Optimization of Line-Focusing Geometry for Efficient Nonlinear Frequency Conversion from Copper-Vapor Lasers

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Abstract— **Detailed parametric investigations of line foci for efficient nonlinear frequency conversion of copper-vapor lasers are presented. For a single medium-scale copper-vapor laser (nominally 20 W), the optimum focal geometry for efficient second-harmonic and sum-frequency generation in BBO is to focus a 3.75-mm-diameter beam into the crystal with an f = 60 mm cylindrical lens. Using such a focal geometry, UV powers of up to 1.75 W (SHG of the green), 1.2 W (SHG yellow), and 1.5 W (SFG) have been produced with peak instantaneous conversion efficiency of up to 48%. Conversion efficiencies are most sensitive to the F-number of the cylindrical focusing, with the optimum F-number being approximately 16, and are relatively insensitive to the width of the focused beam.**

I. Introduction

NONLINEAR frequency conversion is becoming an increasingly important technique for the generation of new wavelengths from copper-vapor lasers (CVL's) [1]–[7]. Of particular interest is the production of high average power UV (>1 W average at 255.3, 289.1, and 271.2 nm) by second-harmonic and sum frequency generation from the green (510.6 nm) and yellow (578.2 nm) CVL outputs [5]–[8]. This work has in part been stimulated by the need for UV sources suitable for micromachining and microlithographic applications, for which the frequency-doubled CVL with its high PRF and excellent beam quality represents a very attractive candidate [9].

Recently, it has been reported that use of a line focus offers significant advantages over spherical focusing for efficient high power second harmonic generation from CVL's when using β-barium borate (BBO) as the nonlinear material [5]. A line focus has the advantages of ensuring that all the CVL beam propagates within BBOs' narrow acceptance angle while maintaining high focal power densities required for the nonlinear interaction. Further advantages include improved thermal management for high average power generation [10] and reduced effects of beam walk-off. The introduction of line focusing has enabled practical UV power scaling beyond the 0.5 W range typically obtained with spherical focusing [4], [11] up to powers of 1.3 W from a single medium-scale (~20 W) CVL [5], 3.6 W from two medium-scale (20 W) CVL's in oscillator-amplifier configuration [6], and more recently 9 W from a very-large-scale (>250 W) CVL oscillator amplifier system [7].

In this paper detailed parametric investigations of line focusing for nonlinear frequency conversion from CVL's are reported. These investigations include variation of CVL peak and average powers, and optimization of line focus parameters including the beam width and cylindrical focusing F-number. An improved focusing geometry from that previously reported [5] has been used to generate UV powers of up to 1.75 W at a peak optical conversion efficiency of 48% from a single, nominally 20 W, CVL. These results represent the highest single-CVL oscillator SH power yet reported and the highest conversion efficiency reported to date for any CVL nonlinear frequency conversion process.

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II. Experimental

The nominally 20-W copper-vapor laser used in the experiments had an active region 25 mm diameter by 1.0 m long and was operated at a pulse repetition frequency of 4 kHz. An M = 100 on-axis unstable resonator consisting of an R = 4 m high-reflector and a $R = -40$ mm × 2 mm diameter spot-reflector was used to provide high beam quality output from the CVL. A 2-in polarizing beamsplitter cube was placed near the high reflector to ensure linearly polarized output. Under these conditions the CVL typically gave non-ASE green and yellow outputs of 5.1 and 3.2 W, respectively. Both of these CVL outputs could be further divided into the "four-pass" temporal component, which corresponds to spontaneous emission having made at most four-passes through the gain medium (up to two round-trips) and that had a divergence of ~100 μrad (~5 times the diffraction limit or transverse coherence radius of 3 mm), followed by the "six-pass" component, which had diffraction-limited divergence (or full transverse coherence) [12]. In order to ensure wavefront integrity of the low divergence CVL output, precautions were taken to minimize CVL window heating effects, including enclosing all optical beam paths to minimize schlieren effects, and insertion of optical scatterers in the laser end pieces [13].

