High-Power, High-Brightness Master-Oscillator Power-Amplifier Copper Laser System Based on Kinetically Enhanced Active Elements

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***Abstract*—We report the performance characteristics of a copper laser master-oscillator power-amplifier system incorporating kinetically enhanced active elements. The advantages provided by kinetic enhancement lead to record brightness levels.**

***Index Terms*—Beam quality, copper laser, high brightness, kinetic enhancement.**

I. Introduction

SINCE the first reported operation of a copper vapor laser (CVL) by Walter *et al.* [1] in 1966, there have been extensive studies of the physics of these complex systems and significant development of CVL technology, driven substantially by the needs for high average power, high pulse rate, and high beam quality (HBQ) for applications as diverse as atomic vapor laser isotope separation, high-speed photography and laser micromachining. Recently, a new variant of the elemental CVL, called a kinetically enhanced CVL (KE-CVL), has been developed which has greatly improved power-scaling characteristics compared with conventional CVLs. In the KE-CVL the otherwise conventional copper vapor/neon gas mixture is modified by the addition of low concentrations of HC1 and H_2 gases (typically 0.2%–0.5% and 1%–2%, respectively) [2], [3]. These additives substantially increase the plasma relaxation rate between successive discharge pulses, resulting in substantially decreased pre-pulse electron densities and much improved spatio-temporal gain characteristics. As a result, the output power of a 38-mm diameter conventional (hydrogen-neon buffer gas) CVL increases from its maximum of 60 W at 6 kHz to 100 W for kinetically enhanced operation at the same pulse rate. Furthermore, KE-CVLs continue to operate efficiently at elevated pulse rates. For example, the same 38-mm diameter KE-CVL produced 135 W at a pulse rate of 12 kHz, and a maximum output power of 152 W at 22 kHz, the highest power ever reported for any CVL oscillator of this size [4]. Most recently, Marshall [5] has reported pulse-rate scaling of a 25-mm diameter KE-CVL up to 100 kHz.

While the overall power capabilities of KE-CVLs are typically a factor of two higher than those of conventional CVLs of the same size, the HBQ output powers extracted from KE-CVL oscillators are enhanced by even larger factors, typically 4 in the lower pulse rate range up to 10 kHz, and 5–10 at pulse rates above 10 kHz [6]. Withford and Brown [7] reported a 38-mm diameter KE-CVL producing HBQ output powers $>$50 W for pulse rates ranging from 6 to 20 kHz; for comparison, the same tube operating as a conventional CVL produced only a maximum of 14 W at a pulse rate of 5 kHz. This improved HBQ performance of KE-CVL oscillators results from the combination of number of factors, as discussed in detail in [7]. These factors include the axially peaked profile of the spontaneous emission seed, the higher extractable power available from these systems, and the modified temporal output characteristics of KE-CVLs. Note that CVL beam quality evolves in a stepwise fashion [8], [9] from highly divergent ASE that has undergone fewer than two roundtrips in the resonator cavity, to low divergent output corresponding to radiation having undergone two roundtrips, and finally, near-diffraction limited output undergoing three or more roundtrips. In the case of KE-CVLs, the increased gain duration and shift of peak gain to later times leads to higher power extraction from the low beam divergence components of the output laser pulse, i.e., those which have undergone two or more roundtrips in the resonator.

While KE-CVL oscillators represent attractive HBQ CVL sources (which are superior in power and beam quality to conventional CVLs), there are fundamental limitations to further power scaling using single gain elements. In particular, aperture and length scaling of the active volume must be accompanied by an increase in the unstable resonator magnification to ensure that the development of HBQ output evolves in a similar fashion. However, increasing the resonator magnification decreases the effective cavity feedback, which ultimately reduces laser output power (and increases sensitivity to perturbation by spurious reflections from external optical elements). A more promising approach to generating increased HBQ power levels is to use KE-CVL active elements in a master-oscillator power-amplifier (MOPA) configuration. In this paper, we present the results of our investigations of a 200-W HBQ MOPA based on kinetically enhanced active elements.

