focal power densities of both wavelengths and all the CVL output is utilized. In this letter we report experimental observations of sum frequency generation at 271.2 nm from the 510.6 and 578.2 nm outputs from a CVL using KDP and β-BBO as the nonlinear media. Data relating to second harmonic generation at 255.3 and 289.1 nm are also given for comparison purposes.

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The authors are with the Centre for Lasers and Applications, Macquarie University, N.S.W. 2109, Australia.

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For the situation where all three fields are collinear, the condition required for sum frequency generation in type 1 phase matching can be expressed in terms of the refractive indexes of the medium as [3]

$$\omega_1[n_e(\omega_3) - n_o(\omega_1)] + \omega_2[n_e(\omega_3) - n_o(\omega_2)] = 0 \quad (1)$$

where ω_1, ω_2, and ω_3 are the angular frequencies of the two pump and sum frequency fields, respectively, and n_o and n_e are the refractive indexes of the ordinary and extraordinary rays. This condition can only be realized in negative uniaxial crystals where $n_e(\omega) < n_o(\omega)$.

For summing of 510.6 and 578.2 nm, the phase matching angle (Θ_m) for the two nonlinear materials KDP and β-BBO can be readily calculated from (1) using the well-documented refractive index variations of these materials [4], [5]. For KDP

$$\Theta_m = 77.2°$$

and for β-BBO

$$\Theta_m = 46.2°.$$

In the experimental arrangement shown in Fig. 1, the green–yellow output from a conventional discharge-heated CVL was focused directly into the nonlinear element C using the achromatic spherical lens $L1$, thus providing a convenient collinear pumping configuration. The CVL was operated either with a standard flat–flat cavity or a fully unstable, edge-coupled confocal cavity having a magnification of 16. Total laser output power for the flat–flat cavity was 7.6 W with green–yellow ratio 2:1, and beam divergence 3 mrad ($1/e$ points full angle). Single pulse energies were 1.2 mJ, corresponding to peak powers of 25 and 12 kW for the green and yellow, respectively, in roughly triangular pulses of FWHM 35 ns. For the unstable cavity in the input power to the CVL was increased slightly (10 percent) to maintain the same output power (7.6 W) at the same PRF (6 kHz) and green–yellow ratio, but with beam divergence $\leq$0.2 mrad. At this input power for a flat–flat resonator cavity, the corresponding CVL output power is approximately 8.5 W. In both cases, the power incident on the crystal was reduced to 6.8 W by reflection loses at the uncoated focusing lens $L1$. An intracavity polarizing cube positioned near the high reflector was used to polarize the output from the CVL (polarization ratio 100:1).

The nonlinear element employed in these experiments was either KDP or β-BBO. The KDP crystal had dimensions of 10 × 10 × 25 mm cut at an angle of 65.15° to correspond to the type I phase matching angle for the yel-

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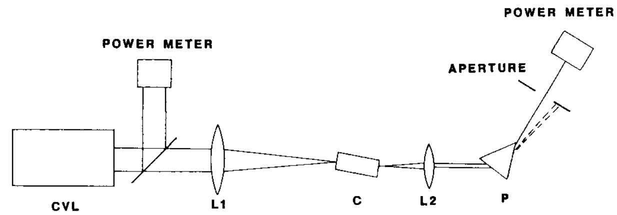

Fig. 1. Schematic diagram of experimental arrangement used for sum frequency generation.

TABLE I
UV POWER OBTAINED FROM 6.8 W CVL INCIDENT POWER

		Plane resonator				Unstable cavity magnification M = 16			
		β-BBO		KDP		β-BBO		KDP	
Focusing lens (mm)	λ (nm)	Power (mW)	Efficiency[a] (percent)	Power (mW)	Efficiency[a] (percent)	Power (mW)	Efficiency[a] (percent)	Power (mW)	Efficiency[a] (percent)
1000	255.3	1.3	0.02			13	0.2		
	289.1			2.7	0.04			30	0.4
	271.2	1.3	0.02	2.7	0.04	13	0.2	74	1.1
500	255.3	2.7	0.04			31	0.5		
	289.1			1.3	0.02			56	0.8
	271.2	2.7	0.04	8.0	0.12	38	0.6	100	1.5
200	255.3	6.7	0.10			49	0.7		
	289.1			4.0	0.06			28	0.4
	271.2	8.0	0.12	11	0.16	64	0.9	50	0.7

255.3 nm = Doubled green,
289.1 nm = Doubled yellow,
271.2 nm = Sum frequency.

