Increased Efficiency of High-Beam Quality Extraction from a Copper Vapor Laser with H_2–Ne Admixtures

Michael J. Withford, Daniel J. W. Brown, David W. Coutts, *Member, IEEE*, and James A. Piper

***Abstract*— We report results of a detailed study investigating the effects of hydrogen additive on the generation of high-beam quality output from a copper vapor laser. Increases up to 390% were observed for the power extracted in the high-beam quality component of laser output, however, the power of the low beam quality output remained relatively unchanged. We attribute these results to modification of the spatio-temporal characteristics of the laser gain with added H_2.**

I. INTRODUCTION

THERE have been numerous reports in recent years of the effects on laser performance of adding H_2 gas to the neon buffer gas of metal vapor lasers (MVL's). These include reports of modest increases (typically 30% to 50%) in the total output power resulting from the addition of small partial pressures of hydrogen (usually 1–2%) to the neon buffer gas of elemental copper vapor lasers (CVL's) [1], [2], copper halide lasers [3] and barium vapor lasers [4] when employing conventional plane/plane resonators. Hydrogen additive has also been reported to alter the voltage/current characteristics of the laser discharge and the spatio-temporal characteristics of the output of CVL's [5] and other MVL's [3], [6].

CVL's are being increasingly used for applications requiring both high beam quality (i.e., low divergence) and high-average power, such as nonlinear frequency conversion [7], pumping of solid-state laser materials (i.e., Ti:Sapphire [8]) and micromachining applications [9]. In order to obtain high-beam quality, CVL's usually employ high-magnification unstable resonators [10], [11], which provide tight geometric constraints on the propagation and amplification of an initial burst of spontaneous emission (the seed) on repeated round-trips within the resonator. The beam quality evolves in a stepwise fashion [12] as the laser radiation completes successive numbers of round-trips through the unstable resonator. The initial output is low beam quality ASE, originating from radiation that has undergone less than one round-trip through the resonator. Subsequent output consists of high-beam quality radiation that has undergone two or more round-trips through the resonator (when using a high-magnification unstable resonator). The gain duration is therefore an important factor in determining the pulse-average beam divergence, with the proportion of high-beam quality (low-divergence) output increasing as the pulse duration lengthens.

A second factor influencing the generation of low divergence output from CVL's is the spatial intensity profile of the seed radiation (single pass amplified spontaneous emission (ASE) or nucleus [10]) that gives rise to all observable output. Both the gain duration, and radial profile of the seed radiation, are strongly dependent on CVL operating conditions. In particular, high-pulse repetition frequency (PRF) operation normally results in a reduced pulse duration (in some cases down to just two round-trips) and an annular seed intensity profile [13]. Such an annular radial profile of the seed radiation results in an annular far-field intensity profile (for an on-axis resonator) and reduced high-beam quality output. Improved seeding efficiency may be obtained by using an off-axis unstable resonator [14], however, the output divergence becomes anisotropic [13].

The addition of hydrogen to the neon buffer gas has been previously reported to alter both the laser pulse duration [5] and the radial profile of laser output [1], however the influence these changes have on the generation of high-beam quality output have yet to be investigated fully. In this paper, we report the results of a detailed study of the effects of hydrogen additive on high-beam quality output from a CVL.

II. EXPERIMENTAL METHOD

The CVL used in this investigation was a small bore device (plasma tube dimensions 18 mm dia. × 750 mm long) employing a standard thyratron-switched (EG&G HY-3001) pulse charging circuit including a resonant voltage doubler [5]. The effects of various hydrogen admixtures (1–5%) on CVL beam quality were investigated for a range of PRF's, namely 4.3, 9.2, and 19.7 kHz (with 8 nF, 4 nF, and 2 nF respective storage capacitance) at a fixed supply voltage of 6.5 kV. These PRF's were selected so that the plasma tube wall temperature was the same (within 1550 ± 5°C) for each set of operating conditions (note the neon buffer gas pressure was held constant at 25 Torr for all experiments).

An on-axis, positive branch confocal unstable resonator (length 1.9 m) of magnification $M = 16$ incorporating a 1 mm diameter convex spot reflector ($R = 25$ cm) and a 50 mm diameter concave high reflector ($R = 4$ m) was employed. The temporal evolution of the laser output was monitored using a fast rise-time vacuum photodiode (Hamamatsu 1193a) coupled

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to an oscilloscope (100 MHz Tektronix 2245) triggered relative to the commencement of the laser pulse.