II. Experimental Details

A. MOPA System

A schematic diagram of the KE-CVL MOPA system is shown in Fig. 1. The master oscillator (MO) was a 25-mm by 1-m active volume CVL employing a two-stage magnetic pulse compression excitation circuit (125-ns voltage rise time at the laser) and was kinetically enhanced using a heated in-line metal chloride ($ZrCl_4$) oven to generate concentrations of HCl

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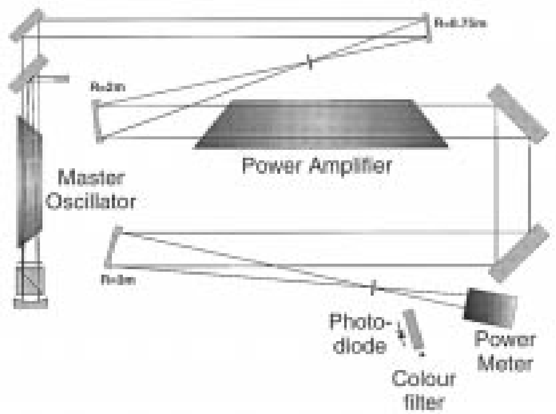


Fig. 1. Layout of the KE-CVL MOPA system.

estimated to be ~0.2% in a 2% H_2/Ne buffer gas mixture. The MO utilized an $M = -80$ unstable resonator, formed by an R =4-m high reflector at one end, with a 1-mm scraper mirror directing the centre of the beam onto an R =50-mm auxiliary reflector at the output end. The output of the MO was propagated through an expanding reflective mirror telescope before injection into the power amplifier (PA). For our first series of experiments (at a PRF of 6 kHz), the telescope was 2× expanding (R =75 cm/R =150 cm). With this expansion factor, the expanded MO beam "overfilled" the amplifier aperture everywhere, except at the top of the PA tube where the (inverted) shadow of the molten copper in the MO sometimes left an un-injected volume. For all subsequent experiments at higher pulse rates, the telescope was reconfigured to be 2.7× expanding (R =75 cm/R =200 cm) to totally eliminate problems with the MOs copper shadow. A small (~1 mm) water-cooled aperture at the common focus removing amplified spontaneous emission (ASE) from the output beam.

The PA CVL was essentially the same as that described previously [4], [7] although with a slightly smaller plasma tube. The PA was a 36-mm diameter (i.e., slightly smaller than that of [4]) by 1.5-m active volume CVL utilising a three-stage magnetic pulse compression exciter producing 50-ns voltage rise-time at the laser, and was kinetically enhanced using an in-line metal chloride oven. For operation at 6-kHz pulse repetition frequency (PRF), the storage capacitance was set at 8 nF, while for operation at higher PRFs, the storage capacitance was reduced to 4 nF. The relative timing of the MO and PA was controlled using a digital delay generator.[1]

Both the MO and PA CVLs were fitted with magnesium fluoride windows to ensure the highest possible beam quality. It has previously been shown [10] that MgF_2 is the best material to avoid thermal problems (such as lensing, and turbulent air currents near the windows) arising from the substantial quantity of infrared blackbody radiation generated by the hot plasma tube. The windows used were 1-cm thick in order to avoid aberrations (principally astigmatism) induced by flexure under vacuum, which we have previously observed for thinner (5 mm) MgF_2 windows.

[1]Stanford Research Systems DG535.

During the course of our characterization, we operated the PA both as a conventional CVL and KE-CVL to allow direct comparison of amplification characteristics under both modes of operation. In these cases, the MO was still operated in kinetically enhanced mode. In this case, by conventional operation we mean operation with pure Ne buffer gas (i.e., no added H_2).

B. Power and Beam Quality Characterization

The performance characteristics of the MOPA were measured using the arrangement shown in Fig. 1. The MOPA output was focused using a 3-m radius-of-curvature mirror through a small (~1 mm) water-cooled aperture that eliminated any ASE from the beam, and the transmitted (HBQ) power and optical pulse shapes were monitored. The power was measured using an Ophir FL-250A power meter, while pulse shapes were monitored using fast p-i-n photodiodes (ThorLabs DET2-SI) coupled to a digital oscilloscope (Tektronix TDS350, 200-MHz analog bandwidth). Gain-saturation characteristics of the amplifier were measured by progressively attenuating the MO beam using neutral-density filters through six orders of magnitude, and monitoring the HBQ (amplified) power extracted from the amplifier. To assess the efficiency of power extraction from the amplifier, we also measured the output power of the PA operated as an oscillator (i.e., fitted with a standard plane-plane resonator, 4% reflectivity output coupler). When the PA was operated in this mode, the output power was measured near the output coupler (i.e., without the intervening focusing optics that spatially filter the ASE component).

