

Formation of output in copper vapor lasers

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Detailed mechanisms that control the formation of output from copper vapor laser (CVL) oscillators are investigated. Measurements of the spatial and temporal evolution of gain in a CVL amplifier and a CVL oscillator show that a short period of high gain that occurs at the beginning of the inversion period is the dominant feature. This leads to the formation of a burst of amplified spontaneous emission (ASE), whose subsequent propagation and amplification leads to all observable CVL output. The spatial characteristics of this initial burst of ASE are shown to be strongly dependent on the operating conditions of the laser. The implications of this description of CVL output for the design of unstable resonators and oscillator–amplifier systems is discussed.

1. Introduction

Copper vapor lasers (CVLs) are pulsed visible laser sources that offer high average power capability (10–100 W), high efficiency (~1%), and multikilohertz repetition rate. The high peak and average power capabilities of the CVL are a result of the large small-signal gain, short gain duration, and large gain volume and Fresnel number of the laser medium. However, these gain characteristics lead to difficulty in generating high-beam-quality output from the CVL, because there are insufficient round trips within the resonator to develop a cavity mode. However, recent research on beam quality from CVLs, which has been driven principally by the desire to use CVLs in nonlinear frequency conversion¹ and micromachining,² has shown that advanced resonator configurations, including unstable resonators,³ noncavity resonators,⁴ and injection-coupled oscillators^{5,6} may be successfully used with CVLs to improve output-beam quality dramatically.

To date, investigations of these high-beam-quality CVLs have been principally concerned with examination of spatial-output characteristics (i.e., beam quality),^{7–9} and less attention has been directed toward understanding the detailed interaction of the CVL

gain medium with the resonator structure to produce the observed output. For instance, although it is generally agreed that output from a CVL is initiated by an amplified spontaneous emission (ASE) seed or nucleus,^{3,4,10} there are no reported studies of the spatial or temporal characteristics of this seed radiation. Furthermore, the details of how this seed interacts with the spatiotemporally varying gain of the CVL active medium to produce the observed optical output have never been fully investigated. These issues are of significant importance, however, as detailed understanding and numerical modeling of these high-beam-quality systems requires the spatial and temporal properties of both initial radiation source and the gain medium to be well characterized.

This paper presents a comprehensive study of the processes that control the formation of optical output from CVL devices and incorporates measurements of the spatiotemporal characteristics of the CVL gain medium and the initial ASE seed. In Section 2 the experimental techniques used to measure the spatial and temporal characteristics of the CVL gain medium are described in detail. Measurement of the temporal evolution of CVL gain was performed with a short-pulse CVL oscillator to probe a second CVL gain medium that was configured to operate as an amplifier or as an oscillator. The spatial characteristics of the ASE seed were measured with an imaging technique coupled with a fast-gated diode-array detector. The results of these measurements are presented in Section 3, and their implications and a structured picture for the formation of CVL output are discussed in Section 4.

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2. Experimental Techniques

2.A. Measurement of Temporal Evolution of Gain and ASE in the CVL Active Medium

The spatiotemporal evolution of the gain in the CVL active medium was measured with a probe technique with two identical medium-scale CVL's (nominally 20 W, 25 mm i.d. \times 1 m long active region) that operate as oscillator and amplifier, as shown in Fig. 1. Both CVL's were operated under identical excitation conditions, with a fixed neon buffer gas pressure of 40 mbar. The gain evolution was measured for the CVL's, which operated at two repetition rates (4 and 7 kHz), whereas previous measurements¹¹ had shown significant differences in the spatial-gain characteristics of the CVL.

The major experimental challenge in measuring the temporal evolution of gain in a CVL is to produce a short probe pulse with negligible background level and high beam quality. The high contrast ratio is essential, as the high unsaturated gain of the CVL¹² leads to significant amplification of any background in the probe pulse, distorting the measured gain. Furthermore, the short pulse should ideally have high beam quality, so that the amplified probe pulse can be differentiated from amplifier ASE by the use of spatial-filtering techniques. In this experiment, we have generated a short, high-contrast, high-beam-quality pulse by the use of a dual-cavity approach, in which the probe CVL operates simultaneously with an unstable cavity and a longer stable cavity. The unstable cavity (positive branch confocal with magnification $M = 100$) is formed between a curved high reflector (4-m radius of curvature) and a dot reflector output coupler (resonator length 1.98 m), and the parasitic stable resonator is formed between the same high reflector and an uncoated silica flat placed

outside the unstable resonator (resonator length 2.7 m). The parasitic stable cavity truncates the development of high beam quality in the output by feeding back lower-beam-quality ASE into the unstable resonator to swamp high-beam-quality light reflected from the dot reflector output coupler. The output of this dual-cavity CVL is a short high-beam-quality pulse, mixed with lower-beam-quality light derived from the parasitic stable cavity. The green output is then selected with a dichroic mirror and focused through a Rhodamine 6G dye cell that acts as a saturable absorber to remove the low-beam-quality components. The resulting output typically had a pulse width of ~ 5 – 6 -ns FWHM, with contrast ratio $>1000:1$.

The probe beam is recollimated after it passes through the dye cell and is apertured to ~ 2 -mm diameter with a translatable aperture to provide spatial resolution. The probe is attenuated with neutral density filters, propagated through the amplifier CVL, and spatially filtered at the output to remove any amplifier ASE. The amplified output is measured at two radial positions (namely, on the amplifier axis and near the tube wall) with a fast photodetector (Hamamatsu R1193U-02), and the pulse shape is recorded with a Tektronix TDS 540 digital oscilloscope (400-MHz analog bandwidth). We determined the temporal behavior of the CVL gain by scanning the delay between the oscillator and amplifier with a precision digital delay generator (Stanford Research Systems DG535), which yielded a timing accuracy of better than 0.5 ns. The single-pass power gain of the active medium is calculated from the ratio of the amplified probe's peak intensity to its incident peak intensity.

