Competition of Longitudinal and Transverse Modes in a CW HF Chemical Laser

C. P. WANG and R. L. VARWIG
Aerophysics Laboratory
Laboratory Operations
The Aerospace Corporation
El Segundo, Calif. 90245

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Los Angeles, Calif. 90009

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J. C. Garcia, Lt, USAF
Project Officer

Joseph J. Cox, Jr., Lt Col, USAF
Chief, Advanced Technology Division

FOR THE COMMANDER

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Longitudinal and transverse mode competition in stable and unstable resonators of a single vJ-transition cw HF chemical laser were investigated. Single longitudinal mode operation in a long (>2 m) resonator was achieved, and asymmetric mode spectra were observed. These observations indicate that there is strong mode competition and a frequency-dependent loss mechanism caused by a limiting aperture and the effect of saturation of anomalous dispersion. From these observations, it is possible to measure the effect of saturation on anomalous dispersion in a high-power chemical laser.

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PREFACE

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I. INTRODUCTION

Single longitudinal-mode and lowest-order transverse-mode operation may be necessary to obtain good beam quality or to recombine multiple laser beams coherently.[1,2] However, for high-power chemical and other gas lasers, the mode volumes are rather large. Hence, several longitudinal modes and higher-order transverse modes may occur. When two or more longitudinal and transverse modes oscillate in a laser resonator, mode competition, mode pulling, and related phenomena may occur. These phenomena have been described by Lamb's semiclassic theory[3] and by various numerical computations.[4-7] One or more of these phenomena have also been observed for He-Ne[5,8] and other lasers.[9-14]

Reported here is an experimental investigation of longitudinal and transverse mode competition in a single vJ-transition cw HF chemical laser. Beam profiles, beat spectra, and power spectra associated with longitudinal modes in stable and unstable resonators were investigated and are discussed.

II. DISCUSSION

A comprehensive theory for inhomogeneous broadening effects in a steady-state laser oscillator was developed by Lamb.[3] However, for a cw HF chemical laser, the gain medium is complicated by the nature of the chemical reaction, the rotational-vibration transition, medium nonuniformity, and mixed inhomogeneous-homogeneous behavior.

In the study of inhomogeneous broadening effects[15] on the performance of cw chemical lasers, it was found that laser performance is dependent on the homogeneous linewidth, the Doppler linewidth, the molecular collision rate, the molecular deactivation rate, and the residence time of the molecules remaining inside the gain volume. Because of all of these complexities, only qualitative descriptions of the phenomena are possible.

For the cw HF chemical laser studied here, the ratio of the collision-broadened linewidth to the Doppler linewidth was much less than one. Hence, the gain medium can be considered as nearly inhomogeneously broadened, with hole burning and anomalous dispersion. The saturation intensity of a chemical laser is inversely proportionate to the deactivation time or residence time of the excited molecules. For the HF molecule discussed here, the residence time is of the order of 20 μsec; hence, the saturation intensity is of the order of 100 W/cm^2. In this study, the cavity intensity was of the order of 500 W/cm^2, which is larger than the saturation intensity, so that the effects of saturation could be studied.

The longitudinal mode spacing is C/2L, where C is the speed of light, and L is the resonator length. For the resonator considered here, $L \geq 2$ m, $C/2L \leq 75$ MHz, and the gain linewidth is of the order of 300 MHz. As shown in Fig. 1, for $L \simeq 2$ m and a gain linewidth of 300 MHz, many longitudinal and transverse modes may oscillate. Hence, mode competition and anomalous dispersion influence the output modes.

The number of transverse modes that can oscillate is determined by the Fresnel number of the resonator and the characteristics of the gain medium. For a stable resonator, where the mode volume increases with mode order, gain saturation and mode-competition effects tend to encourage oscillation in those higher-order transverse modes that have a loss that is less than the gain of the medium. These are in addition to lower-order mode oscillation. Thus, it is often found that more than one transverse mode oscillates, and a limiting aperture must be used if lowest-order transverse-mode operation is desired.