The far-field intensity profile of the laser operating at 9.2 kHz was examined by focusing the laser output onto the CCD array of a laser beam analyzer (Spiricon LBA-100) using a lens pair ($f_1 = 200$ mm and $f_2 = 60$ mm achromatic convex lenses) configured as a reducing telescope. The intensity of the image was reduced via neutral density filters to within the linear operating range of the beam analyzer. Once configured, no further changes were made to this arrangement so that the output profiles corresponding to various hydrogen–neon admixtures could be compared directly.

The aforementioned reducing telescope was also used to measure the different components of laser output power. A ~1 mm diameter aperture placed at the focus of the telescope removed the high-divergence component (the ASE with divergence > 2 mrads) from laser output. Subsequently, the average power (green + yellow) for both the total output (ASE + non-ASE) and the non-ASE portion was measured using a calorimetric power meter (Scientech 360001) placed either before or after the lens pair respectively (with correction for reflective losses included).

Finally, the spatial characteristics of the initial burst of seed radiation were investigated by imaging the output of the CVL without a resonator (i.e., output coupler and high-reflector removed) onto a gated diode array (Princeton Instruments IRY-512) [15]. The imaging arrangement (200 mm and 60 mm achromatic lenses with ~1 mm diameter pinhole at the shared focus) was arranged such that only the component of the highly divergent ASE travelling parallel to the laser tube axis was incident on the diode array. Further, a slit placed in the beam path restricted the radiation incident on the diode array to a thin (<0.5 mm) horizontal cross section of the ASE profile. The diode array was gated to capture a 5 ns time-slice at the maximum intensity of the seed radiation for various H_2–Ne admixtures.

III. Results and Discussion

The beam quality of a CVL has been previously shown [12] to evolve in a stepwise fashion from highly divergent ASE (arising from laser radiation that has undergone up to 1 round-trip through the resonator) to low divergence (~1.2 mrads, 2 round-trips) and finally near-diffraction limited output (<0.6 mrads, 3 or more round-trips). The low divergence and the near-diffraction limited components of CVL output are referred to collectively in this discussion as non-ASE output.

Fig. 1 shows CVL output pulse shapes for pure neon buffer gas (the solid line) and various H_2–Ne admixtures at 9.2 kHz operating frequency. Each pulse shape displays the characteristic intensity modulation corresponding to radiation that has undergone successive round-trips through the unstable resonator. It is clear from the data of Fig. 1 that H_2 buffer gas additive significantly increases the total peak power directly associated with the high-beam quality component of the output pulse. Further, a small amount of 4 round-trip output is now readily apparent in Fig. 1. By comparison, the peak power associated with the ASE/low beam quality component of the output pulse increases by only a small amount. We attribute these effects to added H_2 improving the pre-pulse conditions by increasing the rate of electron energy transfer via elastic interactions during the interpulse period [16].

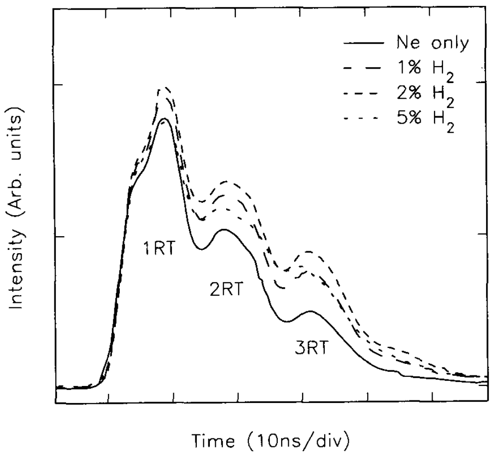

Fig. 1. The temporal evolution of the laser output pulse for a pure neon buffer gas and various H_2–Ne admixtures at an operating frequency of 9.2 kHz. The successive round-trips are labeled as 1RT, 2RT, and 3RT.