To examine the mechanism of CVL output formation, the gain behavior in the low-signal-level regime is of most importance, as this is the gain that ASE-level signals will experience. Rather than attempt to determine the small-signal gain (which would require mapping of the gain evolution over a wide range of input intensities), we have measured the gain evolution at the lowest practicable value consistent with system detectivity. The peak probe intensity used was only ~ 10 – 20 mW/cm² (~ 1 – 2 μ W average power at 4 kHz), which is many orders of magnitude smaller than the peak intensity of both the single-pass ASE (~ 1 kW/cm², as determined from measured ASE power and pulse shape) and typical circulating intensities in resonators (>10 kW/cm²). Even for these very small input signal levels, the peak single-pass gain of the CVL active medium is so high that some difficulties with saturation effects were encountered, and these are discussed fully in Section 3. It is important to note that the aim of these gain measurements is to provide a strong qualitative picture of the temporal evolution of gain, in order to understand how spontaneous emission noise grows to form the laser output in these devices. These gain measurements are not fully quantitative,

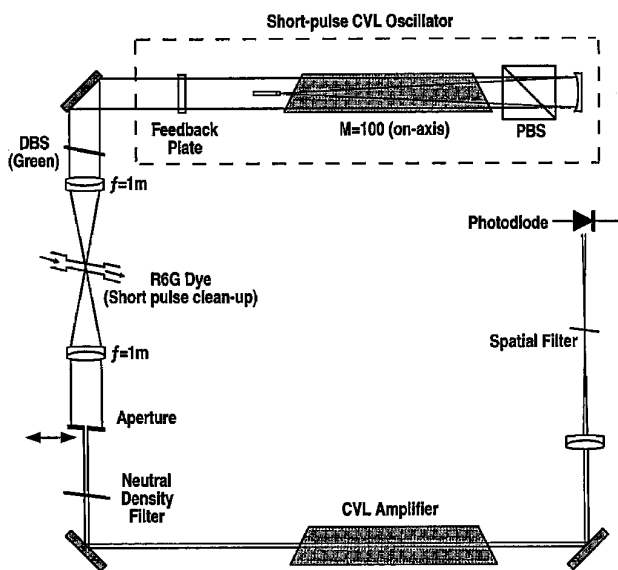


Fig. 1. Experimental setup for measuring the temporal evolution of gain in the CVL active medium. DBS, dichroic beam splitter; PBS, polarizing beam splitter.

as they do not account for saturation behavior and linewidth issues.

The temporal behavior of the single-pass ASE emitted from the amplifier CVL was also measured. The probed CVL was operated without a cavity (and with stringent measures to eliminate any stray scattering that may provide feedback). A fast vacuum photodiode (Hamamatsu R1193U-02) was placed several meters from the exit aperture, and intervening 2-mm-diameter apertures were used to select ASE that travelled parallel to the tube axis (hereafter referred to as paraxial ASE) and originated from the same radial positions (i.e., on-axis and near the tube wall), as measured in the gain probe experiments. The total ASE emitted from one end of the amplifier CVL was also measured by removal of the apertures and focusing of all ASE output onto the vacuum photodiode with a lens. In both ASE measurements the photodiode output was recorded with a Tektronix 7104 oscilloscope (1-GHz bandwidth) coupled to a digitizing system (Tektronix DCS-01).

2.B. Measurement of the Temporal Evolution of Gain and ASE in a CVL Oscillator

The transformation of spontaneous emission into oscillator output was investigated by measurement of the temporal gain evolution in a CVL that acted as an oscillator at 4-kHz pulse-repetition frequency (PRF). A positive branch confocal unstable cavity ($M = 62$) was formed around the probed CVL with polarizing beam-splitter cubes (polarization ratio $> 100:1$), with a high reflector and output coupler positioned as shown in Fig. 2. This bent cavity ensured that only the vertical polarization operated in the cavity. The gain evolution was mapped by injection of a short-pulse probe (derived from the same hybrid oscillator as that used for the amplifier gain measurement) that

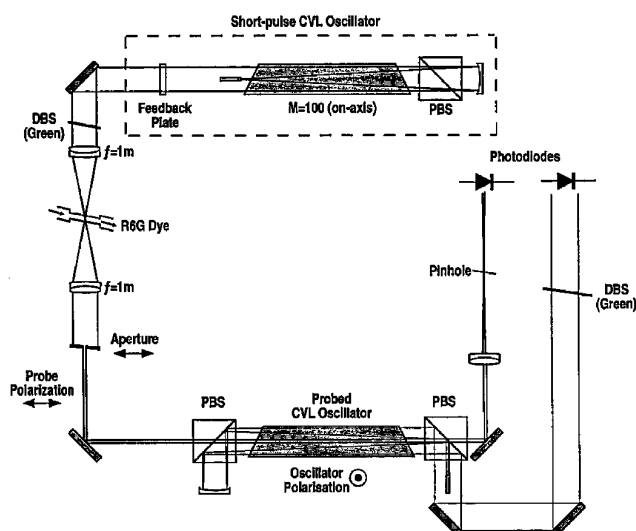


Fig. 2. Experimental setup for measuring the temporal evolution of gain in a CVL oscillator. The polarization of the probe beam and the intracavity field in the probed oscillator is indicated. RG6, Rhodamine G6.

was polarized in the horizontal direction and so was transmitted through both intracavity polarizing beam-splitter cubes. Because of the orthogonality of the probe and the intracavity field polarizations, the probe field does not directly couple into the oscillator field. Two different probe intensities were used, with a low-intensity probe (with an intensity of approximately half that used for the amplifier gain measurement) being used to allow comparison of the changes in the gain behavior between amplifier and oscillator operation. A higher-intensity probe ($100\times$ low-intensity probe) was also used to increase the dynamic measurement range, to allow some lower gain features to be resolved. The bent cavity also allowed simultaneous monitoring of the CVL oscillator output and the ASE output from the tube, because the polarized laser output exits the cavity at right angles to the tube axis, whereas half the single-pass ASE (of polarization orthogonal to that of the laser cavity output) exits along the tube axis.

