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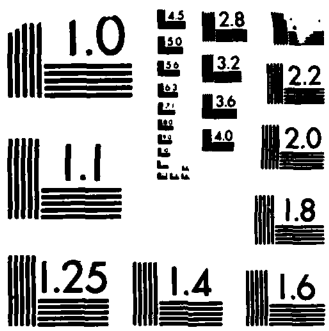


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REPORT SD-TR-83-99

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AD A137983

# Temporal Measurement of Spectrally Resolved Output of Multiline HF Lasers

J. M. BERNARD, D. H. ROSS, J. G. COFFER,
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31 December 1983

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This report has been reviewed by the Public Affairs Office (PAS) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

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An indium-arsenide detector array installed at the focal plane of a grating spectrometer provides the time history of the intensity of each output line of multiline HF chemical lasers. The construction and calibration of this instrument are discussed, and representative data presented. Line competition measurements are shown for a 200-W supersonic-diffusion-type HF laser; individual line outputs fluctuate more than total multiline → cont

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output. The spectral effects of forward/reverse-wave competition on an unstable ring resonator operating at 350 W are detailed. Simultaneous single-line gain measurements on a multiline HF medium are demonstrated. Other applications of this useful instrument are discussed.

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SUBJECT: Temporal Measurement of Spectrally Resolved Output of Multiline HF Lasers, by J.M. Bernard, D.H. Ross, J.G. Coffer, R.A. Chodzko, and S.B. Mason (SD-TR-83-99), TR-0084(4930-01)-4, dated 31 December 1984

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1. Page 11: The third paragraph on this page should read as follows:

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2. Pages 18 and 19: The figure on page 19 belongs with the caption on page 18. The figure on page 18 belongs with the caption on page 19.

## PREFACE

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## TABLES

# I. INTRODUCTION

The outputs of HF and DF chemical lasers are multiline because of the chemical production of the excited molecules in many vibration-rotation states.[1] An important diagnostic of the output beam of these devices is the individual temporal history of the intensity contribution from each lasing line. Of great interest is the competition between lines, as well as the spectral effects of competition between modes of the laser resonator. We have developed an instrument to monitor the intensity of 23 separate lines, plus the sum of the intensities of an unresolvable pair, on the output of HF lasers. This instrument consists of a grating spectrometer equipped with a 24-element detector array, and includes a 18-channel preamplifier array that provides signals whose voltage is proporti nal to the intensity of the corresponding spectral line.

The construction and calibration of the array spectrometer are presented below with several examples of its use. Line competition effects were measured on a typical supersonic diffusion CW HF laser. Simultaneous measurements of the gain of several lines in an HF amplifier using a multiline probe laser beam are shown, along with the measurement of the single-line fringe patterns produced by a multiline Mach-Zehnder interferometer. Other uses of the array spectrometer are discussed.

## II. SPECTROMETER DESCRIPTION

An Optical Engineering, Inc. HF laser spectrum analyzer[2] is used to spectrally resolve the multiline laser output. This instrument is a 0.75-m, f/35 grating spectrometer that disperses the 2.5-to-3.3-μm HF laser wavelength range over a 20-cm distance at its focal plane. Designed for visual determination of the spectral content of an HF beam, this unit is supplied with a fluorescent thermal image screen at the focal plane. Floodlit with near-ultraviolet light, this screen ceases its fluorescence when illuminated with approximately 4 $mW/mm^2$ of infrared radiation. The presence of a particular line in the HF laser output is thus indicated by a dark image of the spectrometer entrance slit at the focal position corresponding to that line.

Our array spectrometer is made by substituting a 24-element, room temperature indium-arsenide detector array manufactured by Judson Infrared, Inc.,[3] for the thermal image screen on the Optics Engineering device. The positions of the individual detector elements are based on measurements of the wavelength scale supplied with the spectrometer. Detectors were placed at the focal positions of each of the lines $P_1$ (3 through 15) and $P_2$ (3 through 14), with the exception that $P_1(11)$ and $P_2(8)$ are unresolvable by the instrument, so that one detector measures the sum of the intensities of these two lines. Figure 1 shows the spectrometer optical path and detector array location, and Table 1 gives the line identification, wavelength, and distance from the first element for each detector.

