Enhanced Efficiency of UV Second Harmonic and Sum Frequency Generation from Copper Vapor Lasers

DAVID W. COUTTS, MARK D. AINSWORTH, AND JAMES A. PIPER

Abstract—**Enhanced efficiency for nonlinear second harmonic and sum frequency generation in β-BBO from the two copper vapor laser (CVL) outputs (511 and 578 nm) is reported. Over 460 mW UV output at 255 nm (SHG of 511 nm) and 271 nm (SFG), and up to 300 mW at 289 nm (SHG of 578 nm) have been obtained with wall plug efficiencies up to 0.016% for a 16 W CVL with an M = 26.5 off-axis unstable cavity.**

THERE is an increasing demand for ultraviolet laser sources of moderate average power (> 1 W) for industrial applications such as photolithography [1]. Copper vapor lasers with high average power (up to 100 W) at high pulse repetition rates (~ 10 kHz) and relatively high wall plug efficiency (up to 1%) in the green (510.6 nm) and the yellow (578.2 nm) are now widely available commercially. Second harmonic and sum frequency generation (SHG and SFG) of CVL output therefore represents an attractive approach to UV source development. However, doubling efficiencies from CVL outputs have been disappointing due to the difficulties of achieving high focal power densities in the nonlinear medium resulting from the poor beam quality from the CVL.

Use of high magnification unstable optics and injection seeding techniques have recently led to considerable improvements in CVL beam quality, with consequent improvements in the nonlinear conversion efficiency. Kuroda *et al.* [2] have reported over 230 mW at 255.1 nm by SHG in β-BBO from the 510.6 nm output of a 10 W CVL and Naylor *et al.* [3] have reported up to 630 mW at 255.1 nm based on a 100 W injection seeded CVL. In earlier experiments in our own laboratory with a 7 W CVL we have obtained similar SHG efficiencies in BBO and KDP, and reported sum frequency generation (510.6 + 578.2 nm) at 271.2 nm with conversion efficiencies comparable to SHG [4].

Further improvements in SHG and SFG efficiencies require careful attention to the design of the CVL cavity to achieve a higher fraction of the output power within the high quality (low divergence) portion of the beam, and to delivery optics in the nonlinear conversion arrangement. We now report recent experiments in SHG and SFG based on a higher power (16 W) CVL and aimed at optimizing CVL resonator design and focusing geometries. SHG (255 nm) and SFG (271 nm) powers of 460 and 465 mW, respectively, have been achieved at conversion efficiencies from the nonASE component of the CVL beam up to 9.6% and wall plug efficiency ~0.016%.

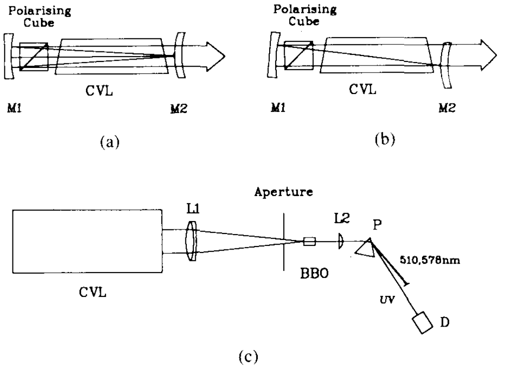

Fig. 1. (a) On-axis unstable resonator. (b) Off-axis unstable resonator. (c) Experimental arrangement for generation and detection of SHG and SFG.

The experimental arrangement is shown in Fig. 1. The CVL is fitted with either an on-axis edge-coupled unstable cavity (positive branch confocal) [Fig. 1(a)] or an off-axis cavity of the same type [Fig. 1(b)] [5]. The resonators are in each case formed by a high reflector curved mirror (R = 4 m), and a spot mirror on a nominally zero power AR-coated meniscus lens with radii of curvature R = 246, 75, or 39 mm, giving magnifications of 16, 26.5, and 51 times, respectively. For all cases, the reflecting films had $R > 99.9\%$ for both 510.6 and 578.2 nm. An intracavity polarizing cube was positioned near the high reflector to give a polarized output (polarization 100:1).