2.C. Measurement of the Spatial Variation of the ASE Seed Intensity

In the measurements detailed in Subsection 2.A. (results given in Subsection 3.A.), the intensity of the initial ASE burst (seed) is not uniform across the tube aperture. To obtain high-spatial-resolution measurements of the transverse intensity profile of this initial ASE burst, the experimental arrangement shown in Fig. 3 was used. The CVL was operated without a resonator, and the possibility of any optical feedback from stray reflections was eliminated when a dark specularly reflecting screen was placed at a 30° angle to the optic axis at the remote end of the laser tube. The single-pass ASE output of the CVL active medium was imaged with an $f = 400$ mm achromat through a small (0.5-mm) aperture in a black metallic plate placed at the focus of this lens. This aperture acts to reject any ASE that is not propagating parallel to the tube axis. A horizontal slice through the seed-intensity profile is obtained when a slit aperture is placed at the image plane of the far end of the active medium. This slice is then imaged with a $f = 160$ mm achromat (after reflection off an antireflection-coated wedge to reduce its intensity) onto a fast-gated (5-ns) diode-array detector (Princeton Instruments IRY-512), which recorded the seed-intensity profile. The detector gating was set to coincide with the peak ASE (seed) intensity.

3. Results

A. Temporal Evolution of CVL Gain and ASE at 4-kHz PRF

The measured temporal gain evolution for the 510.6-nm transition at the tube axis and near the tube wall in the CVL active medium (without resonator), which operated at 4 kHz, is shown in Fig. 4, in which the single-pass power gain is plotted on both logarithmic [Fig. 4(a)] and the linear [Fig. 4(b)] scales. The peak probe intensity is 14 mW/cm^2 .

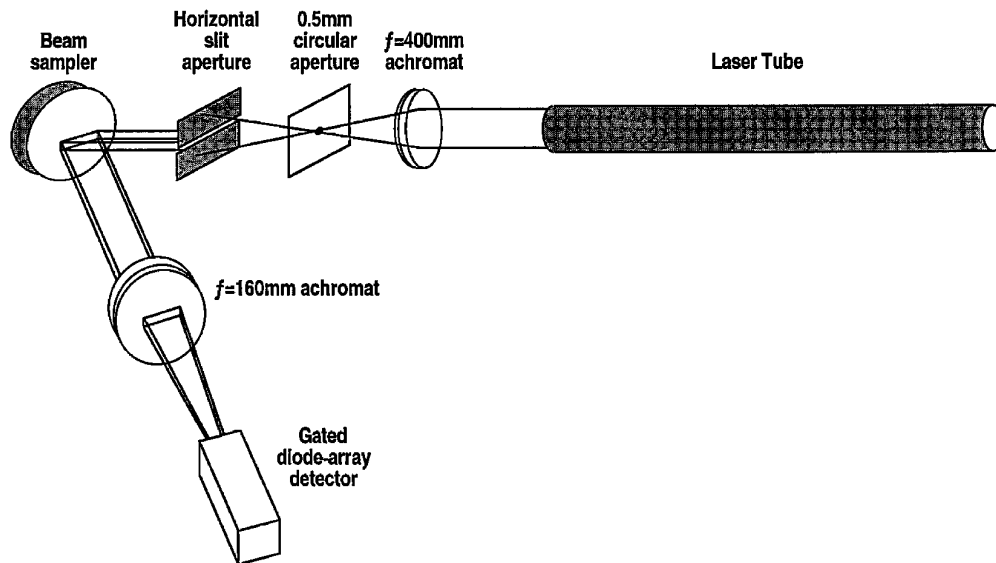


Fig. 3. Experimental arrangement for measuring the spatial profile of the seed in the CVL. The first lens ($f = 400$ mm) images the far end of the CVL plasma tube onto the horizontal slit aperture; the second lens ($f = 160$ mm) images the slit aperture onto the gated diode-array detector.

The gain behavior at 4 kHz PRF is dominated by an initial short (~ 5 -ns FWHM) spike of high gain that occurs *simultaneously* at both measured radial positions. As the medium switches into inversion, the single-pass gain rapidly rises to a magnitude of 6.5×10^5 near the wall and 2.9×10^5 on-axis (at this probe intensity) and just as rapidly collapses to a much-reduced level ($\sim 3\text{--}5 \times 10^3$) for the remainder of the inversion period. Gain terminates on-axis some 45 ns after switch-on but persists a further 9 ns near the wall.

At the peak of the gain spike, the injected probe signal (14 mW/cm^2 peak) is amplified to an intensity of $\sim 10 \text{ kW/cm}^2$, which is more intense than ASE and comparable with the circulating intensity in a CVL resonator. The probe amplification must therefore lead to significant gain saturation at the peak of the gain spike. On the other hand, the probe undergoes much less amplification at later times during the gain duration, with correspondingly reduced gain saturation on transit through the active medium. This difference in saturation behavior implies that the measured temporal evolution of the gain is somewhat distorted, with the measured peak gain being pulled down relative to the measured gain at later times. The gain spike is therefore an even more dominant feature than the measurement indicates, with higher relative magnitude compared with the gain at later times. One further point to note is that the gain spike has a narrower FWHM duration than measured, because of both the saturation behavior and the finite probe pulse width.

A comparison of the measured axial gain behavior with the total ASE output from one end of the CVL active medium [shown in Fig. 4(c)] confirms that the observed gain evolution is consistent with gain-switched behavior.¹³ The initial switch-on of high

gain, which is due to the rapidly increasing upper-laser-level population, leads to the occurrence of rapid amplification of spontaneous emission at this time. The resulting ASE field grows quickly until it becomes sufficiently intense to begin depleting the inversion and hence to saturate the gain. As gain saturation occurs, the significant ASE flux takes up to 3 more nanoseconds to exit the CVL active medium, during which time the ASE further depletes the gain. This rapid growth in ASE followed by gain saturation gives rise to an ASE spike or burst. The total ASE output does not fall to zero on the trailing edge of this ASE burst, as there is sufficient gain and spontaneous emission (because the spontaneous emission rate increases throughout the inversion period^{14,15}) to provide a significant ASE field within the active volume. This ASE field clamps the gain in a partially saturated state for the remainder of the gain duration, as has been previously predicted by computer modeling.¹⁶ The persistence of the gain to later times near the tube walls is a result of the detailed upper-laser-level kinetics, as discussed by Brown *et al.*^{14,15}