CW HF lasers whose output is outside the spectral range covered by our instrument are rare.[4] HF laser output with $J > 15$ has only been observed in pulsed devices. CW R-branch lasing has not been observed. CW operation on HF with $J < 3$ or $J > 11$ requires special conditioning of the gain medium, which results in a loss of total output power.

Closely coupled to the detector array is an 18-channel preamplifier array of current-to-voltage converters, a typical channel of which is shown schematically in Fig. 2. The LF 356 operational amplifier was selected for minimum offset in order to facilitate the tape recording of small signals. Small lead lengths and close-coupling of components resulted in a linear response from 0 Hz to the 3-dB roll-off point of 8 MHz. These signals were typically recorded with a wideband tape recorder, an analog-to-digital data logger, or an oscilloscope.

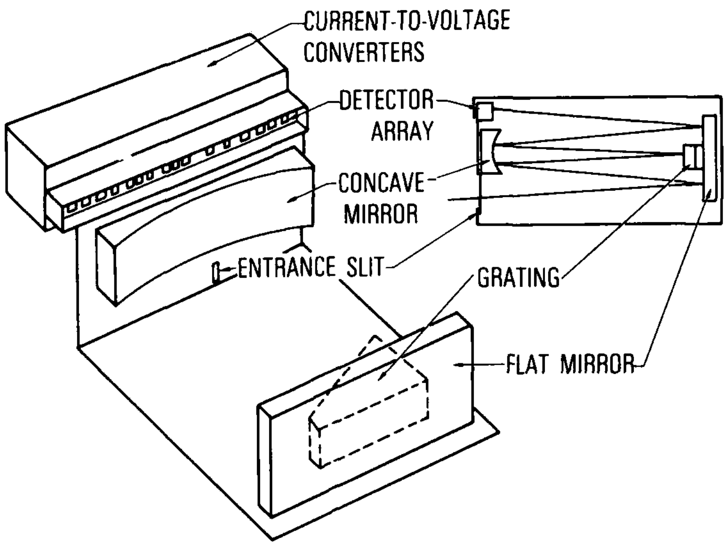


Fig. 1. Spectrometer Optical Layout

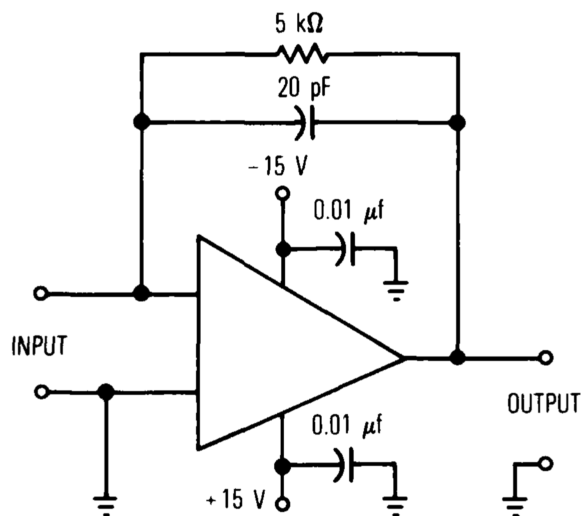


Fig. 2. Schematic of Current-to-Voltage Converter

Table 1. Wavelength, Line, and Position Identifications for the 24-Element Detector Array

| Detector | λ, μm | Line | Distance from Detector No. 1, mm |
|---|---|---|---|
| 1 | 2.60837 | $P_1(3)$ | 0.0 |
| 2 | 2.63966 | $P_1(4)$ | 7.77 |
| 3 | 2.67265 | $P_1(5)$ | 15.88 |
| 4 | 2.70743 | $P_1(6)$ | 24.59 |
| 5 | 2.72747 | $P_2(3)$ | 29.56 |
| 6 | 2.74404 | $P_1(7)$ | 33.70 |
| 7 | 2.76043 | $P_2(4)$ | 37.85 |
| 8 | 2.78256 | $P_1(8)$ | 43.46 |
| 9 | 2.79522 | $P_2(5)$ | 46.63 |
| 10 | 2.82306 | $P_1(9)$ | 53.62 |
| 11 | 2.83189 | $P_2(6)$ | 55.85 |
| 12 | 2.86563 | $P_1(10)$ | 64.41 |
| 13 | 2.87052 | $P_2(7)$ | 65.66 |
| 14 | 2.91075 | $P_1(11) + P_2(8)$ | 76.10 |
| 15 | 2.95395 | $P_2(9)$ | 87.20 |
| 16 | 2.95727 | $P_1(12)$ | 88.06 |
| 17 | 2.99892 | $P_2(10)$ | 98.73 |
| 18 | 3.00654 | $P_1(13)$ | 100.74 |
| 19 | 3.04618 | $P_2(11)$ | 111.23 |
| 20 | 3.05826 | $P_1(14)$ | 114.40 |
| 21 | 3.09583 | $P_2(12)$ | 124.36 |
| 22 | 3.11252 | $P_1(15)$ | 128.73 |
| 23 | 3.14799 | $P_2(13)$ | 138.46 |
| 24 | 3.20275 | $P_2(14)$ | 153.19 |