The output of the CVL is focused directly into the nonlinear crystal with lens $L1$ (spherical or preferably achromatic). The crystal outputs are recollimated with a short focal length silica lens $L2$ (f = 50 mm) and the UV component separated with a quartz prism P. Average powers were measured with a thermal power meter (Scientech 360001) and pulse shapes recorded with a vacuum photodiode (Hamamatsu R1193U-02) and displayed on a fast oscilloscope (Tektronix 7904). The nonlinear crystal used

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TABLE I
COMPARISON OF UNSTABLE RESONATORS

Cavity	$M = 16$	$M = 26.5$	$M = 51$	$M = 26.5^a$
Spot Mirror Diameter	2 mm	1 mm	1 mm	2 mm
Total Power	17.5 W	16.0 W	16.5 W	16.0 W
Non-ASE power (P)	8.9 W	8.0 W	6.2 W	8.4 W
Beam Divergence ($\Delta\theta$)	0.94 mrad	0.28 mrad	0.23 mrad	0.16 mrad
Figure of Merit ($P/\Delta\theta^2$)	10	100	120	330
Yellow Fraction	45%	45%	43%	42%

[a] Off-axis cavity.

was β-BBO of dimensions 6 × 8 × 7 mm cut at an angle of 51° corresponding to the phase match angle for SHG of the green, but the large aperture of the crystal enabled angle tuning for both SFG (271 nm) and SHG of the yellow (at 289.1 nm) as well. The crystal was mounted in a precision gymbal mount for accurate orientation.

For present experiments the CVL (plasma tube dimensions 1 m × 25.5 mm diameter) was operated at a pulse repetition frequency of 7 kHz drawing 2.9 kW from the high-voltage power supply. Under these excitation conditions with a plane–plane resonator (HR-4% coupler), the total unpolarized output power was 16.8 W with a green to yellow ratio of ~3:2. The performance of the various confocal edge coupled unstable cavities was evaluated for the CVL operating under these same excitation conditions. CVL beam divergence was measured by focusing the beam with a 600 mm focal length achromatic lens and projecting an enlarged image of the focus on a distant screen. In normal operation the ASE component was removed by spatial filtering, which was also used to analyze beam quality.

Unstable resonator parameters and associated CVL beam characteristics are summarized in Table I. Note the total output power for the unstable cavities is similar to that for the plane–plane cavity, but after removal of the high divergence ASE component, available beam power is reduced by a factor of about two. However, the beam divergence of the non-ASE component also decreases progressively, allowing substantial increases in focal power densities. The performance of the cavities can be compared conveniently by reference to a figure of merit given by non-ASE power divided by the square of the beam divergence. For the on-axis cavities, the $M = 26.5$ and $M = 51$ arrangements have similar figures of merit and indeed give comparable performance in nonlinear conversion. Note that the $M = 26.5$ cavity is optimized for the CVL tube diameter of 25.5 mm, whereas the $M = 16$ and $M = 51$ cavities are optimal for larger tube diameters, 33 and 51 mm, respectively.

The $M = 26$ off-axis unstable cavity gave best performance in terms of available power density, giving 8.4 W average power in a beam with a time averaged divergence of 0.16 mrad ($1/e$ full angle), and a figure of merit more than three times larger than the equivalent on-axis cavity. Approximately 3.8 W (45% of the non-ASE component) was diffraction limited with a beam divergence of ~45 μrad. The off-axis cavity takes advantage of the large delay (~15 ns) observed for the peak gain at the center of the laser tube with respect to that near the walls, a phenomenon which is observed in many high-power CVL's [6], [7]. The off-axis cavity allows a low divergence optical field to build up before the maximum gain occurs in the bulk of the lasing medium giving a larger fraction of diffraction limited output.

TABLE II
AVERAGE UV POWERS (mW) OBTAINED FROM 2.9 kW INPUT TO CVL

Cavity F/mm		$M = 16$	$M = 26.5$	$M = 51$	$M = 26.5^a$
200	255 nm	205	245	c	c
	271 nm	150	140	c	c
	289 nm	95	90	c	c
300	255 nm	185	215	245	c
	271 nm	140	110	115	c
	289 nm	95	80	125	c
500	255 nm	165	190	230	275
	271 nm	125	145	155	170
	289 nm	80	90	95	140
400[b]	255 nm	205	215	185	460
	271 nm	170	165	135	465
	289 nm	80	80	55	230

[a] Off-axis cavity.
[b] AR-coated achromatic lens.
[c] Beyond damage threshold.

Table II shows results for SHG and SFG in BBO where average powers in the UV account for avoidable losses totalling 20% at the surfaces of lens $L2$ and the prism P (neither of which had AR coatings).

Where a spherical lens is used for $L1$, spherical aberration reduces the focal power density below that which is due to beam divergence alone, hence tighter focusing is required for significant UV generation. The maximum powers obtained for SHG of the green and yellow and for SFG were 275 mW (at 255.3 nm), 140 mW (at 289.1 nm), and 170 mW (at 271.2 nm), respectively, obtained with the $M = 26.5$ off-axis unstable cavity and a (spherical) $f = 500$ mm focusing lens.

