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OPTICALLY PUMPED FAR INFRARED MOLECULAR LASERS. (U)

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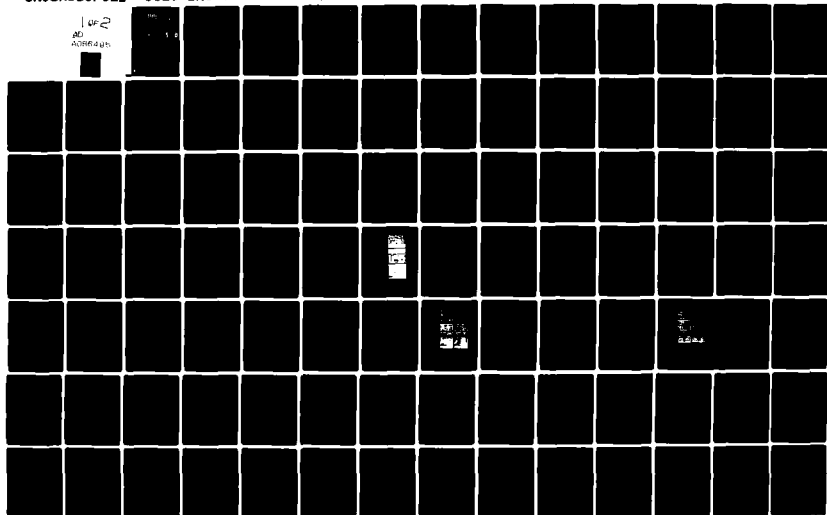
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OPTICALLY PUMPED FAR INFRARED MOLECULAR LASERS.

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Paul D. Coleman

Electro-Physics Laboratory
Electrical Engineering Department
University of Illinois
Urbana, Illinois 61801

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→ pumped molecular laser systems, and the study and analysis of nonlinear processes (Raman and hyper-Raman) that can occur in optically pumped systems.

The theoretical density matrix analysis of the gain spectra of nonlinear systems and the first detailed experimental measurements of these systems are presented. It is demonstrated that third and fifth order nonlinear processes can exceed first order laser processes.

An experimental study of the generation of a 22.653 GHz signal (the largest wavelength yet reported) in optically pumped NH_3 is described. The frequency tunability and single shot spectral characteristics of the signal were measured with precision.

A single laser pump in a four-level system can yield two laser signals, which in the linear case are not coupled together. However, with stronger pumping, nonlinear effects can couple the two laser signals with the result that the behavior of one laser signal is determined by the other and vice versa. The self-consistent analysis of this problem is described.

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OPTICALLY PUMPED FAR INFRARED MOLECULAR LASERS

I. INTRODUCTION - P. D. Coleman

The objective of grant AFOSR 76-2988 was the study of optically pumped far infrared molecular lasers, including nonlinear Raman and hyper-Raman processes, and associated technology.

The wavelength range from approximately 20 to 1,000 μm remains an unsolved coherent source problem with respect to prime, practical sources. There are no counterparts in the far infrared of devices like IMPATTs, magnetrons, laser diodes, gyrotrons, etc.

While in principle, megavolt electronics sources like free electron lasers, can reach into the far IR, and tubes like the carcinotron can be extended to around 1,000 GHz, the only proven, high spectral quality, modest technology, coherent source available to all researchers in the area, is the optically pumped molecular gas laser. Its one flaw is that it is not a prime source, but a frequency translator in that it is a laser pumped laser, subject to the Manley-Rowe restriction.

As a quantum system, molecules are ideal in that they possess all of the far infrared frequencies of interest. The problem is that it has not been discovered how to efficiently excite them from a DC energy source.

In spite of the Manley-Rowe limitations, the optically pumped molecular gas laser has done more by far than any other

device in opening the far IR region for development and practical application. It was the aim of this grant to contribute to this development.

II. SUMMARY OF ACCOMPLISHMENTS - P. D. Coleman

The research accomplishments of this grant were associated with four topics:

- 1) Far infrared integrated optics
- 2) Far infrared technology
- 3) New optically pumped systems
- 4) Nonlinear studies and analysis

One of the first achievements of the grant was the first demonstration of waveguide propagation in single crystal (α -SiO₂) quartz waveguide in the far IR ($\lambda=496.1\mu\text{m}$), the evaluation of waveguide attenuation, prism and grating couplers. This work was documented in the annual grant reports, the IEEE Journal of Quantum Electronics paper, "Far IR Guided Wave Optics Experiments with Anisotropic Crystal Quartz Waveguides", in May 1977 and the Ph.D. thesis of E. J. Danielewicz. This study identified and solved a number of the problems unique to integrated optics in the far IR.