[a]Efficiencies are for the conversion of total (green plus yellow) laser power into UV power. Note green to yellow ratio is 2 : 1.

low (578.2 nm) copper laser line at normal incidence. The β-BBO crystal had dimensions 3.8 × 5.7 × 7 mm cut at an angle of 50.2° corresponding to the type I phase matching angle for the green (510.6 nm) line at normal incidence. Both crystals were mounted in a precision *X*-*Y* gymbal stage for accurate orientation.

The output from the crystal was recollimated using a short focal length ($f = 50$ mm) quartz lens *L*2 and dispersed using a quartz prism harmonic separator *P*. Losses from these (uncoated) elements *L*2 and *P* were measured at 20 percent total. Apertures were positioned to block scattered pump radiation from the detectors. Average output powers were monitored using a blackbody thermopile detector (Scientech 36-0001) and pulse shapes recorded with a vacuum photodiode (Hamamatsu 1193U-02) and displayed on a fast oscilloscope (Tektronix 7904).

Results for sum frequency generation and, for comparison, second harmonic generation from the two pump wavelengths are presented in Table I for three different focal lengths of *L*1 and for the two different CVL cavities. The phase matching angle (between incident beam and the *z* axis of the crystal) for maximum UV output at 271.15 nm was measured to be $\Theta_m = 77° \pm 1°$ for KDP and $\Theta_m = 46 \pm 1°$ for β-BBO, in good agreement with the calculated values.

For the CVL fitted with the plane resonator, the maximum average power at the sum frequency (allowing for losses in *L*2 and *P*) was 11 mW with $f = 200$ mm for *L*1. The corresponding conversion efficiency, based on average power incident on the crystal, was 0.16 percent. By comparison the second harmonic powers at 255.3 and 289.1 nm were 7 and 4 mW, respectively. The performance of β-BBO was marginally inferior to that of KDP under the same conditions. Note that the scattering losses at the β-BBO faces were high, ≥20 percent; reflection losses for both β-BBO and KDP were ~12 percent at the sum frequency angle.

For the unstable ($M = 16$ confocal) resonator, sum frequency power and conversion efficiency increased dramatically due to the increased beam quality of the CVL. Maximum average power adjusting for losses at *L*2 and *P*) at the sum frequency observed for KDP was 100 mW with $f = 500$ mm for *L*1; for β-BBO, 64 mW was obtained with $f = 200$ mm for *L*1. The corresponding conversion efficiencies (based on total incident power) were 1.5 and 0.9 percent, respectively. Best output powers at the second harmonic frequencies of green and yellow were 49 mW using β-BBO at $f = 200$ mm and 56 mW using KDP at $f = 500$ mm corresponding to conversion efficiencies based on incident green and yellow pump power of 1.1 and 2.4 percent, respectively. These latter efficiencies when based on total incident CVL pump power are reduced to ~0.7 and ~0.8 percent, respectively.

In general, sum frequency and second harmonic powers and conversion efficiencies increased with tighter focusing, however, in the case of KDP the use of short focal length lenses ($f \leq 200$ mm) reduced the power. This latter effect we believe is primarily due to the onset of surface and volume damage which was clearly visible after the experiments [6]. However, the shorter effective path length for tighter focusing is also expected to result in declining efficiency for the larger KDP crystal. The observation of higher conversion efficiencies for KDP than β-BBO was unexpected, however the quality of the β-BBO crystal was poor, there being large surface scattering losses.

For all cases the pulse shape of the sum frequency output follows closely that of the 578.2 nm pump. Thus the efficiency of sum frequency generation depends critically on the temporal overlap of the green and yellow pulses. For the CVL of the present experiments the onset of the 578.2 nm pulse is 5 ns delayed from that of the 510.6 nm pulse so that although up to 25 percent of the energy in the green does not contribute to sum generation, overlap occurs in the trailing edge of the pulse where beam quality is at its best.

In summary, we have obtained 100 mW output power at 271.2 nm by sum frequency mixing of the 510.6 and 578.2 nm outputs of a CVL in KDP. Conversion efficiency based on the total optical power incident on the crystal was 1.5 percent, approximately double the best efficiencies achieved for SHG from either the green or yellow. We note that SHG efficiencies (for the CVL with the $M = 16$ unstable cavity), based on the total laser power available (8.5 W) from the device when fitted with a conventional flat–flat resonator, were ~ 0.6 and ~ 0.7 percent for green and yellow, respectively, similar to the efficiency for SHG from the green achieved by Kuroda *et al.* [2]. On the same basis maximum sum generation efficiencies observed in the present experiments was ~ 1.2 percent. For high-quality KDP and β-BBO crystals cut at the sum frequency phase matching angle and using AR coatings on all optical elements we estimate overall conversion efficiencies of at least 2 percent can be achieved for sum frequency generation using a CVL of the present specifications. Higher efficiencies are expected for higher power CVL's with higher magnification unstable resonators.

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