Mode competition in an unstable resonator has been studied very little. For a negative branch unstable resonator, the mode competition is similar to that in a stable resonator, except that the output coupling is usually higher, so that fewer longitudinal modes can oscillate.

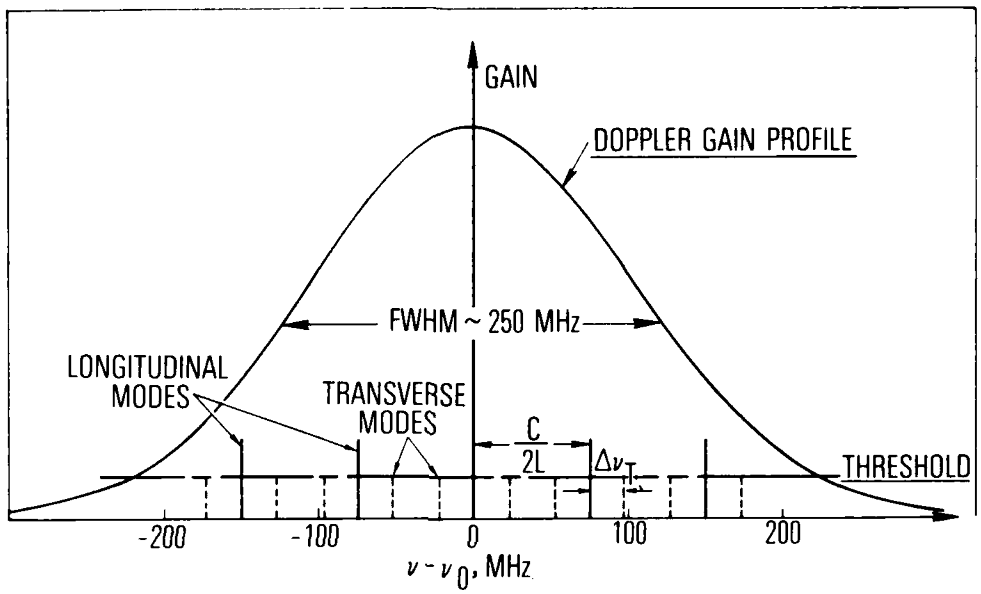

Fig. 1. Typical gain profile and mode spacings of longitudinal and transverse modes. Gain bandwidth is 250 MHz (FWHM). Resonator consists of flat and 3-m radius-of-curvature reflectors separated by distance of 200 cm

III. EXPERIMENTAL RESULTS

Experiments were carried out with a cw HF chemical laser similar to that described in Ref. 17. Briefly, F atoms were generated by an electric discharge in a gas mixture of He, O_2, and SF_6, and then mixed with H_2, which was injected just upstream of a transverse optical cavity. Typical flow rates were 0.11 g/sec He, 0.31 g/sec O_2, 1.75 g/sec SF_6, and 0.098 g/sec H_2. The gain medium was 30 cm long and about 3 mm high, with a small signal gain of 0.06 cm^{-1}. With a stable resonator with 20% output coupling, typical single-line output power was 3 W at $P_2(7)$ and 15 W at multiple-line output. The $P_2(7)$ line with 3-W output power was chosen for all the experiments reported here.

The optical resonator consists of a flat 80% efficiency grating for single-line operation and output coupling and a curved total reflector mirror. Mirror curvatures R_1 varied from 1 to 10 m. Cavity length L was also varied from 0.5 to 2 m. That is, $g_1 = 1 - L/R_1$ varied from -1 to +1 and $g_2 = 1 - L/R_2 = 1$, which applies for both stable and unstable resonators. A plot of stable resonator spot size versus $g_1 = 1 - L/R_1$ is shown in Fig. 2, where $g_2 = 1 - L/R_2$ was kept constant. R_1 and R_2 are the radii-of-curvature of reflectors 1 and 2, respectively. Also plotted in Fig. 2 is the magnification m of an unstable resonator versus g_1. More high-order transverse modes tend to oscillate when g_1 approaches 0, from either side of $g_1 = 0$ in Fig. 2, which corresponds to a larger spot size or greater magnification.