## III. CALIBRATION

The relationship between the voltage output of a given preamplifier and the corresponding single-line intensity of the beam entering the spectrometer slit is required for the quantitative use of this device. By the procedure described below, we have estimated the relative sensitivity of each line's optical and electronic circuits to within ± 5%.

First, the relative sensitivity of each detector-preamplifier pair to the others was measured by floodlighting each detector element with light of the same intensity derived from a filtered blackbody, and recording the voltage out of the corresponding preamplifier channel. The filter bandpass wavelengths were between 2.5 and 3.4 μm. The result agreed with Judson's measurement of relative detector sensitivity to within 2%. The relative optical efficiency of the spectrometer is different for each line (and each polarization) as a result of the grating. The grating efficiency was estimated from a typical curve supplied by Bausch and Lomb for the grating used by Optics Engineering in their spectrometers. The product of relative detector-preamplifier sensitivity and relative grating efficiency was used as the relative calibration constant for that particular line (and polarization). The results of these measurements for our spectrometer (and vertical polarization) are summarized in Table 2.

Absolute calibration of this instrument, or relative calibration within 1%, would require a more detailed, spectrophotometric procedure. A known intensity of infrared radiation from a monochromator would have to be transmitted through the spectrometer entrance slit and be completely absorbed by the appropriate wavelengths of HF laser output lines, and its bandwidth would have to be narrow enough to ensure that no radiation spilled over the detector edge.

Note that an HF probe laser does not output enough of the lines covered by this instrument to accomplish a complete calibration.

Table 2. Spectrometer Calibration for Vertical Polarization

| Line | Preamplifier Channel Number | Detector Number | Relative Detector Efficiency | Relative Grating Efficiency | Relative Overall Efficiency |
|---|---|---|---|---|---|
| $P_1(5)$ | 1 | 3 | 0.650 | 0.536 | 0.348 |
| $P_1(6)$ | 2 | 4 | 0.889 | 0.590 | 0.524 |
| $P_1(7)$ | 3 | 6 | 0.798 | 0.641 | 0.512 |
| $P_2(4)$ | 4 | 7 | 0.821 | 0.663 | 0.544 |
| $P_1(8)$ | 5 | 8 | 0.897 | 0.692 | 0.621 |
| $P_2(5)$ | 6 | 9 | 0.774 | 0.722 | 0.559 |
| $P_1(9)$ | 7 | 10 | 0.916 | 0.806 | 0.451 |
| $P_2(6)$ | 8 | 11 | 0.804 | 0.821 | 0.660 |
| $P_1(10)$ | 9 | 12 | 0.871 | 0.876 | 0.763 |
| $P_2(7)$ | 10 | 13 | 0.592 | 0.882 | 0.522 |
| $P_1(11) + P_2(8)$ | 11 | 14 | 0.833 | 0.923 | 0.769 |
| $P_2(9)$ | 12 | 15 | 0.874 | 0.955 | 0.835 |
| $P_1(12)$ | 13 | 16 | 0.744 | 0.957 | 0.712 |
| $P_2(10)$ | 14 | 17 | 0.734 | 0.989 | 0.726 |
| $P_1(13)$ | 15 | 18 | 0.979 | 0.988 | 0.967 |
| $P_2(11)$ | 16 | 19 | 1.000 | 0.973 | 0.973 |
| $P_2(12)$ | 17 | 21 | 0.752 | 0.955 | 0.718 |
| $P_2(13)$ | 18 | 23 | 0.976 | 0.902 | 0.880 |