The CVL output powers over a range of PRF's and buffer gas admixtures are shown in Fig. 2(a)–(c). As the PRF of the CVL is increased the pulse duration shortens [5], [13], thereby restricting the number of round-trips laser radiation can make through the active volume (e.g., from 5 round-trips at 4.3 kHz to only 2 round-trips at 19.7 kHz PRF). As a result, the amount of useful high-beam quality output available from the laser is reduced at elevated PRF's for systems using pure neon buffer gas. At 4.3 kHz PRF the CVL produced ~5 W of non-ASE output yet only ~1 W of non-ASE output was observed at 19.7 kHz PRF in pure neon buffer gas (leftmost data points in Fig. 2(a) and (c)). In contrast, the ASE power over the range of PRF's investigated remains relatively constant at 2.0 W (±0.8 W) for pure neon buffer gas (left-most data points Figs. 2(a)–(c)). It is due to the poor yield of non-ASE output at elevated PRF's that CVL's have been limited in the past to low PRF operation when utilized for applications requiring high-beam quality.

Significant increases in non-ASE output power were observed as H_2 was added to the buffer gas, as illustrated in Fig. 2(a)–(c). At 4.3 kHz PRF a maximum increase in non-ASE power of 17% was observed for a 2% H_2–Ne admixture. Much larger improvements in non-ASE power were observed at higher PRF's with the addition of H_2 to the neon buffer gas. At 9.2 kHz a maximum increase in non-ASE power of 150% was observed using a 5% H_2–Ne admixture while at 19.7 kHz a 390% increase in non-ASE power resulted using a 5% H_2–Ne admixture. In contrast, only relatively minor increases in ASE power were observed with added H_2 over the range of PRF's investigated. The greatest increase in ASE power of 45% was observed at 19.7 kHz PRF (compared to a 390% increase in non-ASE power at this PRF).

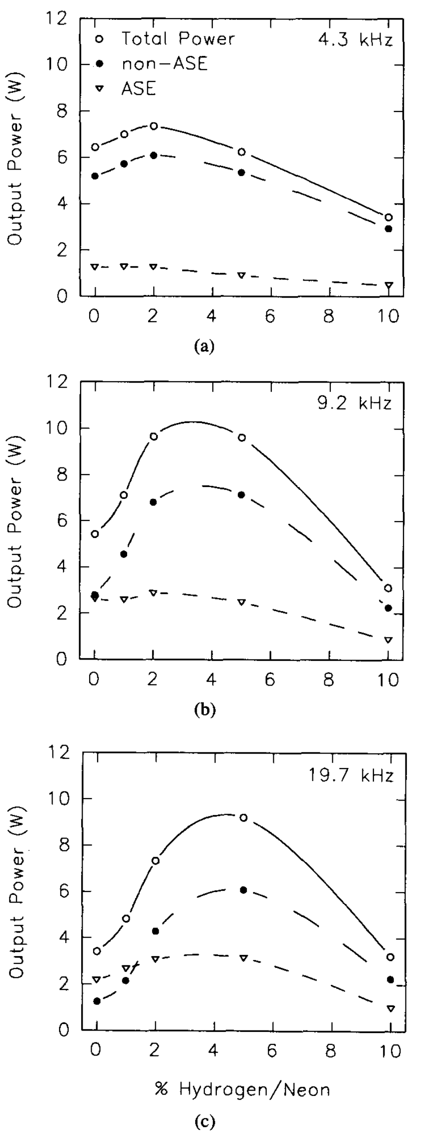

Fig. 2. (a) The total output power, (b) the ASE output power, and (c) the non-ASE output power for pure neon buffer gas and various H_2–Ne admixtures over a range of operating frequencies (4.3, 9.2, and 19.7 kHz). An on-axis unstable resonator ($M = 16$) was used for all cases.

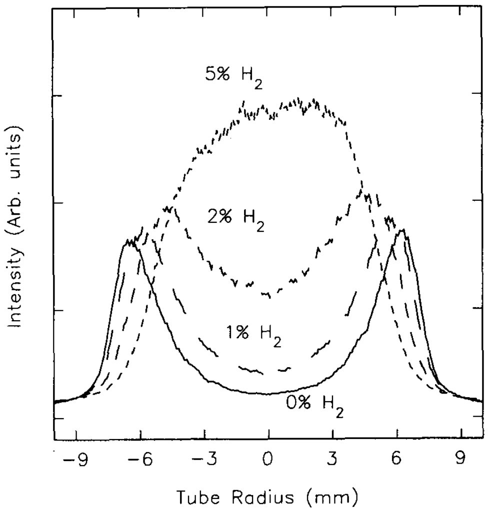

Fig. 3. The seed radiation intensity profiles for pure neon buffer gas and various H_2–Ne admixtures (1, 2, and 5%) at an operating frequency of 9.2 kHz.