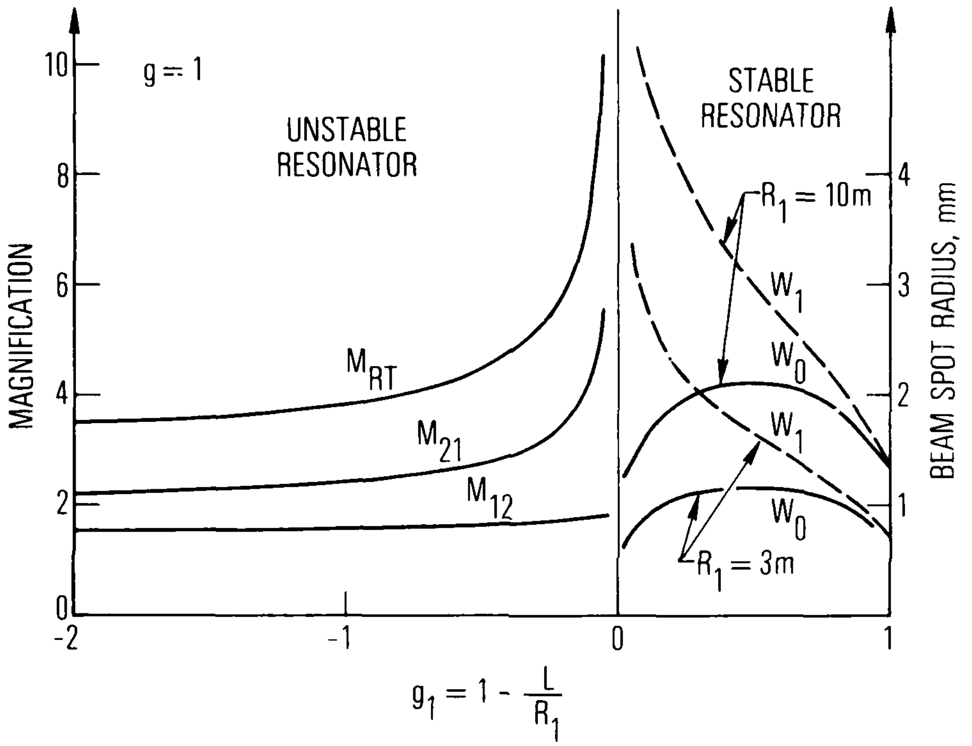

Fig. 2. Magnification of unstable resonators and spot sizes of stable resonators vs g_1 for $g_2 = 1$. M_{RT} is round-trip magnification, M_{21} and M_{12} are single trip magnification from mirror 2 to 1 and mirror 1 to 2, respectively, and W_0 and W_1 are spot radius at waist and at curved reflector, respectively.

For a free-running laser, it was observed that the longitudinal modes were not temporally constant in amplitude or frequency, although the total output power remained constant. The variation in amplitude and frequency was due to drift of the laser of the order of a few tens of megahertz, which resulted from such phenomena as acoustic vibration and thermal drift. This frequency drift also caused strong mode competition, which was a function of the frequencies and the longitudinal mode spacings.

A servo loop and a stable reference cavity were used to stabilize the laser frequency to less than 1 MHz frequency drift in order to reduce the temporal fluctuations. As a result, random mode competition and temporal fluctuations were reduced considerably. Since the laser frequency was locked to the reference cavity, the laser frequency easily could be changed by changing the reference cavity frequency.

The experimental setup is shown in Fig. 3. Part of the laser output was sampled and fed to a scanning interferometer, a reference cavity, and a rotating mirror. The rotating mirror scanned the laser beam across a small-area (0.1 mm^2) InAs detector (Judson J-12). For stable resonator, the transverse mode structure then could be determined from the measured beam profile.[10] When the mirror was not rotating, the beat signal from the longitudinal modes could be detected by the InAs detector and a spectrum analyzer (Hewlett-Packard 141T system). The difference between the measured beat frequency of longitudinal modes in a gain medium and the corresponding beat frequency in an empty resonator is a good measure of the anomalous dispersion or mode pulling effect.