The paraxial ASE output from the CVL active medium is shown in Fig. 4(d), along with the measured gain evolution. An initial burst of ASE (as observed in the total ASE output) is clearly evident at both radial positions, and is in fact the dominant feature of the paraxial ASE. The relative timing of the ASE burst and the gain spike shows that the maximum optical intensity corresponds to that spontaneous emission that has propagated from the far end of the laser tube through the duration of the gain spike, thereby interacting with the maximum gain length. The duration of this ASE burst (~ 3 -ns FWHM) indicates that the gain saturates within a single pass through the gain medium. In Subsection

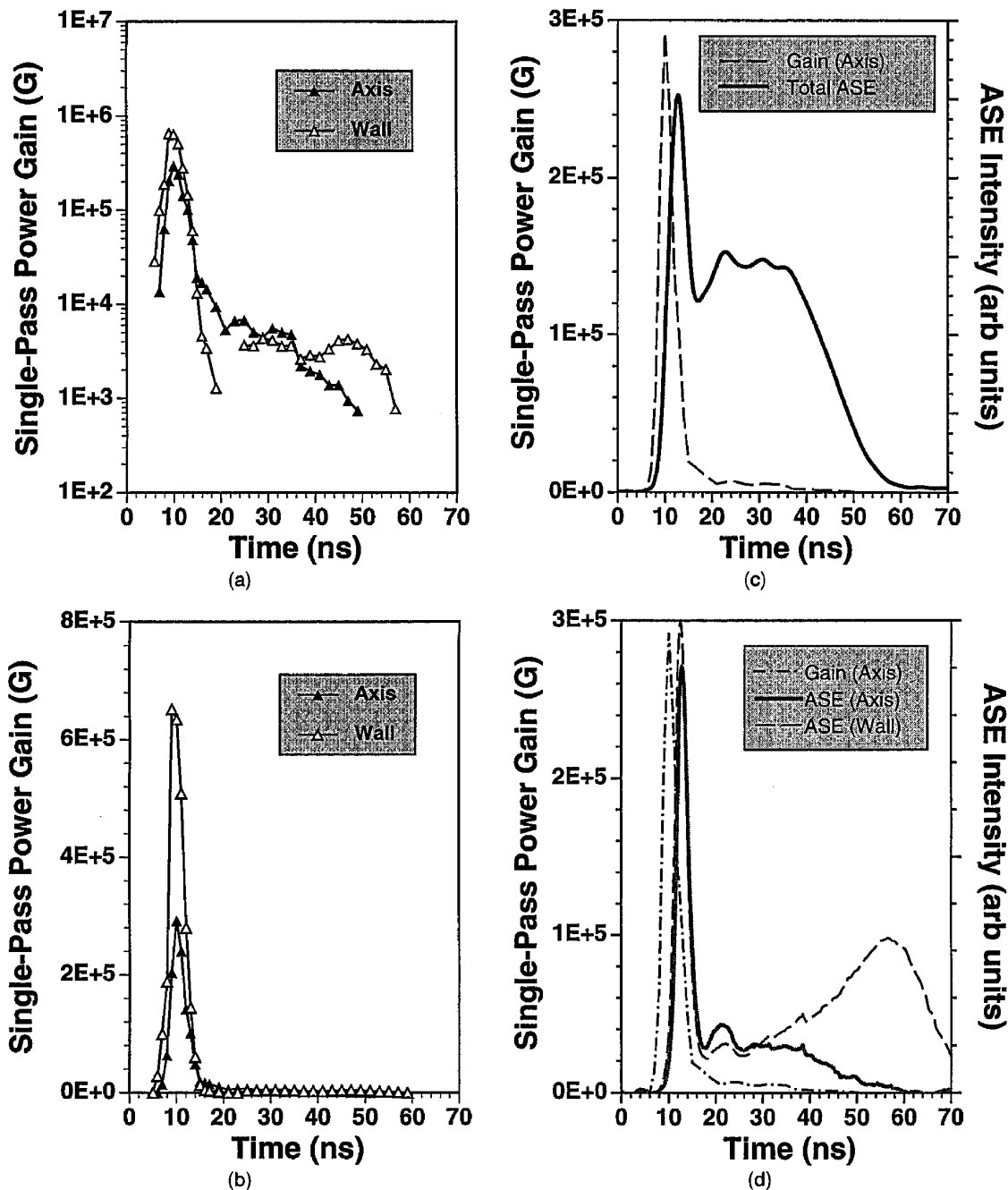


Fig. 4. Measured temporal evolution of single-pass power gain (G) at two radial positions in the CVL active medium (on-axis and near the tube wall) operating at 4-kHz PRF, plotted on (a) logarithmic and (b) linear scales. The peak probe intensity was 14 mW/cm^2 . The total single-pass ASE output (i.e., without cavity) is shown in (c), with the on-axis gain evolution overlaid for comparison. The paraxial ASE output is shown in (d), with the on-axis gain evolution again overlaid for reference.

3.B. it is demonstrated that this initial burst of paraxial ASE is the seed from which all subsequent output from a CVL oscillator originates.

The paraxial ASE output after the initial ASE burst is substantially reduced from its peak value at both radial positions, in contrast to the total ASE [Fig. 4(c)], which recovers to approximately half its initial peak value. The ASE output of the CVL active medium is therefore initially most intense in the direction parallel to the tube axis, as photons that

are propagating paraxially interact with the greatest gain length. However, as gain saturation occurs, nonaxially propagating photons (i.e., skew rays) begin to dominate the total ASE output. The ASE flux that is due to skew rays is therefore the most significant factor holding the gain in its partially clamped state after the initial gain spike.