As the PRF was elevated, the optimum percentage admixture of H_2 increased. This observation is consistent with our earlier investigation of PRF scaling in CVL's with plane-plane resonators [5], where it was shown that the shift in optimum H_2 concentration is most probably due to slight changes in impedance matching, which is both PRF and buffer gas pressure dependent. We attribute the progressive improvement in laser performance at elevated PRF's to enhanced plasma relaxation when H_2 is added to the neon buffer gas [16].

The seed radiation intensity profiles for pure neon buffer gas and various H_2–Ne admixtures are shown in Fig. 3 for 9.2 kHz operation. The spatial profile of the seed radiation has also been shown to be dependent on the operating frequency of the laser [13]. At low PRF's the seed radiation has a fairly uniform spatial profile which becomes increasingly annular (in pure neon buffer gas) as the PRF is elevated, as illustrated by the solid line in Fig. 3. Decreasing the buffer gas pressure also increases the annularity of the seed intensity distribution. Consequently, the seeding efficiency of the active volume is reduced due to poor matching between the on-axis resonator and the annular seed distribution, necessitating the use of off-axis resonators at elevated PRF's (and low buffer gas pressures).

H_2 additive significantly alters the seed intensity profile (Fig. 3), the seed intensity profile is observed to *fill-in* and constrict radially as the percentage of added H_2 is increased at 9.2 kHz operating frequency. Similar modification of the seed-intensity profile was also observed at 19.7 kHz PRF, an operating frequency at which the seed intensity (for pure neon buffer gas) was entirely suppressed on-axis. This modification of the radial profile of the seed with added H_2 favors the continued use of on-axis resonators at elevated PRF's, thereby avoiding the problems generally associated with the use of off-axis configurations (i.e., difficulty of alignment and anisotropic beam divergence [13]).

Fig. 4(a)–(c) present the far-field intensity profiles of laser output for the cases of pure neon buffer gas, 2% H_2 and 5% H_2 additive. The low divergence/2 round-trip component of laser output gives rise to the annular ring observed in Fig. 4(a). The near-diffraction limited component of laser output gives rise to the central peak in all three far-field intensity profiles (Fig. 4(a)–(c)).

Coutts [13] showed that each point of the disc of seed radiation from which 2 round-trip output originates, is imaged directly into the far-field. Consequently, 2 round-trip output appears as an annular ring in the far-field (pure neon buffer gas case, Fig. 4(a)), replicating the annular seed intensity distribution at 9.2 kHz PRF (solid-line, Fig. 3). Under these