The thermal characteristics of the PA enabled it to be operated without overheating up to input power levels of 12 kW (measured at the power supply) at both 6 and 12 kHz (with different capacitor sets) and for both modes of operation (i.e., conventional and kinetically enhanced). For kinetically enhanced operation, the PA could be operated at even higher power loading (as when the pulse rate was elevated beyond 12 kHz). For instance, the PA appeared thermally stable up to 15 kW (at 15 kHz) and only overheated very slowly at 16 kHz. In fact, the performance of the PA was relatively insensitive to input power when kinetically enhanced, reaching ~85% of maximum power for input power of only 9 kW. For measurements of saturation and power extraction at pulse rates of 6 and 12 kHz, the PA was therefore operated at the 9-kW condition to avoid stressing the power supply over long periods.

The MOPA output beam quality was assessed by examining the far-field profile, using the same method as detailed in [7]. After separating the green output from the yellow using a dichroic mirror, a low-power sample of the green output was taken by reflection from the uncoated surface of a Fresnel beam sampler (Newport NC.1). An f = 1-m achromatic lens brought the beam to focus, and a magnified image of the focal plane (i.e., far field) was produced at a CCD camera (Cohu 4800) by using an f =50-mm lens (Pentax camera lens SMC 50-mm $f/1.7$, image distance =2.44 m). A Spiricon LBC-500PC (12-bit) beam analyzer was coupled to the CCD camera to allow storage and analysis of the far-field profiles. The output wavefront was also examined using a radial-shear interferometer, with the resulting interference patterns stored for later analysis using the Spiricon beam analyzer.

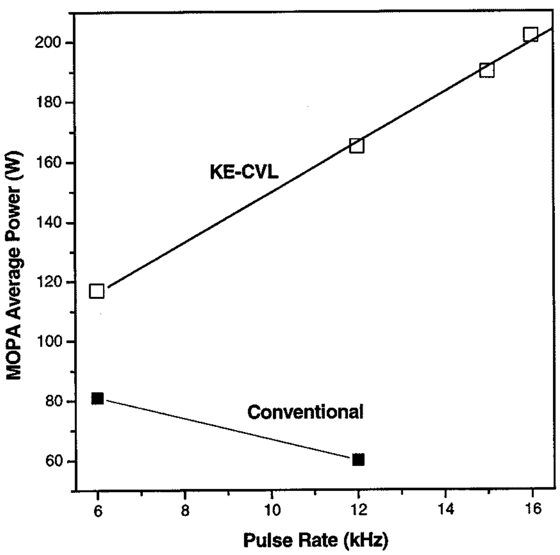


Fig. 2. Maximum MOPA output power as a function of pulse repetition frequency for the PA operated in kinetically enhanced and conventional modes.

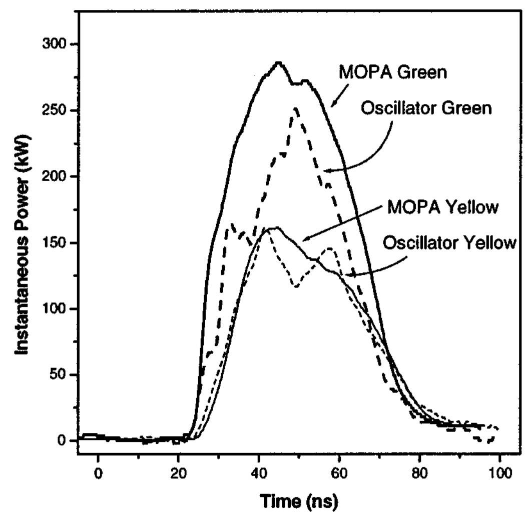
III. Results

A. Pulse Rate Scaling of MOPA Output

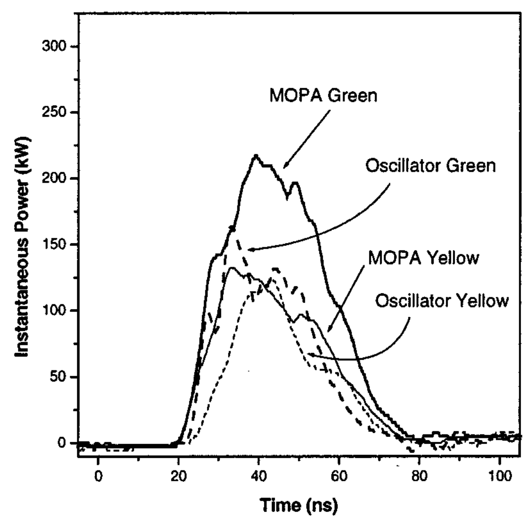
KE-CVL MOPA power and beam quality performance was extensively characterized at PRFs of 6 and 12 kHz, and the power performance was also briefly investigated at higher PRFs (up to 16 kHz). Fig. 2 shows the maximum output power generated by the KE-CVL MOPA system as a function of pulse rate. The output power generated by the same system, but with the PA operating in the conventional mode (i.e., not kinetically enhanced), is also shown for PRFs of 6 and 12 kHz.