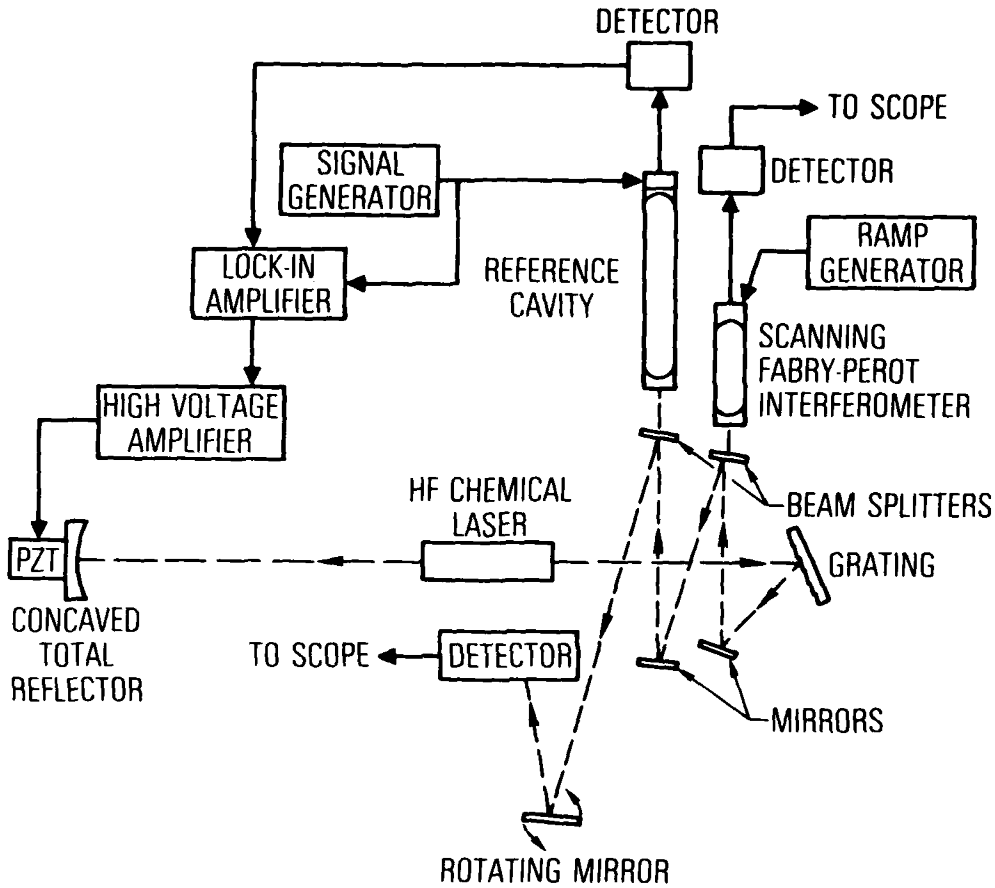

Fig. 3. Experimental setup. 50-cm confocal reference cavity used for laser frequency stabilization, 25-cm confocal Fabry-Perot interferometer to obtain the longitudinal mode power spectra, and rotating mirror and detector to obtain transverse beam profile

For direct observation of the longitudinal modes, a confocal scanning interferometer was employed. The mirror spacing was equal to the radius of curvature of each mirror, which was 25 cm. The free spectral range of the interferometer was therefore 300 MHz. This scanning interferometer produced information on mode distribution and mode competition. In addition, comparison of repeated scans yielded information on resonator stability and the time scale of dynamic processes. However, the interferometer scan linearity was not good enough to permit an accurate measurement of mode spacing by itself. Longitudinal-mode beat frequency was measured to calibrate the interferometer.

Although the longitudinal modes were not temporally constant in amplitude and frequency because of the strong mode competition instabilities and saturation, total power in the laser transition, monitored by a fast detector, was relatively constant compared to the observed individual mode amplitudes. That is, the power available in the transition appeared to be conserved in the presence of mode competition. Hence, it was possible to operate at one single longitudinal mode without loss of output power.