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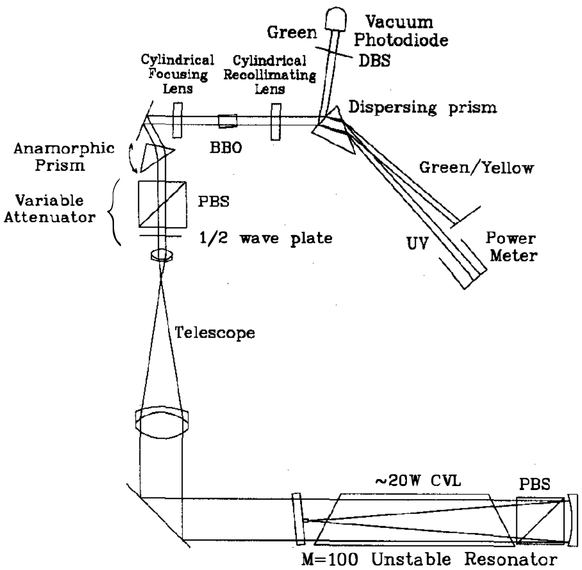

Fig. 1. Experimental layout for second-harmonic and sum-frequency generation of the CVL.

Fig. 1 shows the optical layout for SHG and SFG from the CVL. The CVL output was first compressed with an achromatic-lens telescope to a beam diameter of 3.75 mm, and then focused into the BBO crystal with a plano-convex cylindrical lens. A 0.5-mm pinhole was placed at the focal point within the telescope to remove the ASE from the CVL output. The BBO crystal was 6 mm wide by 8 mm long and cut at 46.2° corresponding to the type I phase match angle for sum frequency generation and had sufficient aperture to enable angle tuning for SHG of the green or yellow. A quartz prism was used to separate the UV from the CVL fundamental outputs after recollimation with a second cylindrical lens. In order to measure the variation of SHG/SFG conversion efficiency with pump power, a variable attenuator (consisting of a half-wave plate and a polarizing beamsplitter) was inserted in the pump beam before the cylindrical focusing lens. Experiments characterizing the effects of varying the width of the line focus were performed by inserting a 45° BK7 anamorphic compression prism after the attenuator. Rotating the prism varied the width of the line focus from 1–5.8 mm, while the changing Fresnel reflection losses were compensated for using the variable attenuator.

UV and fundamental powers were recorded using thermal power meters (Scientech 360001 and 360201). The reflection off the first face of the quartz prism was used to monitor the fundamental pulse shape using a fast vacuum photodiode (Hammamatsu R1193U-02) and dichroic beam splitters to select the desired fundamental wavelength. Pulse shapes were observed with both a fast analog oscilloscope (Tektronix 2446B 200 MHz) and a digital oscilloscope (Tektronix TDS320 100 MHz), the latter providing multi-pulse averaging and storage facility.

Internal conversion efficiencies (i.e., within the nonlinear medium) were determined by comparing the CVL fundamental pulse transmitted through the BBO crystal when oriented away from phase matching (corresponding to the undepleted fundamental) to that when phasematching occurs (corresponding to the depleted fundamental). This provided a very convenient method for monitoring conversion efficiencies using a single fast photodiode allowing more rapid optimization of the optical alignment.

III. Results

Fig. 2 shows fundamental, depleted fundamental and UV pulse shapes corresponding to SHG of the green (a), SHG of the yellow (b) and SFG (c). Instantaneous conversion efficiencies based on the fractional depletion of the fundamental pulse shapes are also included. These results were recorded for a line focus of 3.75-mm-width (SH green and SFG) or 1.9 mm (SH yellow) and a cylindrical-focusing F-number of 16, and correspond to focal parameters for maximum observed conversion efficiencies as will be discussed below.

The two principal temporal components (the four-pass and six-pass outputs) of the green and yellow pulses can readily be resolved as two peaks in the pulse shapes, and are indicated as such in Fig. 2. Peak instantaneous conversion efficiencies were typically higher for the 6-pass output than for the 4-pass output at both wavelengths, reflecting the higher beam quality of the 6-pass outputs even though the 4-pass outputs have the higher peak power. For the CVL six-pass outputs, both SHG of the green and SHG of the yellow yielded peak instantaneous conversion efficiencies of over 47%.

For sum-frequency generation peak instantaneous depletions of the green and yellow outputs were 25 and 30%, respectively. Green and yellow CVL outputs were converted to the sum-frequency with different and fluctuating instantaneous conversion efficiencies. This results from mixing two outputs with different pulse shapes and intensities, under the constraint that equal quanta of green and yellow photons must contribute to the sum-frequency output. The one-to-one conversion ratio was confirmed by comparing the measured UV pulse-shape with those derived from green and yellow pump depletion. Sum-frequency pulse shapes calculated in such a way correspond accurately with the measured UV pulse shapes.