At a PRF of 6 kHz the MO produced 13 W of high-beam-quality (HBQ) output power (8.5-W green, 4.5-W yellow), of which 50% was coupled into the PA due to the over-expansion of the MO beam. The MOPA system produced 81 W (53-W green, 28-W yellow) of HBQ power when the PA was operated with conventional buffer gas composition. With the PA operated under kinetically enhanced conditions, the MOPA output increased by almost 50% to a peak of 117 W (73.5-W green, 43.5-W yellow). In either mode of operation, the power supplied to the amplifier was ∼12 kW. When the PRF was elevated to 12 kHz (with appropriately modified capacitor sets), the MO output increased to 22 W of HBQ power (13-W green, 9-W yellow). Even with the higher injected signal level at 12 kHz, the MOPA HBQ output fell to ∼60 W (37.5-W green, 22.5-W yellow) for the conventional PA. However, in kinetically enhanced mode, the MOPA output rose to 160 W (85-W green, 75-W yellow), an increase of more than a factor of 2 compared to the conventional PA. At higher PRFs, the MOPA output power continued to increase, reaching 202 W of HBQ power (112-W green, 90-W yellow) at 16-kHz PRF. To the authors' knowledge, this is the highest HBQ power reported using a simple (two-element) CVL system based on small/medium scale CVL devices.

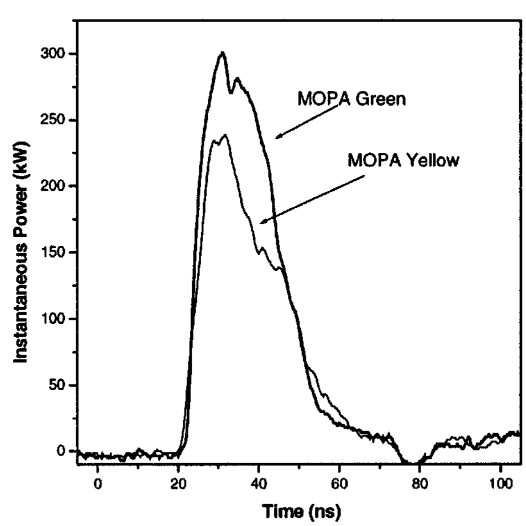
Output pulse shapes for operation in the MOPA configuration, and for the amplifier KE-CVL configured as an oscillator, are shown in Fig. 3(a) and (b) for PRFs of 6 and 12 kHz. The output pulse shapes for the MOPA operating at 16-kHz PRF are



(a)



(b)



(c)

Fig. 3. Output pulse shapes for MOPA operation at: (a) 6-kHz PRF; (b) 12-kHz PRF; and (c) 16-kHz PRF. The output pulses when the amplifier CVL is being operated with a plane-plane resonator are shown for comparison.

shown in Fig. 3(c). The MOPA output pulse duration (at base) was ~60 ns for the 6-kHz case, decreasing to 55 and 45 ns as the PRF was elevated to 12 and 16 kHz, respectively. Note that the duration of the MO output pulse (HBQ component only, ASE removed), which was measured to be 55–60 ns when operating at 6- and 12-kHz PRFs, is sufficient to fully extract all the available power from the PA. The MOPA output, therefore, consisted of amplified versions of all the beam-quality components that were present in the spatially filtered MO output. The pulse duration for the PA operating as an oscillator at 6-kHz PRF was equal to that produced when operating in MOPA mode, confirming that under MOPA operation we were extracting for the entire gain duration. It is also interesting to note that there was little change (difference of only 3%) in the amount of yellow light extracted from the PA when operating in either oscillator or MOPA mode. The most notable difference is that the average green power extracted from the PA increased significantly (35%) when the laser was operated in the MOPA mode. At a PRF of 12 kHz, the increase in average green power (69%) is also substantially greater than that for extracted yellow (increase of 36%); however, in this case, lengthening of the pulse duration (from 45 to 55 ns) also contributes to these improvements. Note that the temporal waveform of PA output was also modified when the PA was operated in MOPA mode: roundtrip modulations in the instantaneous power are no longer evident in the MOPA output pulses at PRFs of 6-, 12-, and 16-kHz. At all PRFs, the MOPA output delivered peak instantaneous powers in excess of 350 kW (200-kW green, 150-kW yellow). Indeed, at the 16-kHz operating condition, the peak instantaneous power exceeded 500 kW (300-kW green, 250-kW yellow).