The gain behavior for the yellow (578.2-nm) laser transition was not measured in this study. However, comparison of the single-pass ASE output on

the yellow transition shows that it is very similar (in form) to the green output, although it is slightly delayed with respect to the green and is of much lower intensity. From this we can deduce that the temporal evolution of gain in the yellow is similar to that in the green, but with the peak gain on the yellow transition being lower than in the green. This is consistent with the detailed inversion kinetics of these two transitions.¹⁷

3.B. Temporal Evolution of CVL Gain and ASE at 7-kHz PRF

The temporal evolution of the 510.6-nm gain on the tube axis and near the tube wall for a 7-kHz CVL (shown in Fig. 5) shows a much more pronounced radial variation than the 4-kHz amplifier case, although an initial gain spike is observed at both radial positions at essentially the same time. Near the tube wall, the initial spike has a peak gain of 2.0×10^6 , which is 3 times higher than the peak gain

measured in the 4-kHz condition. In contrast, the peak gain during the initial gain spike on-axis of 6.6×10^4 is 4.4 times lower than at 4 kHz. The increase in repetition rate from 4 to 7 kHz has therefore resulted in an increase of the ratio of the peak gain near the wall to that on-axis from ~ 2 to ~ 13 . As was observed at 4 kHz, the gain for the remainder of the inversion period is significantly depressed in comparison with the initial gain spike at both radial positions. The gain near the tube wall is $\sim 10^5$ over the remainder of the inversion period, whereas on-axis the gain is approximately an order of magnitude lower ($\sim 10^4$). As in the 4-kHz case, the difference in saturation behavior for the gain spike and for the remainder of the gain duration means that the gain spike is a more dominant feature than Fig. 3 indicates.

The temporal form of the paraxial ASE output at 7 kHz that arises from this gain variation is shown in Fig. 5(c). An initial burst of ASE is evident at both radial positions, although the intensity of the burst

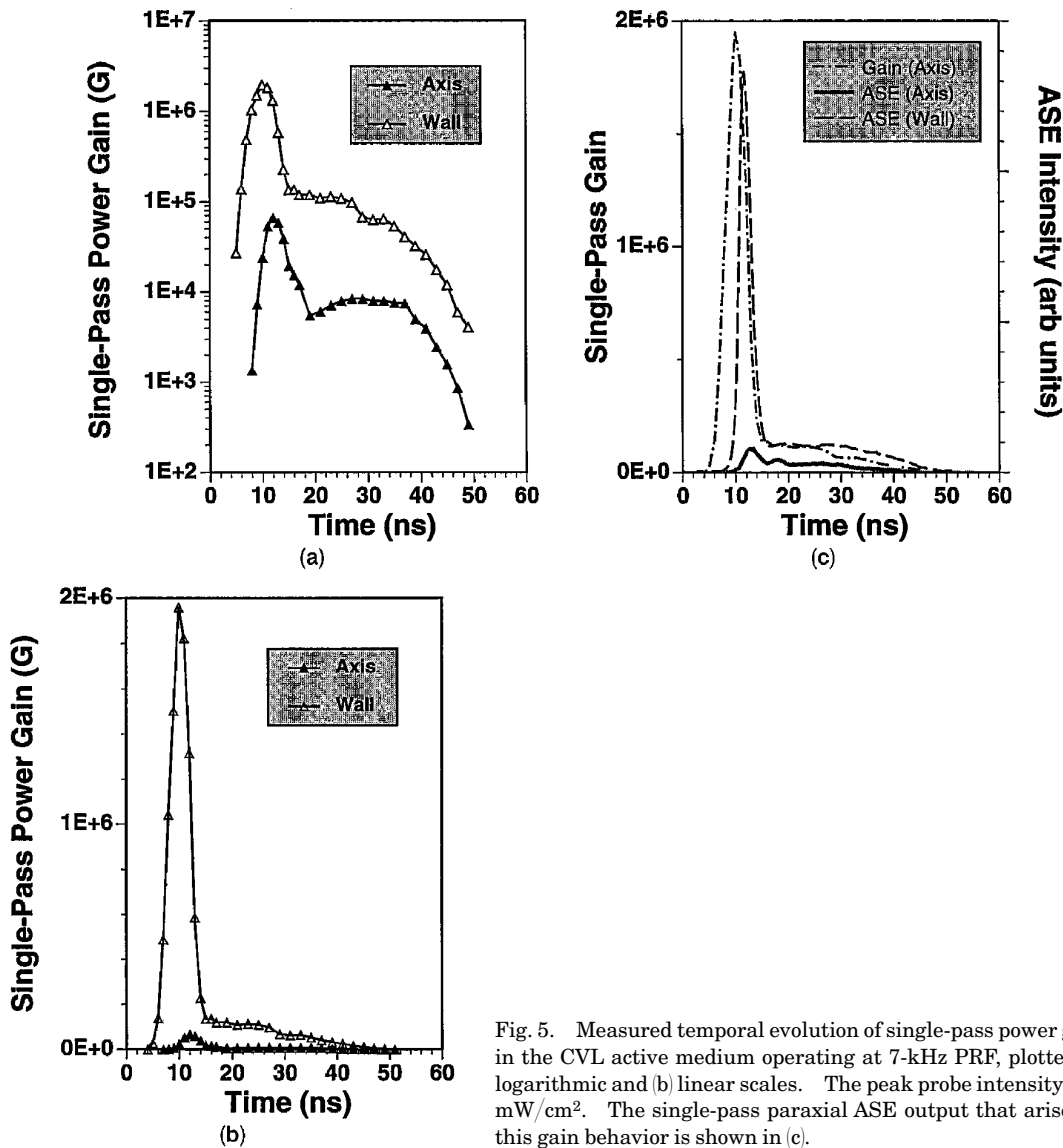


Fig. 5. Measured temporal evolution of single-pass power gain (G) in the CVL active medium operating at 7-kHz PRF, plotted on (a) logarithmic and (b) linear scales. The peak probe intensity was 14 mW/cm^2 . The single-pass paraxial ASE output that arises from this gain behavior is shown in (c).

near the wall is significantly higher than on-axis. As in the 4-kHz case, the initial ASE burst (or seed) is much more intense than any subsequent paraxial ASE at either radial position.