## IV. LINE-COMPETITION MEASUREMENTS

The first use of this instrument was to monitor the output of a CW supersonic-diffusion-type HF laser that had a confocal unstable resonator. A portion of the laser output was focused onto the entrance slit of the spectrometer. Typical analog tape recordings of the time histories of several lines are shown in Fig. 3. During the time shown in this figure, fluctuations in the total integrated laser-power output (nominally 200 W) were much smaller than those on individual lines. Apparently, laser oscillation on one spectral line competes for the same chemical energy that can pump other lines. Of the lines monitored in Fig. 3, $P_2$(5 and 6) are the strongest, and are positively correlated. Note that $P_1(10)$ seems to be anticorrelated with $P_2$(5 and 6). If all possible output lines of a given HF laser are monitored, the array spectrometer can elucidate the dynamics of this line competition.

The time scale of this competition can be assessed by power spectral analysis of the signals shown in Fig. 3. The results shown in Fig. 4 for $P_1(9)$ and $P_2(5)$ are typical of all of the laser output lines. These spectra, measured with a Hewlett-Packard real-time spectrum analyzer, are shown for each line on two different frequency scales. They show that essentially all of the fluctuations above the level of electronic noise occur at frequencies below a few hundred Hz. These frequencies are much lower than one would expect to be caused by optical effects (whose time scale, typically tens of nanoseconds, is $2L/c$, where c is the speed of light and L is the laser cavity length) or supersonic flow fluctuations (whose time scale, typically microseconds, is $\ell/v$, where v is the flow velocity and $\ell$ is the width of the laser cavity at the gain region location). Fluctuations at these low frequencies are probably caused by mechanical vibrations, thermal drift of the laser-cavity support structure, or perturbations in the flow upstream of the supersonic nozzles. These results are similar to those we obtained on a higher power (10 kW nominal) supersonic device.