B. Power Extraction and Saturation Characteristics

1) 6 kHz: Investigation of MOPA performance at 6-kHz concentrated on a moderate PA input power condition (~9 kW), where the amplifier CVL generated 80 W (46-W green, 34-W yellow) when operated as a kinetically enhanced oscillator [shown as a dotted line in Fig. 4(a)].

Fig. 4 compares the gain-saturation behavior of the amplifier operating in the KE and conventional modes. The functional form of saturation is similar in both the KE-CVL and conventional CVL, although the extracted output power levels are notably higher for the KE-CVL. As we noted earlier, the green power extracted from the PA is substantially higher (27%) than that extracted from the same CVL when operated as an oscillator. This behavior is attributable to longitudinal gain saturation effects in the oscillator, where the gain modulation experienced due to seed propagation leads to incomplete power extraction in some sections of the plasma tube [11]. The yellow power extracted is essentially the same as obtained in oscillator-mode operation, which we attribute to the reduced importance of longitudinal effects for the yellow laser transition. These effects indicate that achieving maximum power extraction from kinetically enhanced oscillators requires the use of higher reflectivity output couplers than those typically employed with conventional copper laser oscillators.

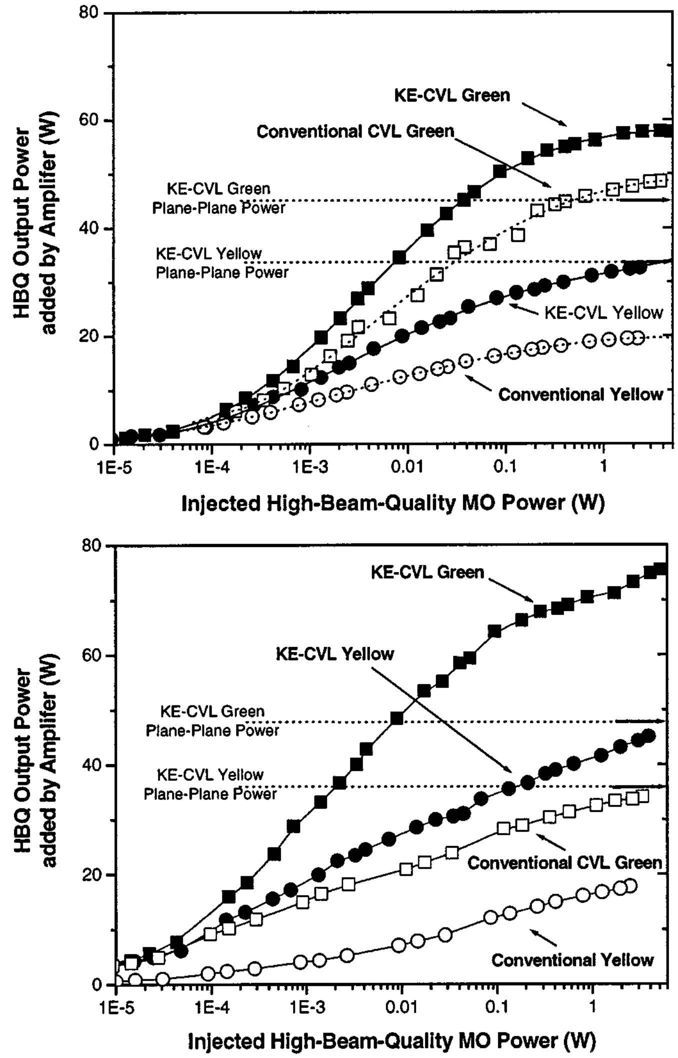


Fig. 4. HBQ power extracted from PA as a function of injected power from MO. (a) 6 kHz. (b) 12 kHz.