In practice conversion efficiencies based on measured UV power generation are lower than those calculated from pump power depletion due to losses from reflections off the uncoated BBO crystal faces (12% total) and UV absorption within the nonlinear medium (measured at ~5% for an 8-mm-long BBO crystal). For example, for SHG of the green the average conversion efficiency based on depleted and undepleted pump pulse shapes was ~38%. However, the maximum *measured* UV power (corrected for measured 10% loss at the dispersing prism) was 1.75 W from a fundamental power of 5.1 W corresponding to an average *practical* conversion efficiency of 34% (and wall-plug efficiency of 0.06%).

Maximum sum frequency output was 1.5 W with an average optical conversion efficiency (based on CVL green + yellow non-ASE powers) of 19% and wall-plug efficiency of 0.05%. For SHG of the yellow, maximum UV power was obtained by using a green-to-yellow dye amplifier converter [14] that makes use of the otherwise unused green output. From 4.23 W

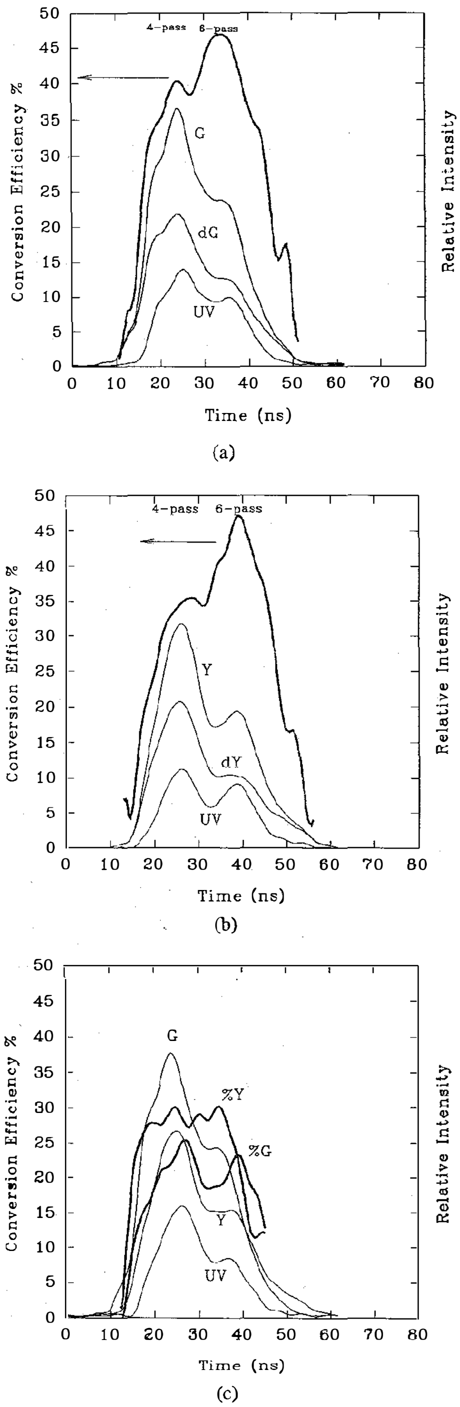

Fig. 2. Pulse shapes of the fundamental (G, Y), depleted fundamental (dG, dY) and UV outputs, and the instantaneous conversion efficiencies calculated from pump depletion for: (a) SHG of the green, (b) SHG of the yellow, and (c) SFG (where depleted pump pulses are not shown for clarity). The four-pass and six-pass components of the pump pulses are also indicated.

of amplified yellow, 1.22 W at 289.1 nm was generated with a corresponding total average optical conversion efficiency (green + yellow to UV) of 17% (0.04% wall-plug), and peak conversion efficiency based on yellow depletion of 48%. These results represent both the highest conversion efficiencies for CVL conversion into the UV, and the highest UV powers obtained from frequency conversion from a single CVL oscillator reported to date.