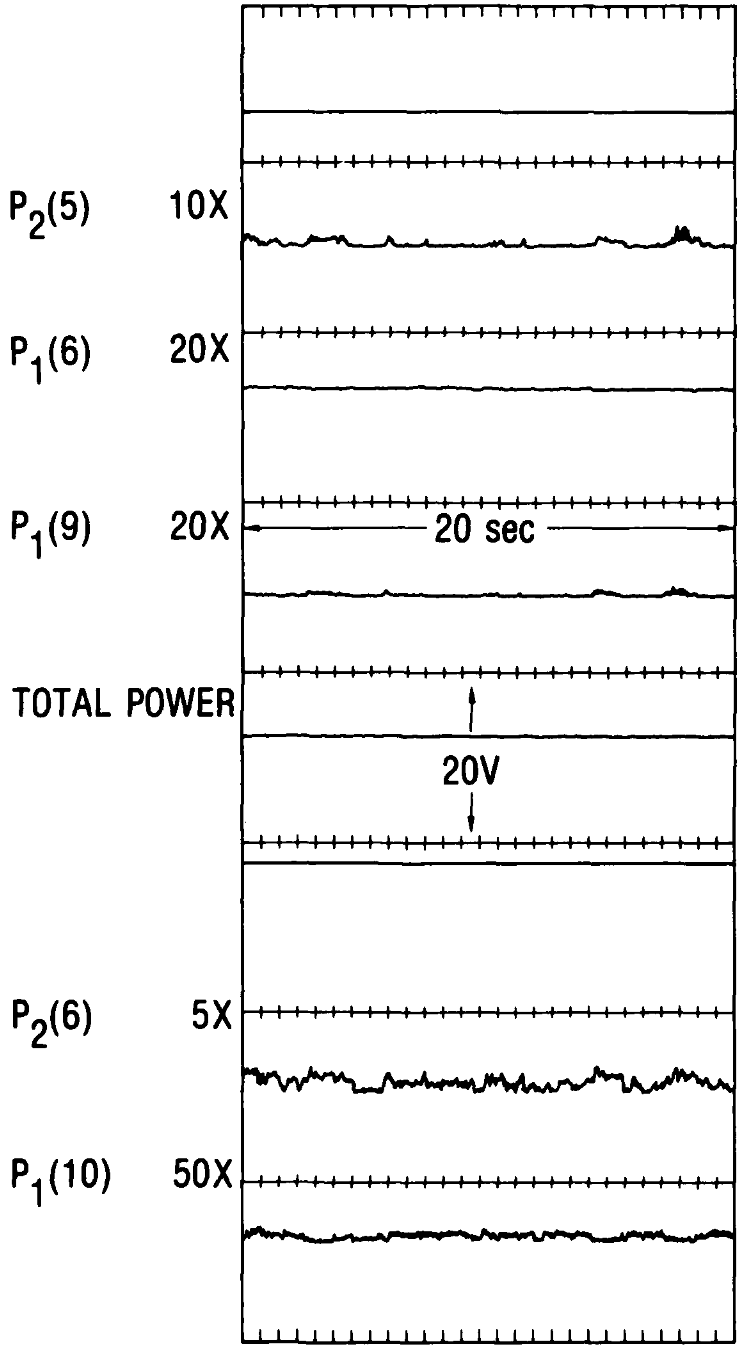


**Fig. 3. Typical Time History of a 200-W CW HF Laser**

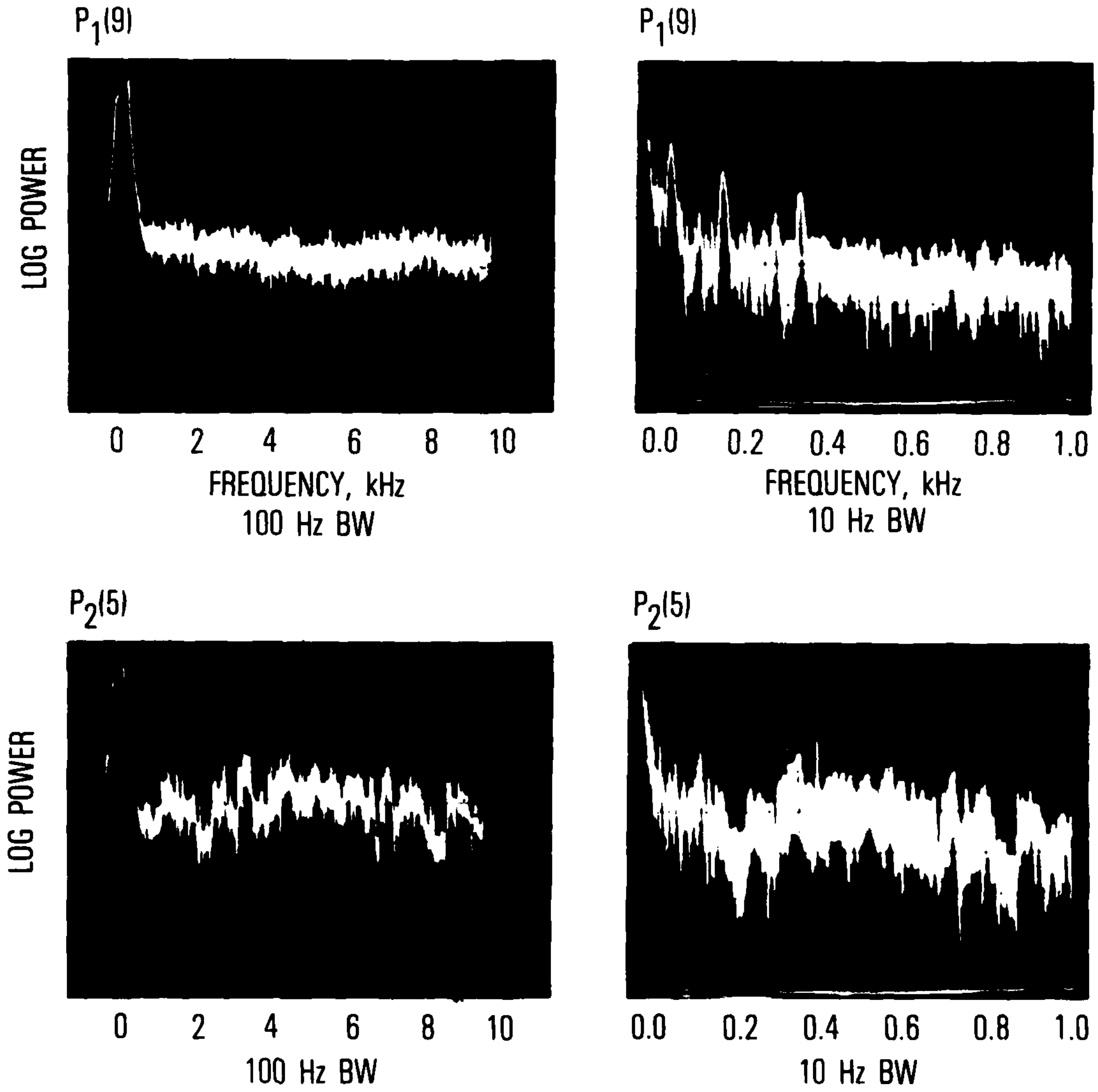


Fig. 4. Power Spectral Analysis of Two of the Signals Shown in Fig. 3. The scan rate was 5 sec/division and the measurement bandwidth is indicated.

We have recently used two array spectrometers to monitor both the forward- and reverse-wave outputs of an unstable ring resonator on the same supersonic-diffusion gain medium used in the first tests. Figure 5 shows a typical result for $P_1(4)$, $P_1(6)$, $P_2(4)$ and $P_2(6)$; this figure suggests that the forward and reverse waves compete independently for the gain on any particular line. Here, $P_1(4)$, $P_1(6)$, and $P_2(6)$ are preferred in the forward-wave output, while $P_2(4)$ is favored in the reverse direction. Data such as these are required to unravel the effects of forward/reverse-wave competition from the effects of line competition on the ability to suppress the reverse wave. These measurements have shown that both forward/reverse-wave competition and line competition occur independently in the output of the multiline ring laser.