2) 12 kHz: Gain saturation and power extraction measurements at 12-kHz PRF were also undertaken at a slightly below-optimum input power, at which point the PA generated 84 W (47.7-W green, 36.3-W yellow) as a kinetically enhanced oscillator. The power added by the PA in MOPA operation (i.e., the total extracted output power minus the injected power) is shown as a function of injected power in Fig. 4 for the PA operated both conventionally and kinetically enhanced. At this PRF, the performance of the kinetically enhanced PA exceeds both the kinetically enhanced oscillator and conventional PA by a larger margin than at 6 kHz. In particular, operation as a MOPA with the PA kinetically enhanced generated HBQ output powers of 130 W (81-W green, 49-W yellow) at this input power, which is 55% higher than the kinetically enhanced oscillator power, and 116% higher than the MOPA output with conventionally operated PA of 60 W (37.5-W green, 22.5-W yellow). Note also that the power extracted in kinetically enhanced amplifier mode ex-

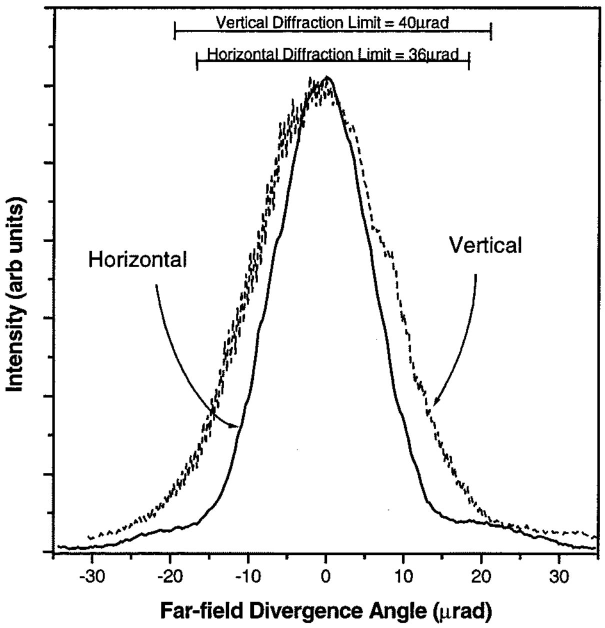


Fig. 5. Far-field intensity profile for KE-CVL MOPA output at 6-kHz PRF.

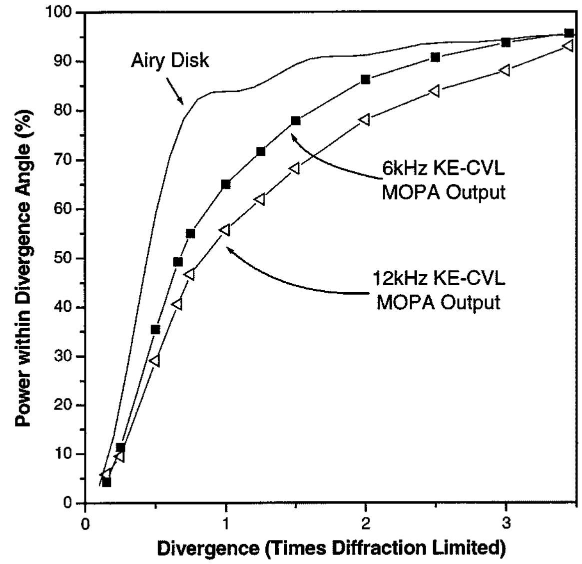


Fig. 6. Far-field energy spread ("power-in-the-bucket") for KE-CVL MOPA output. The energy spread for a diffraction-limited beam with a top-hat near-field profile is shown for comparison.

ceeded that in the kinetically enhanced oscillator mode for both laser transitions.

C. Beam Quality and Brightness

Horizontal and vertical slices through the far-field intensity profile of the KE-CVL MOPA output (at 6 kHz) are shown in Fig. 5. The far-field profile is characteristically axially peaked, as we have observed previously for kinetically enhanced oscillators [6], [7] with a substantial fraction of the output contained within the diffraction limit [12]. The slight anisotropy in the horizontal and vertical directions is due to vignetting of the beam by copper pieces in the base of the amplifier tube, which correspondingly increases the divergence in the vertical direction. Measurements of the near-field beam size (by producing a demagnified image on a CCD camera) confirmed that the beam is ~4-mm smaller in the vertical direction than in the horizontal direction. Note also that the near-field profile was essentially a top-hat, although the profile was slightly rounded at the edges, as we have observed in previous KE-CVL oscillator measurements [3]. Based on the measured beam dimensions, the diffraction-limited divergence (assuming a top-hat irradiance profile) is 36 μrad in the horizontal and 40 μrad in the vertical direction. Note that similar profiles are observed when the KE-CVL is operated at higher PRF.