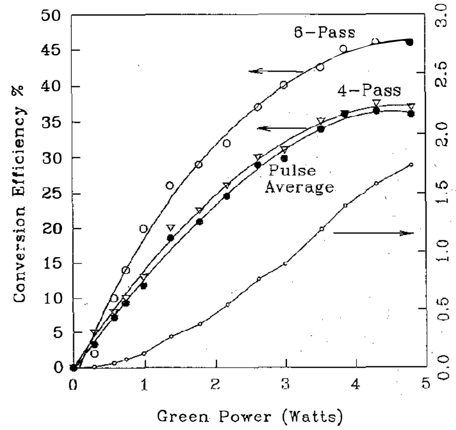

Fig. 3. SHG conversion efficiencies (based on pump depletion) for the peak of the four-pass component, the peak of the six-pass component, and integrated pulse-average (energy conversion) as a function of green pump power. UV powers calculated from pump depletion are also included.

The variation of green second harmonic conversion efficiency (based on pump power depletion) with pump power was measured by variable attenuation of the pump, where an $f = 60$ mm cylindrical lens was used to focus a 3.75-mm-diameter beam into the BBO crystal. The observed variation of peak instantaneous conversion efficiencies of the four-pass and six-pass outputs, and the integrated pulse average conversion efficiency with pump power are shown in Fig. 3. UV powers generated within the crystal were calculated based on the green depletion and are also given in Fig. 3 (note that all other UV powers quoted in this paper are based on measured UV powers corrected only for the measured 10% losses at the dispersion prism). Due to the significant pump depletion, the UV conversion efficiency rapidly deviates from the initial linear dependence on pump power (~20%/W six-pass and ~13%/W four-pass and average), to saturate at conversion efficiencies of 45% for the six-pass and ~37% for the four-pass and pulse average. Note however the focal parameters were optimized in this case for a pump power of 4.8 W and may not be optimal for efficient conversion at lower pump powers.

The variation of instantaneous conversion efficiency can also be plotted as a function of instantaneous pump power as shown in Fig. 4. In Fig. 4 the plotted points correspond to the data points of Fig. 3, where each point was taken from pulse shapes recorded for different pump powers. The curves plotted in Fig. 4 correspond to the instantaneous conversion efficiencies as a function of instantaneous green intensity throughout the pump pulse. These two independent measurements of the peak power dependence of conversion efficiency exhibit very similar functional form, highlighting the instantaneous nature of SHG. Note however, that these pulse shapes represent an average of 16 pulses recorded with a limited-bandwidth (100 MHz) oscilloscope, which may lead to some inaccuracy in calculated conversion efficiencies on their leading and trailing edges. The temporal evolution of CVL beam quality and

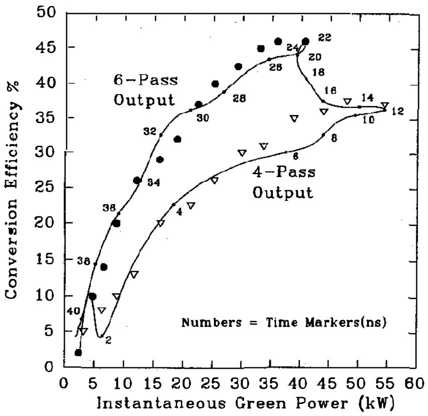

Fig. 4. Instantaneous green SHG conversion efficiency as a function of instantaneous pump intensity derived from the pump and depleted pump pulse shapes. Times (in ns) during the pump pulse are indicated by small numbers along the curve. Points derived from peak conversions of the four-pass and six-pass outputs given in Fig. 3 are also plotted for comparison.

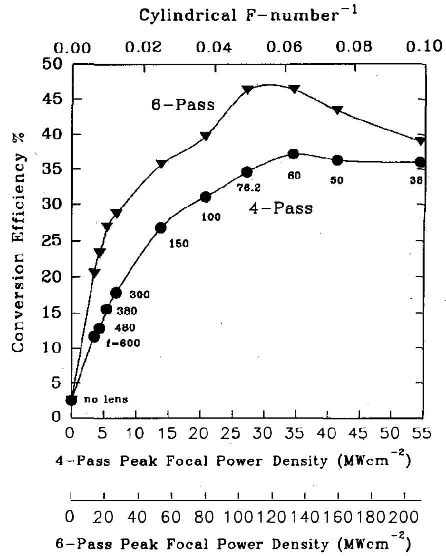

Fig. 5. Variation in peak conversion efficiencies (four-pass and six-pass, based on green depletion), with the focal length of the cylindrical lens. Conversion efficiency is plotted as a function of $1/F$-number, and also the resulting peak focal power densities for the four-pass and six-pass outputs. The actual focal lengths of the cylindrical lenses used are also indicated. Note the beam width was 3.75 mm.