Chromatic aberrations in the spherical lenses also reduce the efficiency of sum frequency generation by reducing the spatial overlap of the two CVL output wavelengths within the crystal. These problems are overcome by using an achromatic doublet for lens $L1$ where both chromatic and spherical aberrations are corrected. For the $M = 26.5$ off-axis cavity, a dramatic increase in conversion efficiency is observed when the $f = 400$ mm achromatic focusing lens is used. In this case, average powers for SHG of the green and yellow were 460 and 230 mW, respectively, and 465 mW for SFG.

The nonlinear conversion efficiencies can be expressed in three ways as in Table III. Conversion efficiencies based on the relevant spectral components of the non-ASE power are 9.6% for SHG at 255 nm, 6.4% for SHG at 289 nm, and 5.5% for SFG at 271 nm. These figures are the highest reported to date for SHG and SFG of a CVL. Conversion efficiencies can also be calculated based on the total laser power and represent the potential nonlinear UV output achievable from a given CVL. Efficiencies based on total CVL output power for SHG at 255 nm and SFG are both 2.9%, and for SHG 1.4% at 289 nm. Finally, UV generation efficiencies can be calculated based on the power drawn from the CVL high-voltage supply and these can be used to compare CVL based UV generation with other UV sources. The total CVL–UV system efficiencies were 0.016% for SFG and SHG at 255 nm and 0.008% for SHG at 289 nm. These values are typically an order of magnitude greater than wall plug efficiencies for the UV outputs available from high-power argon ion lasers (i.e., directly in the 300 nm region or by frequency-doubling to 257 nm [8]).

A model for SHG of focused partially coherent beams has been proposed by Kuroda *et al.* [2] which predicts a conversion efficiency in BBO of ~3% for the 2.6 W of 0.16 mrad divergence green output, and a conversion efficiency in excess of 12% for the ~2 W of diffraction limited green output. This gives a calculated total SHG conversion efficiency of ~9% for the conditions of our experiment and is close to the measured value of 9.6%.

Multiple shot volume damage thresholds quoted in the literature [9], [10] are ~32 GW/cm^2 for BBO, and ~17 GW/cm^2 for KDP and KD*P, however, surface damage thresholds are typically an order of magnitude lower than these. For the present experiments, peak power densities over 10 GW/cm^2 have been achieved resulting in visible damage to the crystal under conditions indicated in Table II. Optical damage which clearly limits further improvements to UV generation power and efficiency may be avoided in a number of ways however, for example by beam shaping and scanning techniques [9], or employing longer crystals to reduce the surface power densities.

Still higher conversion efficiencies may be achieved by operating the laser at a lower pulse-repetition frequency, where there is an increase in CVL peak power, and the longer pulse duration gives further improvements in output beam quality. In preliminary experiments in which the CVL PRF was reduced from 7 to 4 kHz with the same input power and with the $M = 26.5$ off-axis cavity, rapid damage to the nonlinear crystal resulted for all $L1$ focal lengths up to 1.0 m. Nevertheless we measured a 50% increase in SFG power in KDP and a 33% increase in SHG of the green in BBO, where a 1000 mm focal length lens was used for $L1$. Note that the 9% optical conversion efficiency for SHG at 255 nm reported by Kuroda *et al.* was for a CVL operating at a PRF of 4 kHz, whereas we have achieved an optical conversion efficiency of 9.6% at the greater PRF of 7 kHz. If crystal damage could be avoided, optical conversion efficiencies well in excess of 10% could be achieved by operating the CVL at a lower PRF. Also note that enhancement of the yellow component of the CVL output using a *R*590 dye amplifier-converter [11] is expected to result in significantly enhanced powers at 289.1 nm by SHG. Preliminary experiments using this approach have thus far demonstrated UV powers at 289.1 nm close to 300 mW.

TABLE III
CONVERSION EFFICIENCIES FOR UV PRODUCTION

	Base of efficiency calculation		
UV Wavelength	Non-ASE Laser Power at Relevant Wavelength(s)	Total Laser Power	Electrical Input Power to Laser
255 nm	9.6%	2.9%	0.016%
271 nm	5.5%	2.9%	0.016%
289 nm	6.4%	1.4%	0.008%

In summary, we have generated over 460 mW output power at 255.1 and 271.2 nm with a wall-plug efficiency of 0.016%, and 300 mW at 289.1 nm with a wall-plug efficiency of 0.008%. Using an off-axis unstable resonator matched to the plasma tube geometry and gain characteristics, along with focusing lenses with reduced achromatic and spherical abberation, has allowed the highest efficiencies for nonlinear UV generation from a CVL reported to date. Current UV output powers are limited by crystal damage which may be reduced by modifying the delivery optics.

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James A. Piper, for a biography see p. 1104 of the June 1990 issue of this JOURNAL.