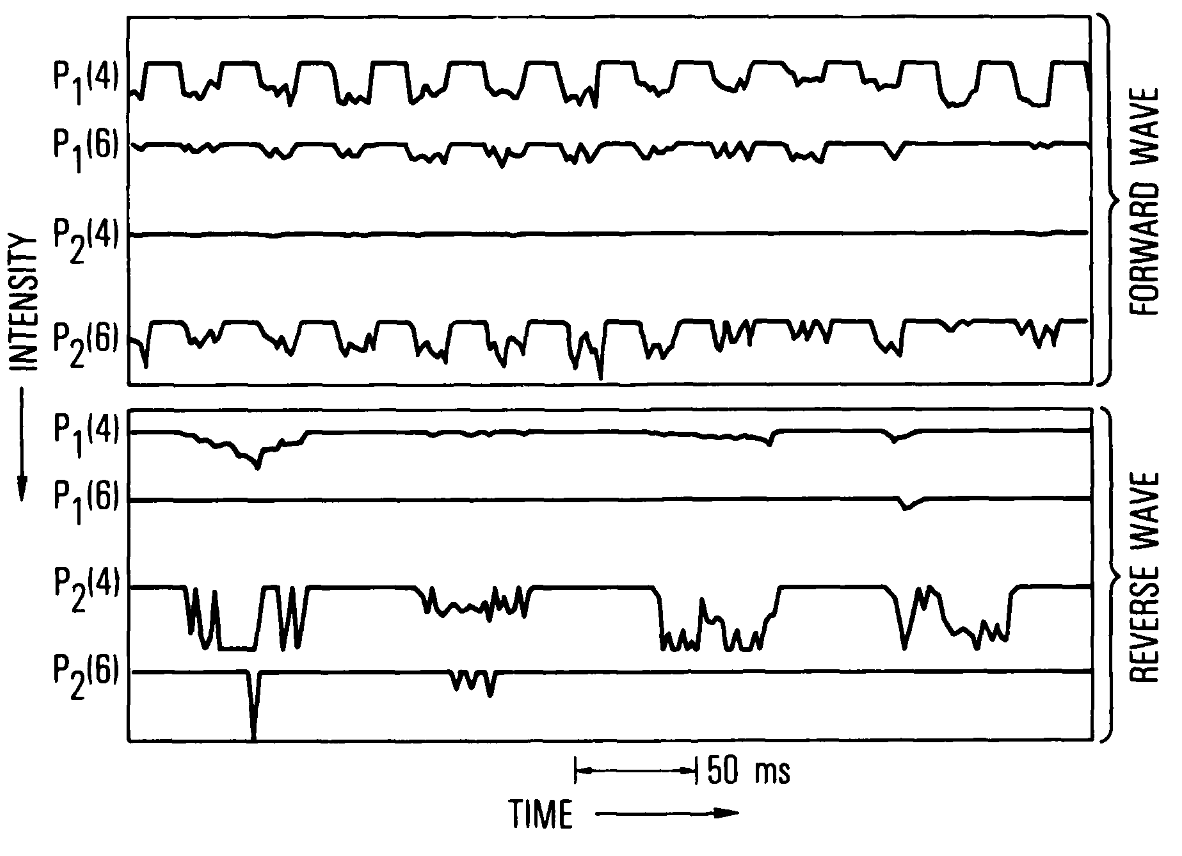


Fig. 5. Typical Chopped Time Histories of the Forward and Reverse Outputs on Lines $P_1(4)$, $P_1(6)$, $P_2(4)$, and $P_2(6)$ of an HF Ring Laser

## V. GAIN MEASUREMENTS

A novel use of our spectrometer was to measure simultaneously the gain of several lines on the supersonic-diffusion HF gain medium. Details of the experiment and data reduction can be found in Ref. 5. A low-power multiline CW HF "probe" laser beam was split and recombined after it traversed the same optical path length as is found in a Mach-Zehnder interferometer. Inserting the gain medium into one arm of the interferometer reduces the visibility of the interferometer output fringes while increasing their intensity. The output fringe pattern was focused onto the spectrometer slit and the single-line fringe visibilities were measured by varying the path length in one arm of the interferometer so that both minimum and maximum fringe intensities could be recorded. Visibility is defined as

$$(I_{max} - I_{min})/(I_{max} + I_{min}) \tag{1}$$

where $I_{max}$ is the intensity of the bright *fringe and* $I_{min}$ is the intensity of the null fringe. Without gain, the intensities in both arms of the interferometer were equal (denoted by $I_0$). In this case, $I_{max} = 2I_0$ and $I_{min} = 0$. A typical recording taken without the gain generator operating is shown in Fig. 6. The optical path length (OPL) of one arm of the interferometer was continuously varied over approximately 200 wavelengths during this recording, which resulted in many fringes being scanned past the spectrometer slit. Thus each detector in the spectrometer sees many samples of $I_{max}$ and $I_{min}$ for its corresponding line. In Fig. 6 it can be seen that the intensity of the null fringe is zero, which implies a fringe visibility of 1.

When the gain generator is turned on, the intensity in the arm with gain becomes $I_0 + I_0e^G$, where G is the single-pass gain averaged over the 3-mm-diameter Mach-Zehnder beam. The intensity in the other arm is still $I_0$. In this case[5]

$$I_{max} = \frac{1}{2} I_0(1 + e^{G/2})^2 \tag{2}$$

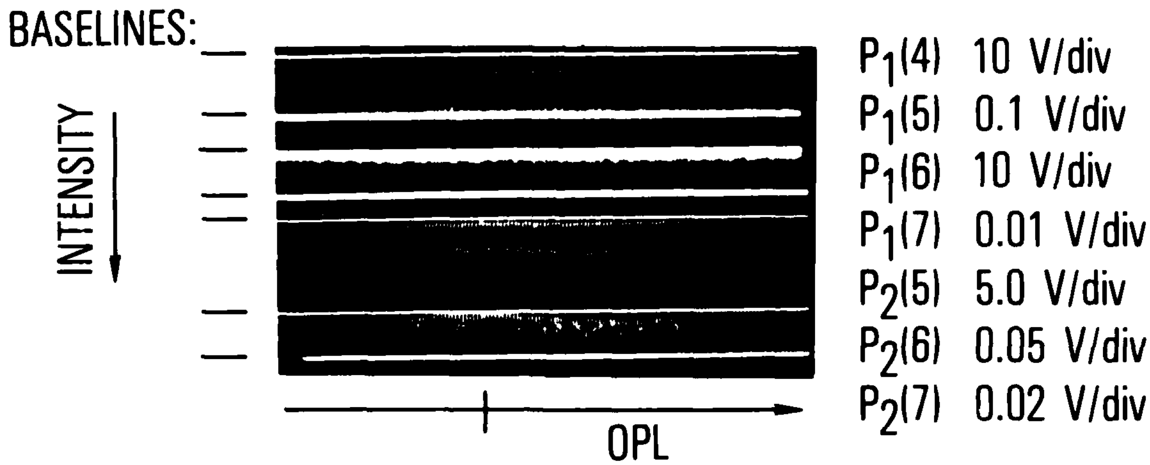


Fig. 6. Single-Line Fringe Scans of a Mach-Zehnder Interferometer without Gain in Either Arm.