A stable resonator with a grating used as an output coupling and a 10-m radius-of-curvature mirror separated by 200.5 cm was used to demonstrate single longitudinal mode operation in a long resonator. The empty resonator mode spacing was $C/2L = 75$ MHz. The measured beat frequency, which corresponds to the mode spacing in a gain medium, was 71 MHz. The corresponding dispersion parameter $\beta = (75-71)/71 = 0.056$ was rather large, indicating a large anomalous dispersion effect.

For the free-running case, there were always many longitudinal modes. For the frequency-stabilized operation (Fig. 4), the laser frequency could be tuned such that three, two, or even a single longitudinal mode could be obtained. The scanning Fabry-Perot interferometer output at various laser frequencies is shown in Fig. 4. Trace 4 is the single longitudinal mode operation. At other frequencies, the laser can be operated at two or three longitudinal modes, while the output power remains the same, i.e., about 2.7 W.

The corresponding beam profile is shown in Fig. 5. The measured beam diameter is about 2.5 times the calculated TEM_{oo}-mode beam diameter. Hence, high-order transverse modes existed. Note that there was little change in the beam profile when the laser frequency and number of longitudinal modes were changed and the aperture size was kept constant.

The mode power spectra at various laser frequencies is shown in Fig. 6. The unstable resonator consisted of an 80% efficiency flat grating, and a 1-m radius-of-curvature total reflector separated from the grating by a distance of 200.5 cm. The output power was constant, about 3 W for all four traces in Fig. 6. From Trace 1, it is evident that it is possible to obtain single-longitudinal mode operation in an unstable resonator. When the laser frequency is changed, two or three longitudinal modes can oscillate (Traces 2, 3, and 4, Fig. 6).

A variable aperture was inserted in front of the curved total reflecting mirror to investigate competition between modes and the effect of anomalous dispersion. The mode power spectra at various apertures are