its impact on conversion efficiency is revealed in Fig. 4. For the duration of the four-pass output the conversion efficiency shows a consistent functional dependency on instantaneous peak power, even retracing its path as the four-pass peak power falls (t = 10–14 ns in Fig. 4) prior to the rapid switch to the formation of six-pass output. The six-pass output subsequently follows the second (higher) efficiency curve pertaining to conversion of near diffraction-limited CVL output. The beam quality of the UV (measured by analyzing the UV far-field intensity distribution) also reflects that of the pump, with the six-pass output producing near-diffraction-limited UV output, and the four-pass output having divergence about five times the diffraction-limit.

One of the most important focal parameters for SHG using a line focus in BBO was found to be the focal length of the cylindrical focusing lens (or more accurately the F-number of the cylindrical focusing arrangement). Fig. 5 shows the variation in four-pass and six-pass instantaneous conversion efficiency (based on green depletion) for SHG of the green as a function of $1/F$-number of the pump in the focusing plane. For these measurements the CVL beam was telescoped down to a diameter of 3.75 mm prior to focusing into the BBO crystal with a variety of plano convex cylindrical lenses. For an 8-mm-long crystal, conversion efficiencies of up to 2.5% were observed for a collimated pump beam (i.e., without cylindrical focusing lens, peak power density = 0.5 MW/cm^{-2}). By focusing into the crystal with successively shorter focal length cylindrical lenses, the increased peak focal power densities result in higher conversion efficiencies, up to a maximum of 47% for the 60-mm cylindrical lens (F-number = 16). For shorter focal length lenses the conversion efficiencies were reduced, principally because the pump beam no longer propagates within the vertical acceptance angle of the BBO crystal. This was verified by observing that, for $f < 60$ mm, the UV beam profile no longer matched the pump profile, but was truncated at the vertical extremities.

The second independent focal parameter is the width of the line focus (i.e., the width of the collimated beam prior to cylindrical focusing to a horizontal line). Results showing the variation of instantaneous conversion efficiency for SHG of the green as a function of the width of the line focus at two different pump power levels (3.1 and 1.0 W) are plotted in Fig. 6. Focal line widths were varied from ~1–5.8 mm for a green pump power held constant at 1.0 W (using the variable attenuator to compensate for varying reflection losses at the anamorphic prism faces), whereas a pump power of 3.1 W could only be maintained (through compensation of prism losses) for a variation of focal line width from ~2–5.7 mm. For a pump power of 1.0 W the respective conversion efficiencies of the four-pass and six-pass outputs varied from ~14 and 17% for the 5.8-mm line focus (where the focal power density is a minimum) up to 19 and 27% for the narrower 1-mm-wide line focus (where the focal power density is a maximum). The conversion efficiencies of the four-pass and six-pass outputs at the higher average pump power of 3.1 W displayed significantly less variation with line focus width. The conversion efficiency of the four-pass output hovered at about 31.5% with a ±1.0% variation, and displayed no clear trend as a function of focal line width. There was however, a clear maximum (40% peak) in the six-pass conversion for a line width of 3.5 mm, falling to ~33% at the extreme of the range of focal line widths investigated.

IV. Discussion

There are two principal independent focal parameters that may be varied to maximize the conversion efficiency: the width of the beam/line-focus; and the cylindrical focusing F-number. However many factors relating to the CVL output, the optical properties of BBO and other optical limitations, which may produce conflicting constraints on the optimum F-number and

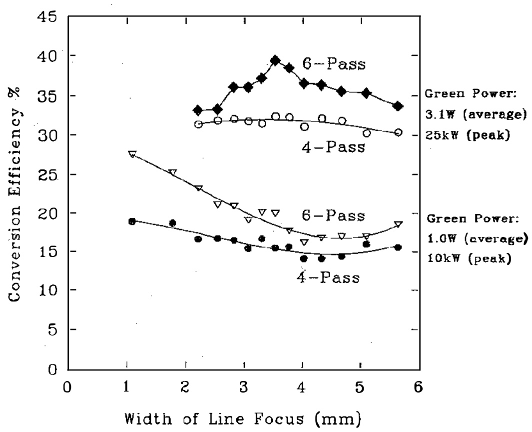

Fig. 6. Variation in peak conversion efficiencies (four-pass and six-pass, based on green depletion), with the width of the focused beam and for two different pump power levels (3.1 W average, and 1.0 W average).