The initial gain spike observed at both radial positions is again the result of gain switching, as noted in the 4-kHz case. Differences between the detailed excitation kinetics at the tube center and edge ensure that the axial gain turns on much more slowly than does the gain near the wall. In particular, the higher axial prepulse electron densities¹⁸ at 7 kHz result in a delay in the radial propagation of the electric field into the plasma during the pump pulse¹⁹ (i.e., skin effect²⁰), although higher prepulse lower-laser-level densities^{21,22} may also play some role.

The rapid fall in gain after the peak of the gain-switched spike is due to the buildup of significant ASE (both axially propagating and skew rays) within the tube. Because the gain near the wall is much higher than on-axis, skew rays that originate from near the wall and propagate through the axis are important in controlling the saturation of the axial gain during the trailing edge of the gain spike. As a consequence, gain saturation occurs essentially simultaneously across the tube aperture, even though the gain turns on more slowly on-axis than near the wall.

Correspondingly, the integrated gain experienced by rays that are propagating parallel to the tube axis is much lower on-axis than near the wall, which accounts for the observed difference in peak paraxial ASE intensity at the two radial positions [Fig. 5(c)].

3.C. Temporal Evolution of Gain and ASE in a CVL Oscillator at 4-kHz-PRF

The measured gain evolution in the CVL oscillator is shown in Fig. 6(a) (low-intensity probe) and Fig. 6(b) (high-intensity probe), along with the oscillator output pulse. The dominant observable gain feature is again the initial gain spike, which exhibits similar behavior to that observed in the amplifier configuration. The subsequent gain behavior differs somewhat from the amplifier case, with the gain being modulated at the cavity round-trip frequency rather than being approximately constant for the remainder of the inversion period. The magnitudes of these subsequent gain peaks are similar to the gains observed at similar times under amplifier operation, although it is important to note that these round-trip gain features are substantially smaller than the initial spike (by at least a factor of 25). These peaks in the gain after the initial spike correspond to troughs in the output intensity. Between these gain peaks, the gain fell below measurable levels for the probe intensities used.

Although these measurements accurately reflect the temporal gain features, gain-saturation effects have of course distorted the relative magnitudes of the measured gain. In particular, the measured gain is pulled down at times when the gain is higher, because of the increased amplification of the injected

probe signal. This effect is most pronounced for the initial gain spike, where both low- and high-intensity probes are amplified to levels ($\sim 5 \text{ kW/cm}^2$ for the low-intensity probe, $\sim 16 \text{ kW/cm}^2$ for the high-intensity probe) comparable with the circulating intensity in a CVL resonator. It can therefore be concluded that, as was noted in Subsection 3.A., the initial gain spike is an even more dominant feature than the measurement indicates.

The single-pass paraxial ASE output from the oscillator is shown in Fig. 6(c). The dominant feature is again the short initial burst of ASE, similar to that observed for the CVL that was operated without a resonator [Fig. 2(c)]. However, there is virtually no ASE output from the oscillator after this initial spike, in contrast to the single-pass ASE from the CVL without a resonator.

The significance of the initial ASE burst in the formation of CVL output was investigated by perturbation of the initial gain spike (which leads to the ASE burst) in the probed oscillator and simultaneous observation of the output of this oscillator. The same experimental arrangement as that for the oscillator gain measurement was used, except that the maximum available probe intensity (80 W cm^{-2} peak) was used to produce significant gain saturation during the probe pulse duration. It is important to note that probe pulse directly affects only the gain of the active medium, not the intracavity field because the probe and intracavity optical fields have orthogonal polarization.

The oscillator output without a perturbing pulse, and with the perturbing pulse overlapping the initial gain spike, is shown in Fig. 7. The initial peak in the oscillator output is substantially reduced ($\sim 2\times$) from the unperturbed case, because the partial saturation of the initial gain spike reduces the available gain for the intracavity field during this period. What is more significant is that the subsequent oscillator output is modified by this initial perturbation. All subsequent output peaks are reduced in intensity from the unperturbed case, as a result of the reduced intensity of the initial ASE burst intensity (within the cavity). Of course this reduction in the oscillator output is not linear (i.e., it is less than half the unperturbed value) because the gain of the active medium saturates. A further consequence of the reduced intensity of the initial ASE burst is that the intensity modulation between the peaks is also decreased. In particular, reducing the intensity of this burst slows down the saturation process, thereby increasing the duration of the initial ASE burst within the cavity. Injecting the probe signal at any later time during the inversion period of the oscillator CVL did not lead to any perturbation of the oscillator output pulse.

3.D. Spatial Variation of the ASE Seed Intensity

The measurements of gain and ASE (Subsections 3.B. and 3.C.) suggest that the initial ASE burst (or seed)