We performed a "power-in-the-bucket" analysis [12] of the absolute output beam quality of the KE-CVL MOPA by using the software functions of the frame-grabber. In particular, the software permitted the accurate determination of the fractional power within a user-defined aperture, and by varying the aperture size, we were able to generate plots of far-field energy spread for operation at 6 and 12 kHz, as shown in Fig. 6. The far-field energy spread for a diffraction-limited top-hat beam (i.e., an Airy disk) is shown for comparison. The far-field energy spread for operation at 6 kHz is slightly tighter than 12 kHz, with 65% of the output propagating within the diffraction limit at 6 kHz, compared to 56% at 12 kHz. This is due to the reduced fraction of the output beam that is derived from the (nondiffraction-limited) two-roundtrip component of the oscillator at the lower PRF. The beam quality at 12 kHz could, therefore, be somewhat improved by operating the MO with a higher magnification unstable resonator, to reduce the divergence of the two-roundtrip component. Based on the "power-in-the-bucket" criterion[2], we can quantify the beam quality as 1.75 $\times$DL for 6-kHz operation, and 2.5 $\times$DL for 12-kHz operation. Based on the more generous Strehl ratio criterion[3], the beam quality is 1.3 $\times$DL for 6-kHz operation, and 1.5 $\times$DL for 12-kHz operation.

Examination of the near-field wavefront of the output beam showed that the only significant aberration present in the output beam was ~0.5 waves of spherical aberration, which is consistent with the excellent measured beam quality. Most of this aberration is introduced in the beam-expansion telescope that couples the MO into the PA, which indicates that even better beam quality may be achievable with a more sophisticated expansion scheme.

IV. Discussion

There are a number of areas of performance of the KE-CVL MOPA where significant improvements were observed in comparison with either single-oscillator KE-CVLs or conventional CVL MOPA systems. For instance, the KE-CVL MOPA

[2]The "power-in-the-bucket" beam quality is defined as

$$\times\mathrm{DL} = \frac{D_{\mathrm{aperture}}}{D_{\mathrm{Airy}}}$$

where D_{Airy} is the diffraction-limited size of the first Airy disk, and D_{aperture} is the aperture size required for 84% transmission of the beam power.

[3]The Strehl ratio S is defined as the measured peak intensity of the far-field profile, compared to the peak intensity of the far-field profile of an ideal (diffraction-limited) beam having the same near-field dimensions. The beam quality is then $1/S$.

TABLE I
PERFORMANCE CHARACTERISTICS OF OTHER MOPA CONFIGURATION EMPLOYING TWO COPPER LASER ELEMENTS

Oscillator: Bore Size (mm)	Injected Power (W)	Power Amplifier: Bore Size (mm)	Total output power (W)	Power Amplifier Active Volume (litres)	Specific Output Power (mW/cc)	PRF (kHz)	Laser	Reference
25	**~10**	**38**	**202**	**1.53**	**125**	**16**	**KE-CVL**	This paper
5.5	0.64	25	22.6	0.49	45	7	CVL	[14]
25	6.5	38	81	1.53	49	6	CVL	This paper
-	-	40	30	0.75	40	4	CVL	[13]
20	5.7	60	200	7.1	27	5	CVL	[22]
20	5.7	60	260	8.5	30	5	CVL	[22]
40	15-20	80	265	-	-	4.4	CVL	[23]
25	20	60	107	6.2	14	17	Cu:HyBrID	[24]
50	40	80-90	320	19.5	14	17	Cu:HyBrID	[25]

exhibited superior repetition rate scalability over other CVL systems. The output power of the KE-CVL MOPA system increased monotonically from 118 to 202 W as the pulse rate was elevated from 6 to 16 kHz, equivalent to a slope of 8.5 W/kHz. In a previous study of KE-CVL oscillator behavior (with a plane-plane resonator and the same storage capacitance) [4], the output power of a 38-mm diameter KE-CVL (similar to the PA used in this study) similarly increased monotonically from 105 to 150 W as the pulse repetition frequency was elevated from 12 to 22 kHz, equivalent to a slope of 5 W/kHz. The rate at which the MOPA output power scales with pulse repetition frequency is, therefore, 70% higher than for a similar size KE-CVL operating as an oscillator, demonstrating the increasing inefficiency of oscillator performance as the gain duration shortens. The significance of this factor is most apparent when comparing the HBQ extraction of these devices. The output power of the KE-CVL MOPA is essentially all HBQ in nature, and increases up to the maximum PRF investigated. However, when the 38-mm KE-CVL was configured with a high magnification unstable resonator [7] it produced a maximum of 60 W at a pulse repetition frequency of 12 kHz, and the HBQ power extracted decreased as the PRF was elevated above this value.