In the area of far infrared technology, the specific accomplishments were:

- 1) Study and evaluation of the optical properties of materials useful in the far IR,
- 2) Analysis of prism and grating couplers for far IR dielectric waveguides,
- 3) First use of metal-mesh hybrid mirrors for output couplers for far IR resonators,

4) The first demonstrated use of capillary, dielectric tube waveguides for high power, optical pumping of nonlinear systems,

5) The first designs of triple resonant (IR-FIW-MW) resonators for optically pumped systems,

6) Development of laboratory built CO_2 pump lasers with output capabilities to 5 joules,

7) Contributor to the use of SAW-RAC devices for the single shot spectral measurement of far IR lasers,

8) Optically pumped molecular lasers at 22.65 GHz.

In the area of new optically pumped systems, lasing was discovered in PH_3 and all lasing lines assigned, hot band lasing in NH_3 extended and explored, and the first lasing line assignment in the important molecule CH_3OH made in December 1976.

For the past two years (1978-80), extensive work has been pursued of high level, two-photon pumping of molecular gases to evaluate nonlinear behavior (Raman, hyper-Raman, parametric) of the system. This has been a combination experiment-analytical study of the quantum systems.

Computer programming of the density matrix equations for three- and four-level systems, has permitted the evaluation of highly nonlinear gain spectra of optically pumped molecular gases on a short time and modest cost scale. Given the basic spectroscopic molecular data, most of the far IR molecular laser systems can now be readily analyzed in detail. An

experimental verification of calculations made on NH_3 has been made. This work has been documented in two papers, "Stimulated Hyper-Raman Scattering in a Molecular Gas", IEEE J. Quan. Electron., March 1980, and "Gain/Absorption Spectra of Several Optically Pumped NH_3 Systems", to appear in IEEE J. Quan. Electron., and the Ph.D. thesis of K. J. Kim.

III. CALCULATED-EXPERIMENTAL EVALUATION OF THE GAIN/ABSORPTION SPECTRA OF SEVERAL OPTICALLY PUMPED NH_3 SYSTEMS - K. Kim

Introduction

The semiclassical analysis of a laser system based on the density matrix equations to calculate the electric polarization $\bar{P}$ and Maxwell's equations to calculate the fields, is capable of describing all the coherent interactions of the system. The practical problem is that the density matrix equations are difficult to solve in closed form for highly nonlinear processes and computer solutions of the equations can become expensive even with approximations. Agreement between calculations and experimental data will then depend upon the approximations and/or restrictive conditions that have been made.

Given the typical approximations, it is the objective of this paper to experimentally measure in detail the gain spectra curves (essentially the complex electric susceptibility) and compare the data with computer calculations to evaluate the validity of the approximations.

Optically pumped FIR molecular lasers were first analyzed by means of rate equations [1-5], which have limited generality. Density matrix analysis of masers [6-8] was used in the late 1950's and later applied to FIR molecular lasers [9-12] in the 1970's. A limited amount of work [13-15], using a Fabry-Perot interferometer, has been done to measure the gain spectra of optically pumped molecular lasers and compare the results

with density matrix analysis. This Fabry-Perot technique is tedious to apply and it has difficulties in measuring finer details, such as M-splittings, of the spectra.

A gain spectra measurement can be a somewhat routine problem if a suitable, frequency tunable, coherent, probe source exists in the frequency range of interest. The lack of such sources in the FIR is one reason one employs a Fabry-Perot interferometer. However, if one would consider an optically pumped molecular gas system where the one or more pairs of energy levels had transitions in the microwave region (i.e., up to 100 GHz), the spectra measurement problem would be greatly simplified, thanks to the availability of tunable sources.

The NH_3 molecule is an excellent candidate to verify density matrix equation calculations since it can be readily pumped with a CO_2 laser and it has many $g \leftrightarrow g$ transitions in the 8-40 GHz range [16]. The spectroscopy, frequency off-sets, matrix elements, T_1 's and T_2 's are well known so that calculations with no free parameters can be made.

In this paper, three NH_3 systems were chosen for study: two two-photon, three-level systems, both have a gain spectrum with different M degeneracies, and a three-photon, four-level system having an absorption spectrum, which can be accessed with an 18-26 GHz tunable BWO probe source. This choice permits accurate measurements of the M-splittings, AC Stark shifts, absolute gains and spectral line widths to compare with

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calculations. Agreement with calculations and experimental data for these fine details, builds confidence that subsequent calculations of laser output power versus pump power, gain saturation, optimum pressure, etc. will also agree with experimental data. One example will be given to substantiate this point.

