Measurements of the divergence evolution of a copper-vapor laser output by using a cylindrical imaging technique

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The temporal evolution of divergence of the output of a copper-vapor laser (CVL) operating with a high-magnification ($M = 26.5$) unstable resonator is measured by using a one-dimensional imaging system together with a fast gated linear diode array detector. The CVL output is found to consist of several temporally resolved components, with each successive component having lower divergence. The final component of the output has essentially diffraction-limited divergence. The divergence behavior is modeled by using an unfolded resonator-equivalent lens guide, with geometric constraints on the propagation of spontaneous emission within the lens guide, and is found to match the experimentally determined behavior.

Recently there has been considerable interest in improving the output beam quality from copper-vapor lasers (CVL's) in order to promote efficient frequency conversion of the CVL output by using nonlinear optical techniques. While it is well understood that the high gain and short inversion time in CVL's necessitate the use of unstable resonators for improved beam quality, some features of the temporal evolution of beam quality in CVL's that are equipped with unstable resonators remain unclear. In particular, while the growth in the transverse coherence of the CVL output during the pulse has been experimentally determined, previous studies of the temporal evolution of the divergence of the CVL output have been only qualitative in nature. Here we report measurements of the temporal evolution of the far-field intensity distribution (and hence divergence) from a CVL that is fitted with a high-magnification unstable resonator. The measurement technique used, which involves recording the far-field intensity distribution of the CVL output, has a significantly simpler experimental realization than transverse coherence measurements, and the results are also more easily interpreted.

The output of the CVL consists of several components with different divergences. Previous approaches to divergence measurements in CVL's have exclusively used some form of one-dimensional sampling (streak camera or scanned pinhole) to record the intensity distribution at the focus of a spherical lens. However, the intensity profile across a two-dimensional focus measured across a single line does not directly yield the energy distribution between the various divergence components, as it overweights those components with low divergence. To obtain the true energy distribution, we must transform the measured intensity profile to take the circular geometry into account. This measurement approach also requires that the focus be scanned accurately through its center. An alternative approach, which was adopted for the measurements reported herein, involves measuring the CVL far-field intensity distribution by using a one-dimensional image technique in conjunction with a fast gated linear array detector to achieve spatial and temporal resolution simultaneously.

The experimental arrangement for measuring the temporal evolution of the far-field intensity distribution (and hence divergence) for the CVL beam is shown in Fig. 1. A cylindrical lens ($f_1 = 300$ mm) focused the CVL beam to a line with a width that was proportional to the beam divergence. This line was imaged with a short-focal-length cylindrical lens ($f_2 = 25.4$ mm) to produce a magnified image of the line focus at a detector placed a distance $d = 1250$ mm.
from the second lens. The CVL beam was then attenuated before detection by reflecting off two Fresnel beam samplers and then passing through an absorbing neutral density filter. A fast gated linear diode array detector (Princeton Instruments IRY-512) was used to record the intensity distribution across the imaged line focus. This permitted a ∼5-ns (FWHM) time slice of the far-field intensity distribution to be recorded for single laser pulses. The gate pulse delay was scanned in 5-ns steps such that the divergence evolution could be measured for the whole pulse, where each time slice was captured from a separate pulse. The divergence of the CVL output at any time during the pulse was then calculated from the measured width $w$ of the line focus by

$$\theta = \frac{w f_2}{d f_1}.$$ 

The 512-element diode array employed in these experiments has a width of 12.6 mm; thus the divergence can be measured with a resolution of ∼2 μrad.

In practice, the far-field intensity distributions were recorded by using multishot averaging, rather than by using single time slices from single CVL pulses, in order to smooth out the effects of some amplitude fluctuations across the line focus. However, some beam pointing jitter associated with thermally induced refractive-index gradients in the air near the laser output window increased the measured divergence by ∼15 μrad (as determined by the comparison of single-shot and multishot averaged data).