The specific power extraction of the KE-CVL MOPA was amongst the best ever attained using any CVL-based system. The MOPA system produced 81 W when the PA was operating in conventional mode (pure Ne buffer gas) at a repetition frequency of 6 kHz. Note that the extracted power per unit volume of 49 mW/cm^3 is consistent with that reported in the literature for other power amplifiers using conventional CVLs of similar bore diameter (e.g., 40 mW/cm^3 produced by a 40-mm diameter PA [13] and 45 mW/cm^3 produced by a 25-mm PA [14]). When kinetically enhanced, the maximum output power produced by the MOPA increased by a factor of 2.5, the PA producing an additional output of 192 W from an active volume of only 1.53 L, equivalent to a unit power extraction of 125 mW/cm^3. To the best of our knowledge, this figure is the highest power yet reported for a simple (two-element) CVL system of this size. Furthermore, the power performance of this system is comparable to other much larger 200-W two-element MOPA systems using either large bore/conventional CVLs or large bore Cu:HyBrID PAs (see Table I) which have, at best, specific power extraction of $\sim$30 mW/cm^3 and $\sim$20 mW/cm^3, respectively. In some cases, the performance of this KE-CVL/MOPA is also comparable to the performance of systems employing multiple PAs such as the 200–250 W four-element MOPA chain described in [15], [16] and the 200-W five-element MOPA chain used in laser guide star applications [17].

The beam quality of the KE-CVL MOPA also compares favorably to other HBQ, high brightness copper laser configurations. For example, large bore Cu:HyBrID oscillators have been reported producing 100 W within 1.6$\times$ the diffraction limit at a PRF of 12.5 kHz [18], and 120 W within 2.3$\times$ the diffraction limit when operating as an injection-seeded oscillator at a PRF of 17 kHz [19]. By comparison, the KE-CVL MOPA produced 97 W within 1.75 $\times$DL at 6 kHz, and 130 W within 2.5 $\times$DL at a PRF of 12 kHz. A convenient "figure of merit" for comparing the brightness of different systems is to calculate the average power of the CVL system per mm^2 of beam area per mrad^2 of output divergence[4]. Using this figure of merit, the KE-CVL MOPA has a spatial brightness of 22 and 17 W$\cdot$mm$^{-2}\cdot$mrad^{-2}, respectively, at PRFs of 6 and 12 kHz, which is approximately a factor of 2 greater than the brightness values for KE-CVL oscillators (i.e., $\sim$6 W$\cdot$mm$^{-2}\cdot$mrad^{-2} for a 25 mm $\times$ 1 m long laser [20] and 10 W$\cdot$mm$^{-2}\cdot$mrad^{-2} for a 38 mm $\times$ 1.5 m long laser [7]. The KE-CVL MOPA spatial brightness even surpasses that of recently reported 100-W single oscillator Cu:HyBrID systems [18], [21] with brightness factors up to 16 W$\cdot$mm$^{-2}\cdot$mrad^{-2} and 9 W$\cdot$mm$^{-2}\cdot$mrad^{-2} for the 120-W injection-seeded oscillator system [19]. Clearly, the

[4]By noting that the diffraction-limited divergence of a laser is inversely proportional to the near-field beam width, then this figure of merit simply represents a scaled version of the intensity, that is power/(beam quality factor)^2.

compact nature of this 200-W KE-CVL MOPA represents an attractive alternative to larger scale conventional CVL MOPA configurations for applications requiring high average power and HBQ such as laser micro-machining and laser guide stars.

V. Conclusion

We have demonstrated that kinetic enhancement can dramatically improve the power and pulse rate scaling of a CVL MOPA system. Using such a system, which incorporated a small-scale 25 mm $\times$ 1 m MO and a 36 mm $\times$ 1.5 m PA, we have generated up to 202 W of HBQ (high brightness) visible output at a pulse rate of 16-kHz. At lower PRFs of 6 and 12 kHz, the same system produced 97 and 130 W of output power with measured beam quality of 1.75 $\times$DL and 2.5 $\times$DL, respectively.

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James A. Piper, photograph and biography not available at the time of publication.