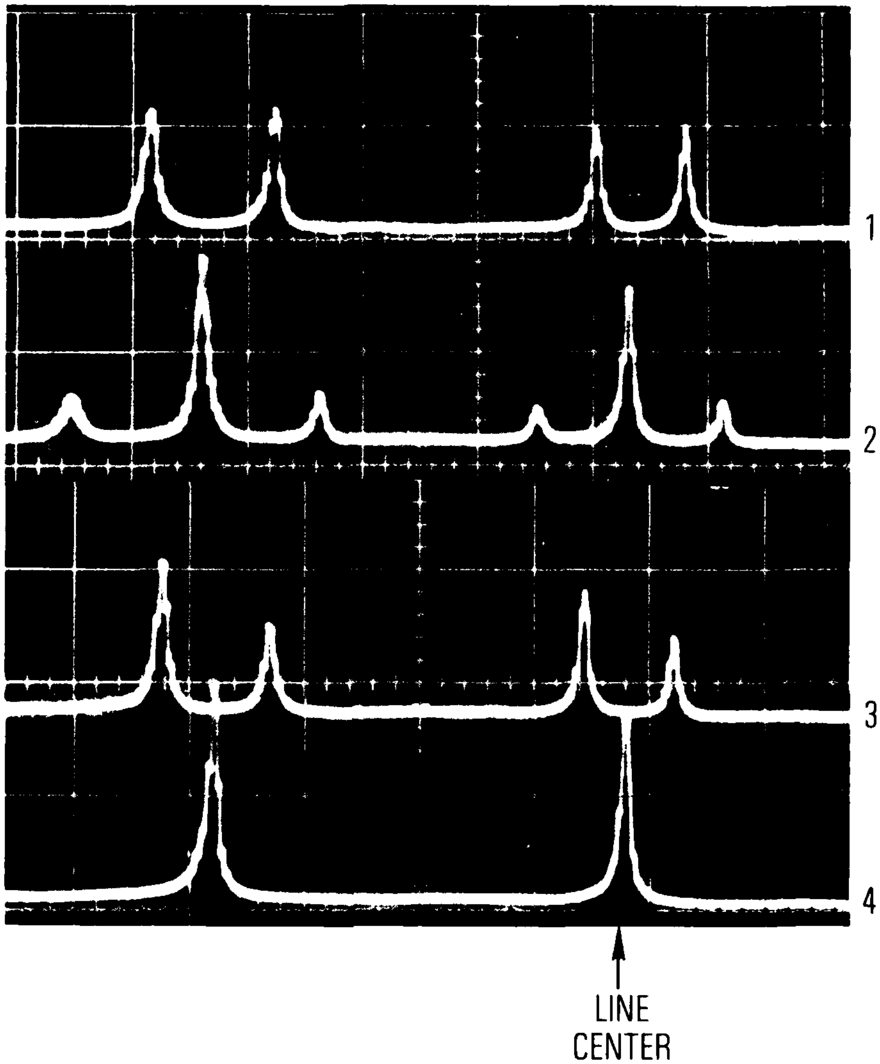

Fig. 4. Mode power spectra with multiple and single longitudinal modes in stable resonator shown. $R_1 = 10$ M, $R_2 = \infty$, and L = 200.5 cm at various laser frequencies. Vertical scale is 0.2 v/div, and horizontal scale 20 MHz/div

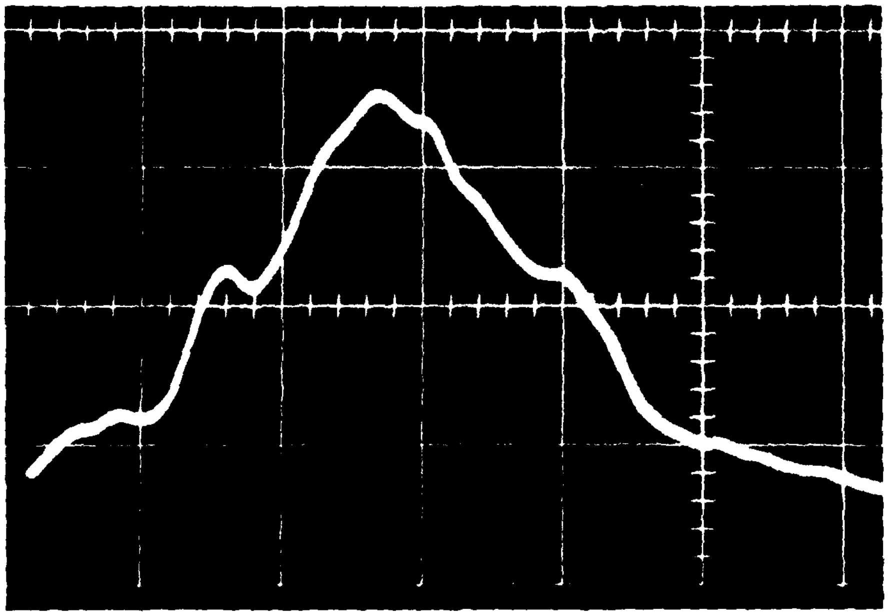

Fig. 5. Typical beam profile for high-order transverse modes. Vertical scale is 5 V/div, and horizontal scale 2.2 mm/div