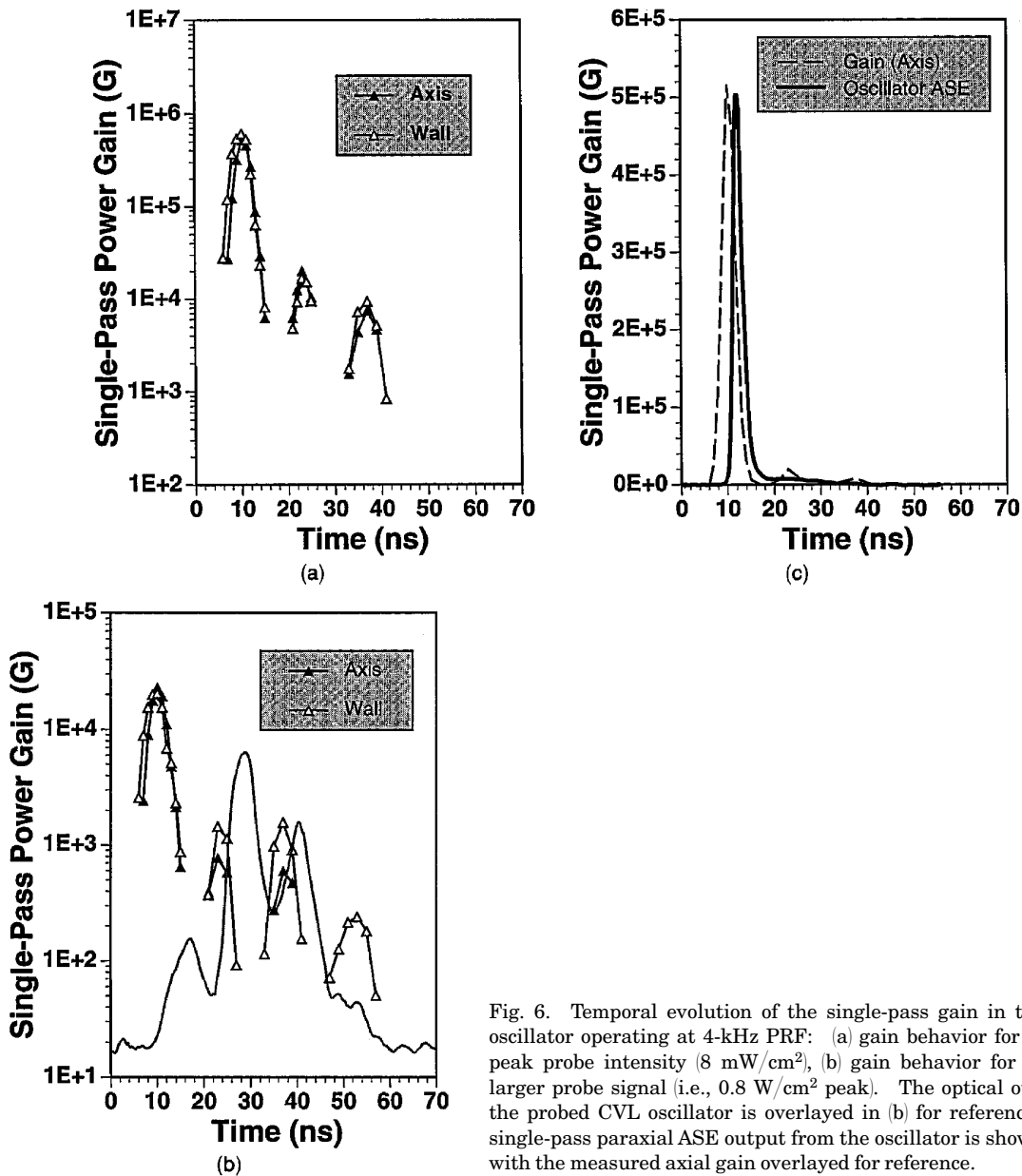


Fig. 6. Temporal evolution of the single-pass gain in the CVL oscillator operating at 4-kHz PRF: (a) gain behavior for a small peak probe intensity (8 mW/cm^2), (b) gain behavior for a $100\times$ larger probe signal (i.e., 0.8 W/cm^2 peak). The optical output of the probed CVL oscillator is overlaid in (b) for reference. The single-pass paraxial ASE output from the oscillator is shown in (c), with the measured axial gain overlaid for reference.

has a nonuniform transverse intensity profile and that this profile depends on the repetition rate of the laser. In Subsection 3.D. the results of high-resolution measurements of the seed-intensity profile are described as a function of the two CVL operating conditions investigated in Section 2. The measurement technique described in Subsection 2.C. isolates the ASE that propagates parallel to the tube axis, as it is only this ASE that may propagate for repeated round trips within a resonator. It is this ASE that forms the seed for the resonator output.

The measured transverse intensity profiles of the ASE seed at the 4- and 7-kHz operating conditions are shown in Fig. 8. As suggested by the temporal gain measurements, the seed profiles at the two repetition rates differ significantly. At 4 kHz, the seed-intensity profile is slightly annular. The maximum

intensity of the seed is $\sim 55\%$ higher than the axial intensity and occurs approximately 7 mm from the tube axis. At 7 kHz, the seed profile is highly annular in nature. In particular, the axial seed intensity is only 1% of the maximum value, and the seed intensity over the central 14 mm of the profile is less than 10% of the maximum seed intensity. The maximum seed intensity also occurs much closer to the tube wall than at 4 kHz, being displaced ~ 11 mm from the tube axis.

Because the transverse intensity distribution of the seed is significantly different for these two repetition-rate conditions, the spatial characteristics of the output differ under these two conditions.^{11,23} In particular, at 4 kHz, where the seed is reasonably uniform, the use of an on-axis-aligned unstable resonator is preferred. At 7 kHz, where the seed has a

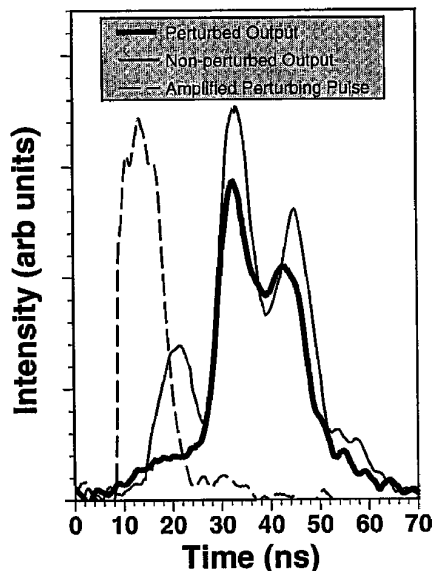


Fig. 7. Perturbation of the probed oscillator output by injection of a saturating optical pulse during the initial gain spike. The unperturbed oscillator output is overlaid for reference.

markedly annular profile, an off-axis-aligned resonator is preferred for maximum high-beam-quality output.

4. Discussion

The measured gain and ASE behavior in a CVL active medium and oscillator, in association with the perturbation experiment, demonstrates that the ASE burst normally produced from the initial gain spike is the sole seed source for the resonator. The output of the CVL oscillator is formed by the propagation and amplification of this seed within the resonator.