TABLE I
OPTIMIZATION OF LINE FOCUS PARAMETERS FOR SHG OF CVLS IN BBO

Factor	Beam width in crystal	Cylindrical F-number
CVL peak power	min	min
CVL average power (thermal detuning)	max	—
CVL transverse coherence	max	—
UV walk-off-(beam overlap)	max	—
Horizontal acceptance angle	max	—
Vertical acceptance angle	—	max
Aberrations in focusing geometry	min	max
Interaction length	—	max

beam width. These factors with their principal requirements on the focal geometry are listed in Table I.

The beam width must be small enough to ensure the necessary peak focal power densities are achieved within the crystal to ensure efficient nonlinear conversion. However, the high average power of the CVL and UV output can result in significant thermal gradients within the nonlinear crystal (principally through the slight UV absorption of BBO). These thermal gradients lead to thermal detuning, which results in a reduction in conversion efficiency and UV power stability, and suggest that the beam width should be maximized. The deleterious effects of UV beam walk-off (the UV propagates as an extraordinary wave for type I phase-matching in BBO) also suggest the use of wider pump beams. Beam walk-off not only reduces the nonlinear interaction at the edges of the beam, but also for the partially coherent output causes increased dephasing where power may flow from the UV back to the pump. That is, for a partially coherent pump the UV generated initially from one region along the width of the line focus walks off into a neighboring region of the pump where the phase relationship between the pump and UV is now uncorrelated. Note that this is equivalent to ensuring that the beam is sufficiently wide that the divergence in the angle tuning plane is less than the crystal acceptance angle, were the acceptance angle varies in inverse proportion to the walk-off angle. For example, when compressed to a width of ~5 mm the four-pass output has a divergence just within the full crystal acceptance angle (for 8-mm interaction length).

In practice, the above mentioned trade-offs relating to optimum beam width result in a conversion efficiency that is only weakly dependent on beam width over the range of practical interest (as determined by typical crystal size and ensuring peak power densities are well below the damage threshold). The optimum beam width observed experimentally for the six-pass output at 3.1 W average input power may be an artifact arising from wavefront distortions induced by the anamorphic beam compression/expansion prism, where such aberrations were the smallest for the optimum beam width (3.5 mm), which corresponded to the angle minimum deviation for the prism.

The second main focal parameter is the F-number in the focusing (non-critical) plane. Lower F-numbers result in the generation of higher peak focal power densities, however this is at the expense of reduced interaction lengths (the Rayleigh range is typically less than the crystal length). For sufficiently low F-numbers the pump may propagate outside the crystal acceptance angle. This arises because a critically phase-matched nonlinear interaction in a uniaxial material such as BBO occurs for a specific angle Θ, which is defined in polar rather than rectangular coordinates [15], resulting in an apparent 'vertical' acceptance angle when considering propagation in rectangular coordinates. For phase-matching angles near $\Theta = 45°$ the full vertical acceptance angle $\Delta\Theta_v$ is related to the full horizontal (critical tuning plane) acceptance angle $\Delta\Theta_h$ by

$$\Delta\Theta_v = 2\sqrt{\Delta\Theta_h \sin(2\Theta)}$$

which gives a vertical acceptance angle of 56 mrad for an interaction length of 8 mm, corresponding to focusing with an F-number of 18.

In practice the interaction length is less than the crystal length and the optimum F-number was found to be ~16. This corresponded to a value for which all the pump beam propagated just within the "vertical" acceptance angle, thereby producing the maximum possible peak focal power within the constraints of critical phase matching. Note that in the experiments the peak focal power density (up to 250 MW/cm^2) was always well below the crystal damage threshold (~30GW/cm^2 [16]) and that for pump power levels of the order of several W, crystal damage is not a limiting factor. However, note that CVL beam quality needs to be well controlled in order that wavefront distortions in the pump beam do not result in the line focus collapsing briefly to a single point where the crystal damage threshold will be exceeded. The extreme phase sensitivity of SHG means that *any* wavefront distortions in the pump beam (which may result from aberrations in optical components such as the cylindrical lenses) will also result in reduced conversion efficiency, as is demonstrated by the lower conversion of the partially coherent four-pass output.