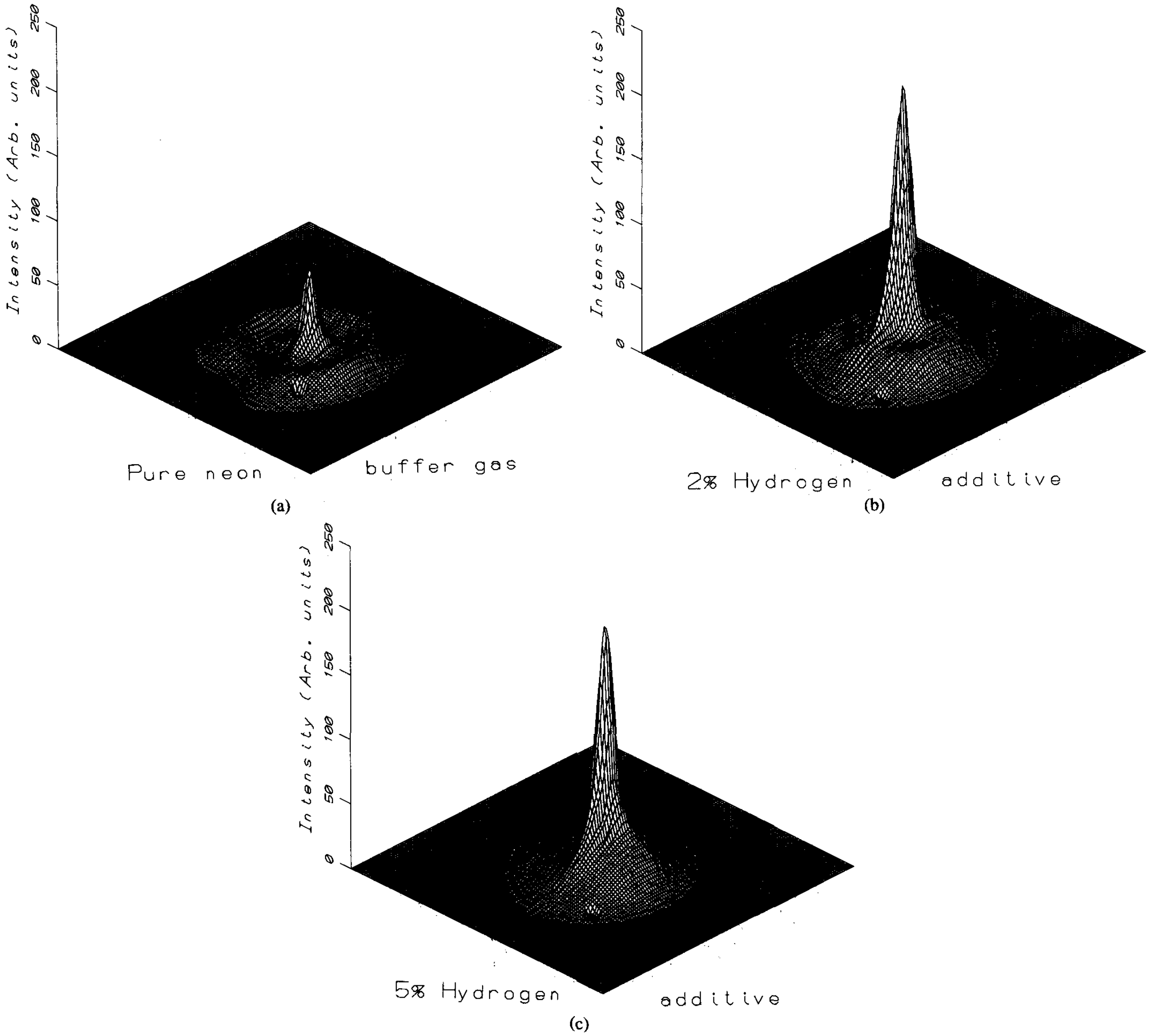

Fig. 4. (a)–(c) The far-field intensity profiles of the output from a CVL with on-axis unstable resonator operating in pure neon buffer gas, 2% and 5% H_2–Ne admixtures, respectively.

circumstances the 2 round-trip component contributes nothing to the laser power available at a tight spot focus. However, as the seed intensity profile constricts and becomes peaked on-axis with added H_2, so too is the 2 round-trip component observed to constrict (note the copper-fill shadow is no longer apparent) and become peaked on-axis in the far-field (Fig. 4(b) and (c)) thereby now contributing to the power available in a tight focal spot.

Probably the most dramatic change to the far-field profiles with added H_2 is observed in the relative intensities of the near-diffraction limited component. The intensity of the near-diffraction limited component (the central peak in Fig. 4(a)–(c)) is observed to increase threefold when 2% and 5% H_2 is added to the buffer gas. This marked change is attributed to the increased peak power of the 3 and 4 round-trip components of laser output, as shown in Fig. 1. Note that 4 round-trip output is observed for the first time at these operating conditions.

Preliminary investigations have shown that H_2 buffer gas additive also increases the peak power of the tail-end of the output pulse and modifies the seed intensity profile of larger diameter CVL's. Consequently, we expect added H_2 to also improve the yield of high-beam quality output from large bore CVL's.

IV. SUMMARY

Addition of H_2 to the neon buffer gas of CVL's has been observed to significantly increase the peak power associated with the tail-end/non-ASE component of the output pulse. These effects translate into an increased proportion of low divergence/near-diffraction limited output available from a

CVL with added H_2. Significant increases in high-beam quality output power (up to 4×) were observed, particularly at elevated operating frequencies. In contrast, only minor increases in ASE were observed. Further, the annular intensity profile of the seed radiation was observed to fill-in when H_2 was added to the neon buffer gas. Under these conditions the use of on-axis unstable resonators at elevated operating frequencies gives good efficiency in high-beam quality extraction and avoids the problems generally associated with off-axis resonators such as anisotropic beam divergence and asymmetric far-field profiles.

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