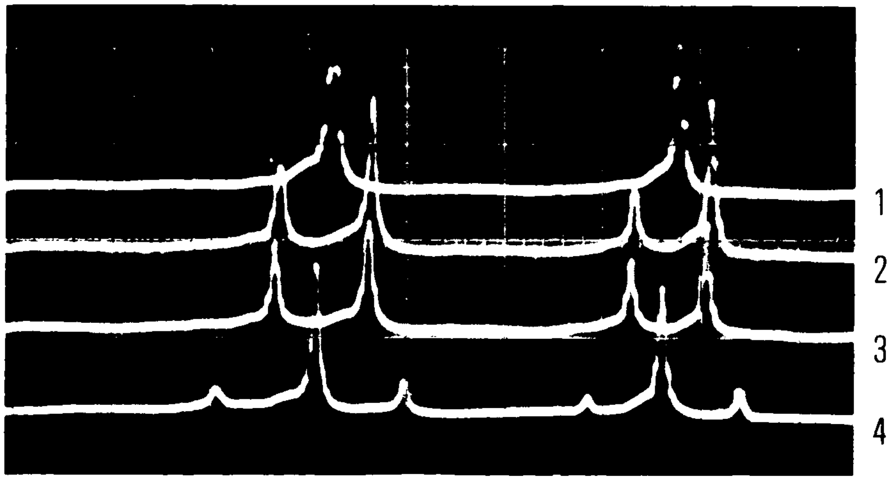

Fig. 6. Mode power spectra with multiple and single longitudinal mode in unstable resonator shown $R_1 = 1$ m, $R_2 = \infty$, and $L = 200$ cm at various laser frequencies. Vertical scale is 0.1 V/div and horizontal scale 17 MHz/div

shown in Fig. 7. When the aperture was reduced to 2 mm in diameter, a large loss was introduced into the cavity, and a single longitudinal mode oscillated near line center (Trace 5, Fig. 7). As the aperture gradually opened, and while the laser frequency was still locked to a fixed frequency, more longitudinal and transverse modes started to oscillate (Traces 3 and 4). When the aperture was fully opened (Trace 1), the dominant modes were transverse modes. This sequence of events has been repeated many times, with major oscillation always on the low frequency side of the gain medium line center. The mode asymmetry is caused by the frequency-dependent loss produced by an aperture in the resonator with anomalous dispersion and mode competition effects. Anomalous dispersion of the gain medium saturates as a function of the intensity of the radiation with which it is interacting. Since the laser intensity inside a resonator is a function of position in the transverse direction, the saturation transverse to the beam will vary accordingly, providing the gain medium with lens-like properties that focus at frequencies below the center frequency of the gain curve and defocus at those above it. This property of the medium produces variations in the loss at the aperture that are a function of the laser frequency. These effects produce the observed asymmetric modes. Similar asymmetric mode spectra also are reported in Ref. 8.

For an unstable resonator with $L = 200.5$ cm, $g_2 = 1$, and $g_1 = 1.05$, mode asymmetry also has been observed (Fig. 8). Here, more longitudinal modes were obtained with the aperture fully open (Traces 1 and 2, Fig. 8) and less longitudinal modes with the aperture partially closed (Traces 3 and 4, Fig. 8).