and

$$I_{min} = \frac{1}{2} I_0(1 - e^{G/2})^2 \tag{3}$$

Thus each single-line gain can be obtained from the corresponding relative intensities of $I_{max}$ and $I_{min}$ by

$$G = 2\ell n[(\sqrt{I_{max}} - \sqrt{I_{min}})/(\sqrt{I_{max}} + \sqrt{I_{min}})] \tag{4}$$

A typical scan with the gain generator on is shown in Fig. 7. The gain calculated from Eq. (4) for the $P_1(4)$, $P_2(5)$, and $P_2(6)$ traces shown in Fig. 7 was 0.11, 0.13, and 0.11 $cm^{-1}$, respectively. These data are comparable to those obtained earlier by using a tunable single-line probe laser.[1] They demonstrate the viability of this more efficient method of obtaining many of the single-line gains simultaneously in a multiline device.

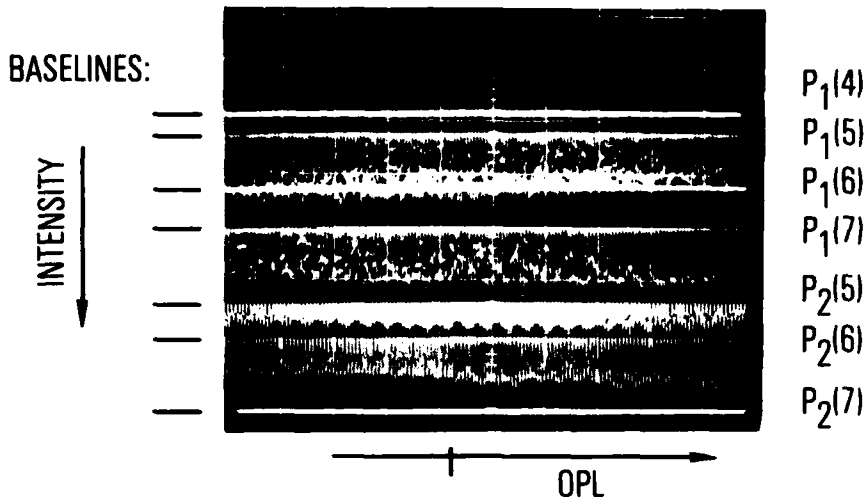


Fig. 7. Single-Line Fringe Scans of a Mach-Zehnder Interferometer with Gain in One Arm.

## VI. CONCLUSIONS

The array spectrometer has been shown to be a valuab e diagnostic tool for HF lasers. It has provided the evidence that fluctuations on individual lines occur at frequencies less than 1 kHz on several multiline devices. This suggests that mechanical, thermal, and fluid-mechanical perturbations are responsible for line competition. Multiline gain measurements have also been shown to be facilitated by this spectrometer. The information provided by this device is indispensable for the complete characterization of multiline HF lasers.

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2. Optical Engineering, Inc. P. O. Box 696, Santa Rosa, CA 95402. (707) 528-1060.

3. Judson Infrared, Inc., 565 Virginia Drive, Ft. Washington, PA 19034. (215) 643-7000.

4. M. A. Kwok, The Aerospace Corporation, private communication. See also Ref. 1.

5. J. G. Coffer, J. M. Bernard, R. A. Chodzko, E. B. Turner, and R. W. F. Gross, "Experiments with Active Phase Matching of Parallel-Amplified Multiline HF Laser Beams by a Phase-Locked Mach-Zehnder Interferometer," Appl. Opt. 22, 142-148 (1983).




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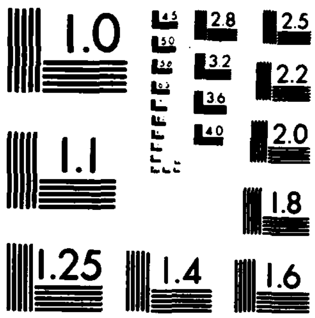


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