A nominally 20-W CVL (active volume 25 mm diameter by 1 m long) operated at a pulse repetition frequency of 4 kHz was used as the source for the divergence measurements. The laser was fitted with a positive branch confocal unstable resonator of magnification $M = 26.5$, consisting of a curved high reflector ($R = 4$ m) and a meniscus lens output coupler with a 1-mm diameter reflecting spot ($R = 151$ mm). The divergence behavior of either the green or

![Fig. 1. Experimental arrangement for measuring the temporal evolution of divergence of the CVL output.](image)

![Fig. 2. Temporally resolved far-field intensity profiles of the green and the yellow outputs of the CVL. The multishot average divergence of each component of the green output is indicated (the divergence of the corresponding yellow component is essentially the same). Note that the absolute timing for the green and yellow time slices is the same with reference to the CVL excitation pulse.](image)

![Fig. 3. Pulse shapes for the different divergence components of the CVL output resolved by spatial filtering. Each component is labeled with its multishot average divergence.](image)
the yellow CVL output could be examined by selecting the appropriate wavelength by using dichroic beam splitters.

The evolution of the far-field intensity distribution for the CVL green and yellow outputs are shown in Fig. 2. Each time slice corresponds to an average of $4 \times 10^4$ gated pulses. Four components of the CVL green pulse can be resolved: the first is highly divergent amplified spontaneous emission (ASE), which has intensity below the detector background level; the second has a divergence of $\sim 500 \, \mu\text{rad}$ (FWHM); the third has a divergence of $55 \, \mu\text{rad}$ (FWHM); and the fourth has a divergence of $43 \, \mu\text{rad}$. These components occur sequentially, with the divergence undergoing rapid transitions between each phase. The yellow output follows exactly the same temporal characteristics as the green, except that the peak power occurs at a slightly later time during the pulse. Note that the green and the yellow time scales have the same absolute origin; however, the origin is set at an arbitrary value with respect to the CVL excitation pulse.

Pulse shapes for three components of the CVL beam can be resolved by spatial filtering, and are shown in Fig. 3. The fourth component cannot be separated from the third because they have similar divergences. There is little temporal overlap for the different components; however, the second and third components have both been captured in the third time slice of Fig. 2 because of the finite detector gate width.

The temporal evolution of divergence for a CVL that is fitted with an unstable resonator can be modeled by following the approach of Eggleston. In this approach the output spatial characteristics of a laser are determined from the propagation of spontaneous emission through the unfolded resonator-equivalent lens guide. All the laser output is assumed to arise from an initial short burst of ASE as this emission experiences the highest (initially unsaturated) gain. The initial burst of greatly amplified spontaneous emission can be seen as the first peak in the mirrorless ASE pulse shape of Fig. 4.

When the CVL is fitted with an unstable resonator [Fig. 5(a)] the initial ASE burst propagates on repeated round trips within the resonator, giving rise to a peak in the output pulse on each round trip. The first peak in the laser output pulse, therefore, consists of amplified spontaneous emission that has made, at most, two passes through the gain medium (reflecting just once off the high reflector). This output, which is called the two-pass output or, more generally, the ASE, has a divergence that is limited geometrically by the laser aspect ratio, as illustrated in Fig. 5(b). For an unstable resonator mirror with separation $d$ and laser tube radius $A$, the ASE full-angle divergence is, therefore, given by $2A/d$.

A very small fraction ($<0.2\%$) of the two-pass output reflects off the spot reflector output coupler to undergo two more passes through the gain medium before leaving the resonator as the four-pass output. As one complete round trip within the unstable resonator is equivalent to propagation through an expanding telescope of magnification $M$ (where $M$ is
Table 1. Comparison of Measured and Calculated Divergence Behavior for the CVL.

<table>
<thead>
<tr>
<th>Output</th>
<th>Calculated CVL Total Divergence (prad)</th>
<th>Experimental CVL Divergence Accounting Effects (prad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASE (two-pass)</td>
<td>14 mrad</td>
<td>Not measured</td>
</tr>
<tr>
<td>Four-pass</td>
<td>525 μrad</td>
<td>~500</td>
</tr>
<tr>
<td>Six-pass</td>
<td>40 μrad</td>
<td>55</td>
</tr>
<tr>
<td>Eight-pass</td>
<td>21 μrad</td>
<td>43</td>
</tr>
</tbody>
</table>

In conclusion, we have investigated a new technique by utilizing one-dimensional imaging and a fast gated linear array detection for measuring the temporal evolution of divergence in a CVL. Using this technique, we have clearly illustrated how the divergence of CVL output decreases in a stepwise fashion throughout the pulse, reaching diffraction-limited divergence within the gain duration. Calculations of the divergence behavior, based on an equivalent lens-guide model for the unstable resonator, are in good agreement with the experimental observations.

References