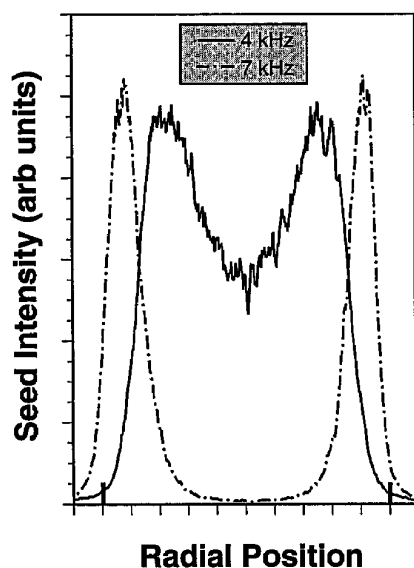


Fig. 8. Spatial-intensity profiles of the seed at 4- and 7-kHz PRF, recorded at the peak of the ASE with a 5-ns gate width on the diode-array detector. The position of the tube walls is indicated by the short black bars on the radial position axis.

Note that the observed temporal duration of the seed pulse (~ 3 -ns FWHM) agrees well with the theoretical assumptions of Borovich and Yurchenko¹⁶ in their CVL optical modeling.

Because the CVL produces a substantial optical field in less than a single pass through the gain medium (as evidenced by the intensity of single-pass ASE), the intracavity field is not subject to the same round-trip phase boundary conditions as more conventional laser devices. Hence it is more correct to view the CVL as a multipass or traveling-wave amplifier of the seed radiation, rather than a true laser oscillator.

The seed formalism allows the chronology for the formation of CVL oscillator output to be described accurately. The initial gain spike leads to the formation of two counterpropagating ASE seeds; one travels toward the output coupler, and the other travels toward the high reflector. The effective reflectivity of the output coupler then determines whether both seeds lead to observable output or whether the seed that is initially traveling toward the high reflector dominates the subsequent development of output. For an unstable resonator of magnification M , the effective reflectivity of the output coupler is $\sim 1/M^2$; for the typical unstable resonators used with CVL's ($M \sim 25$ – 100) the effective reflectivity is so small ($\sim 10^{-3}$ – 10^{-4}) that the seed reflected from the output coupler is dominated by the counterpropagating seed on the second pass through the gain medium, and hence no significant further output originates from this seed. The seed that initially propagates toward the high reflector is then the sole seed in this case. This seed provides access to two passes of gain, and most of this two-pass output (or ASE) exits the cavity past the dot reflector and becomes the first peak in the output. The increased temporal width of this two-pass output in comparison with the single-pass ASE seed results from saturation effects during the second pass through the gain medium. The small fraction of the two-pass output that reflects from the dot reflector into the tube solid angle is much more intense than local ASE, because the gain (and hence ASE intensity) is much reduced after the initial gain spike. This reflected two-pass signal therefore dominates subsequent output development. In particular, the two-pass output reflected from the dot reflector undergoes a further two passes of amplification (with an associated significant improvement in beam quality^{8,23}), leading to the second peak in the output. The gain recovery observed between the first and the second peaks in the output results from the time that the (amplified) seed spends outside the gain medium (but inside the cavity). The amplified seed continues to circulate within the resonator, producing output peaks each time it encounters the output coupler, until the gain terminates because of kinetic mechanisms.

Based on this description of the formation of CVL oscillator output, the round-trip modulation in output intensity commonly observed for the 510.6-nm

line is actually a result of seed propagation, rather than being a gain-recovery effect (askin to relaxation oscillations in solid-state lasers). In the case of a high-magnification unstable resonator, only one seed leads to observable output (as discussed above), and hence the intensity modulation occurs at the cavity round-trip frequency. For a plane-plane resonator or low-magnification unstable resonators, however, the seed that initially propagates toward the output coupler also leads to observable output, as the reflectivity of the output coupler (up to 4%) is sufficiently high to allow the reflected signal to compete with the (amplified) counterpropagating seed. Modulation of the output intensity is therefore observed at twice the cavity round-trip frequency²⁴ because of the propagation and amplification of both seeds within the resonator.

The observed spatial-intensity profile of the seed has substantial implications for analysis and optimizing of beam quality in unstable-resonator CVL's. Because the operation of a CVL oscillator may be described as the propagation and amplification of an initial source of short duration (the seed), the most appropriate formalism for analyzing CVL output is an unfolded lens-guide approach.^{8,25} In this formalism, source radiation is propagated through the equivalent resonator lens guide, which is essentially an imaging system for this source. The spatial characteristics of the output are determined by how the initial spatial-intensity profile of the source (which is the object for the imaging system) is transformed by the propagation through the lens guide. A full description of the spatial characteristics of CVL output is therefore attainable once detailed knowledge of the seed-intensity profile is obtained.

For a CVL of the size investigated in this study, power extraction across the tube diameter is relatively uniform (as evidenced by the tophat near-field profile obtained when a plane-plane resonator is used). Radial effects in the output are therefore directly traceable to the spatial-intensity profile of the seed. In particular, for operating conditions in which the seed is annular, the far-field profile is generally annular for both plane-plane and on-axis unstable resonators,²³ even though the near field is close to tophat. In larger-bore CVL devices, the situation is further complicated by both nonuniform power extraction across the aperture and the significant delay commonly observed between the appearance of gain near the wall and on-axis.²⁶ However, the mechanism of seed formation (i.e., gain switching, with saturation that is due to axially propagating and skew rays) ensures that only a single seed with a purely annular transverse intensity profile is formed in these devices. The spatial characteristics of the output of these devices are still determined largely by seed propagation, with slight modifications to the output profiles because of the nonuniform saturated gain.

Some aspects of the operation of CVL as a power

amplifier or injection-controlled oscillator are also clarified. In particular, an injected signal can only achieve efficient power extraction if the initial gain spike is saturated by amplification of the injected field rather than by amplification of spontaneous emission. Quenching of the gain spike in the amplifier has the additional advantage that the optical signal that is fed back from the amplifier to the oscillator is much lower in intensity and hence less likely to interfere with oscillator operation.

5. Conclusion

In this paper the detailed mechanisms that lead to the formation of output from CVL oscillators have been investigated. The output has been shown to originate solely from an ASE seed, which is formed during the first few nanoseconds of the gain duration by gain switching. The propagation and amplification of this seed lead to all observable output from the oscillator. The transverse intensity distribution of this seed has been shown to vary markedly with operating repetition rate, and this has important implications for unstable-resonator selection.

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