A parameter related to the cylindrical F-number is the crystal length. For optimum focusing the pump beam Rayleigh range is ~0.33 mm, which is significantly less than typical BBO crystal lengths (6–8 mm). Therefore it is unlikely that crystal length is a significant factor in determining overall conversion efficiency, however longer crystals serve to reduce the peak power densities at the crystal faces thus preventing surface damage to the crystal.

For CVL's where the peak power is the major factor limiting conversion efficiencies, (peak power < 25 kW) a line focus remains the preferred focal geometry. Using *spherical* focusing, peak instantaneous SHG conversion efficiencies (for near-diffraction-limited CVL green output) reported by Omatsu *et al.* [17] were 15% for 10 kW peak pump power, and Pini *et al.* [18] reported 32% peak for 22 kW peak pump power. Based on results of Fig. 5, for a 3.75-mm-wide *line* focus conversion efficiencies as high as 20 and 36% can be obtained for the peak pump powers of 10 and 22 kW, respectively. Yet higher conversion efficiencies may be obtained by employing narrower line foci, as was demonstrated in the 1.0-W average pump power results presented in Fig. 6, where peak instantaneous SHG conversion efficiencies greater than 25% were observed for peak pump powers of just 10 kW representing a 66% increase in UV output over spherical focusing.

The results presented in this paper suggest that power scaling of UV output (for example by using CVL oscillator amplifier systems that produce tens of watts of near diffraction-limited visible output), is best preformed using a line focus with F-number close to the optimum used in the present work (16). At high CVL pump powers (20–100 W average) thermal management within the BBO becomes a significant factor. Variation in pump intensity along the line focus results in non-uniform crystal heating and hence some regions of the crystal are detuned from optimum phase-matching reducing the average conversion efficiency. For example, we reported 20% average SHG conversion efficiency for a pump power of 18 W (3.6 W UV) from a CVL oscillator amplifier system based on two nominally 20 W CVL's, where these results were severely limited by thermal variations arising from fluctuations in pump intensity along the line focus [17]. Molander [7] has frequency doubled 113 W of CVL green to yield 9.0 W UV (8% average conversion) using weak focusing to produce a line focus between two BBO crystals arranged in alternating-Z configuration to minimize walk-off effects. These results were again limited by thermal effects in the crystal (and Fresnel losses from the extra crystal faces), even though in both cases [7], [17] the pump beam filled the whole crystal width (~6 mm). Scaling of UV power is therefore dependant on the ability to maintain a uniform pump intensity across the width of the line focus, which places stringent requirements on CVL beam quality and aberrations in the beam delivery optics. Provided uniform pump intensity can be maintained along the length of the line focus, thermal detuning effects within the BBO crystal at very high pump power levels are best offset by using wider crystals (budget permitting), and ensuring that the pump beam fills the whole crystal width. Recent developments in the fabrication of BBO have resulted in the production of larger crystals having lower UV absorption offering the potential for efficient UV generation at high average powers. Slab crystal geometries employing close-contact cooling on the large area faces would also improve thermal stability. Such arrangements should enable high conversion efficiencies (>30% average) to be maintained for UV powers scaled up to 10 W average. Note that generation of 10 W UV at 30% efficiency corresponds to an average pump power of ~35 W which, owing to the longer pulse duration of CVL MOPA output and with the use of wide (~10 mm) crystals, does not result in significantly greater peak focal power densities within the crystal than employed in the present study.

V. Conclusions

Second-harmonic and sum-frequency generation from a copper-vapor laser using a line focus in BBO has been investigated. For a beam width of 3.75 mm focused with a cylindrical lens ($f = 60$ mm) UV powers of up to 1.75 W have been generated from 5.1 W output from a single medium-scale (nominally 20 W) CVL. This corresponds to an average practical conversion efficiency of 34%. Peak instantaneous conversion efficiencies (based on pump pulse depletion) of up to 48% have been observed for the diffraction-limited six-pass CVL output, and up to 40% for the non-diffraction-limited four-pass output. It was found that the conversion efficiency is not strongly dependent on the beam width, but is very sensitive to focusing F-number, with an optimum F-number of 16. Line focusing has been demonstrated to be preferable to spherical focusing for efficient SHG in BBO of any high-beam-quality CVL system producing peak powers in excess of 10 kW.

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David W. Coutts (M'94), for a photograph and biography, see p. 342 of the February issue of this TRANSACTIONS.