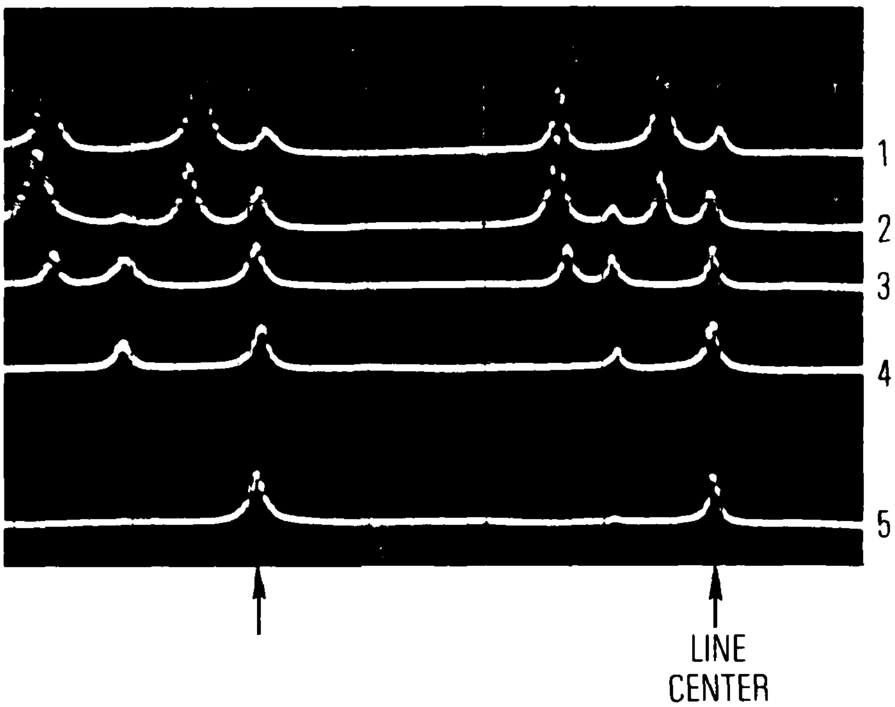

Fig. 7. Mode power spectra with competition and asymmetrics of the modes in a stable resonator shown. $R_1 = 3$ m, $R_2 = \infty$, and $L = 200.5$ cm at various aperture openings. Traces 1 and 5 were obtained when the aperture was fully opened and fully closed (2 mm in diameter), respectively. Traces 2, 3, and 4 were obtained when the aperture was at intermediate aperture openings. Arrows indicate line center. Vertical scale is 0.2 V/div and horizontal scale 18 MHz/div

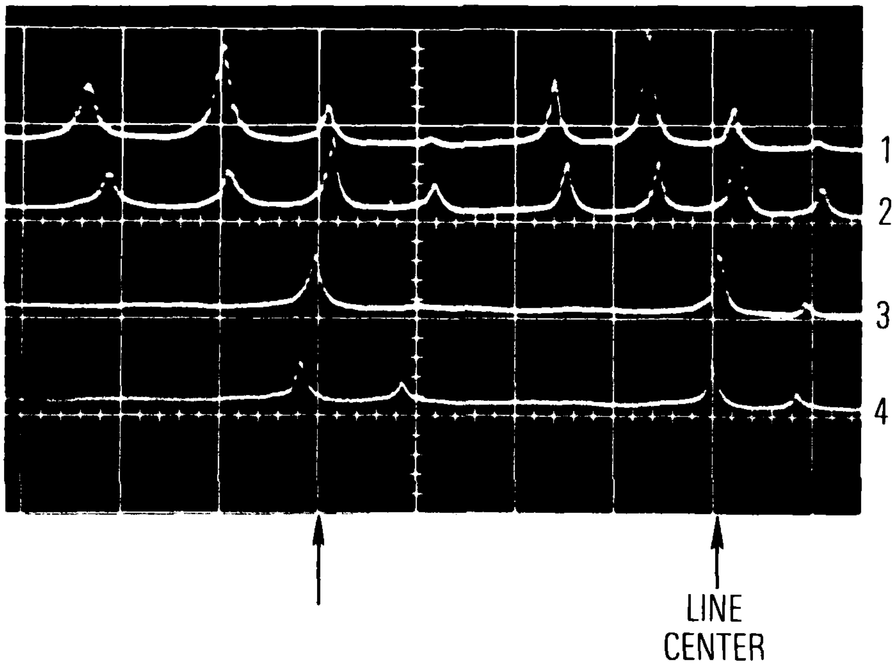

Fig. 8. Mode power spectra with competition and asymmetrics of the modes in an unstable resonator shown. $R_1 = 2$ m, $R_2 = \infty$, and L = 200.5 cm at various aperture openings. Trace 1 was obtained with aperture fully opened, Traces 2 and 3 with apertures partially opened, and Trace 4 with aperture fully closed (2 mm in diameter). Arrows indicate line center. Vertical scale is 0.1 V/div, and horizontal scale 17 MHz/div

IV. CONCLUSION

A single longitudinal-mode operation in both stable and unstable long resonators without any reduction in output power was demonstrated. This lack of power loss resulted from the strong mode competition and saturation effects. The asymmetric mode spectra indicated a frequency-dependent loss mechanism that was introduced by the limiting aperture and the effect of anomalous dispersion and saturation. Hence, anomalous dispersion and saturation play an important role in the performance of the cw HF chemical laser studied. These asymmetric mode spectra, however, can be used to measure the effect of saturation of anomalous dispersion in high-power HF chemical lasers. In addition, it was determined that laser frequency stabilization was needed to avoid excessive frequency and intensity fluctuation in this study of mode structure in chemical lasers.

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