Density Matrix Analysis

The density matrix equations, used in the computer calculations, were taken in the form

$$\frac{\partial \rho_{nn}}{\partial t} + \frac{\rho_{nn} - \rho_{nn}^e}{(T_1)_{nn}} = \frac{1}{i\hbar} \sum_k \left(H'_{nk} \rho_{kn} - \rho_{nk} H'_{kn} \right) \quad (1)$$

and

$$\frac{\partial \rho_{nm}}{\partial t} + \left(\frac{1}{(T_2)_{nm}} - i\Omega_{mn} \right) \rho_{nm} = \frac{1}{i\hbar} \sum_{\substack{k \\ n \neq m}} \left(H'_{nk} \rho_{km} - \rho_{nk} H'_{km} \right) \quad (2)$$

where $H'_{nk} = -(\bar{\mu} \cdot \bar{E})_{nk}$ is the interaction matrix element, $\bar{\mu}$ the electric dipole element and $\bar{E}$ the total electric field.

The electric polarization $\bar{P}$ is given by the expression

$$\bar{P} = N \text{Trace}(\bar{\mu} \bar{\rho}) = \epsilon_0 \chi_e \bar{E} \quad (3)$$

where N is the molecular density and χ_e the complex susceptibility.

The approximations used were the following:

- 1) Steady state (laser pulses longer than the relaxation times).
- 2) Homogeneous linewidths.
- 3) Simple relaxation terms T_1 and T_2 for each level.
- 4) M-changing collisions neglected.
- 5) Pump laser linewidths $\Delta\nu_L$ smaller than $1/T_1$ and $1/T_2$.
- 6) Plane wave electric fields.

The NH_3 molecular data used for the relaxation times were

$$T_2 = T_{1G} = 1.326 \times 10^{-8} \text{ sec-torr},$$

$$T_{1\nu_2} = T_{12\nu_2} = 9.0946 \times 10^{-8} \text{ sec-torr},$$

and for the matrix elements, the values taken were

$G_a \leftrightarrow \nu_2 s$	$\mu_{ij} = 0.23 \text{ debye}$
$\nu_2 s \leftrightarrow 2\nu_2 a$	$\mu_{ij} = 0.27 \text{ debye} = 9.0 \times 10^{-31} \text{ coul-meters}$
$G_s \leftrightarrow G_a$	$\mu_{ij} = 1.475$
$\nu_2 s \leftrightarrow \nu_2 a$	$\mu_{ij} = 1.25$
$2\nu_2 s \leftrightarrow 2\nu_2 a$	$\mu_{ij} = 0.83$

For parallel field polarizations, the change in μ^2 with quantum numbers JKM is given by the expression

$$\mu^2 = \mu_{ij}^2 \frac{K|M|}{J(J+1)} \quad (4)$$

while for perpendicular polarizations, the expression for μ^2 is

$$\mu^2 = \mu_{ij}^2 \frac{K}{J(K+1)} \left(\frac{J(J+1) - M^2}{2} \right)^{\frac{1}{2}} \quad (5)$$

In the case of a two-photon, three-level system, the solution of Eq. (3), for the imaginary part χ_e'' of the susceptibility, will be of the form

$$\chi_e'' = a(\rho_{00}^0 - \rho_{11}^0) + b(\rho_{00}^0 - \rho_{22}^0) \quad (6)$$

while for a three-photon, four-level system, χ_e'' will be of the form

$$\chi_e'' = a(\rho_{00}^0 - \rho_{11}^0) + b(\rho_{00}^0 - \rho_{22}^0) + c(\rho_{00}^0 - \rho_{33}^0) \quad (7)$$

where ^{0} means steady state values, and a , b , c are complicated resonance expressions.

The first term in the equations is the linear (laser) term, the second term is the third order nonlinear (Raman) term, and the third term is the fifth order nonlinear (hyper-Raman) term. This results in the gain or absorption spectra having either two or three resonant peaks, each with possible M-splittings.

The experimental problem is to measure the frequency locations of the gain peaks, the gain peak values, and the widths of the gain peaks. Agreement with calculated data would check the validity of the approximations made in using the density matrix equations.

Experimental IR-MW Configuration

The NH_3 systems to be studied require a test cell that can accommodate one or two CO_2 laser signals plus an 18-26 GHz microwave probe signal. No intentional feedback is provided for any CO_2 or FIR signals that may be present.

A test cell, made from K-band (RG53/U) waveguide as shown in Fig. 1, can serve as a rather general diagnostic setup for a variety of IR-MW experiments. The waveguide is terminated with two KCl Brewster windows for introduction of the CO_2 laser signals, either in parallel or counter propagating.

Two 45° waveguide joints using #28 wire allow the microwave probe signals and CO_2 signals to pass through the cell independently. A Watkins-Johnson WJ2022 BWO was used for the microwave probe source and a matched microwave Schottky diode was used for the detector.

The 18-26 GHz microwave probe signals were well matched, resulting in a single pass through the system. Reflections at CO_2 and FIR frequencies would appear to be small, so that in general only signals with rather high gains would be expected to be generated.

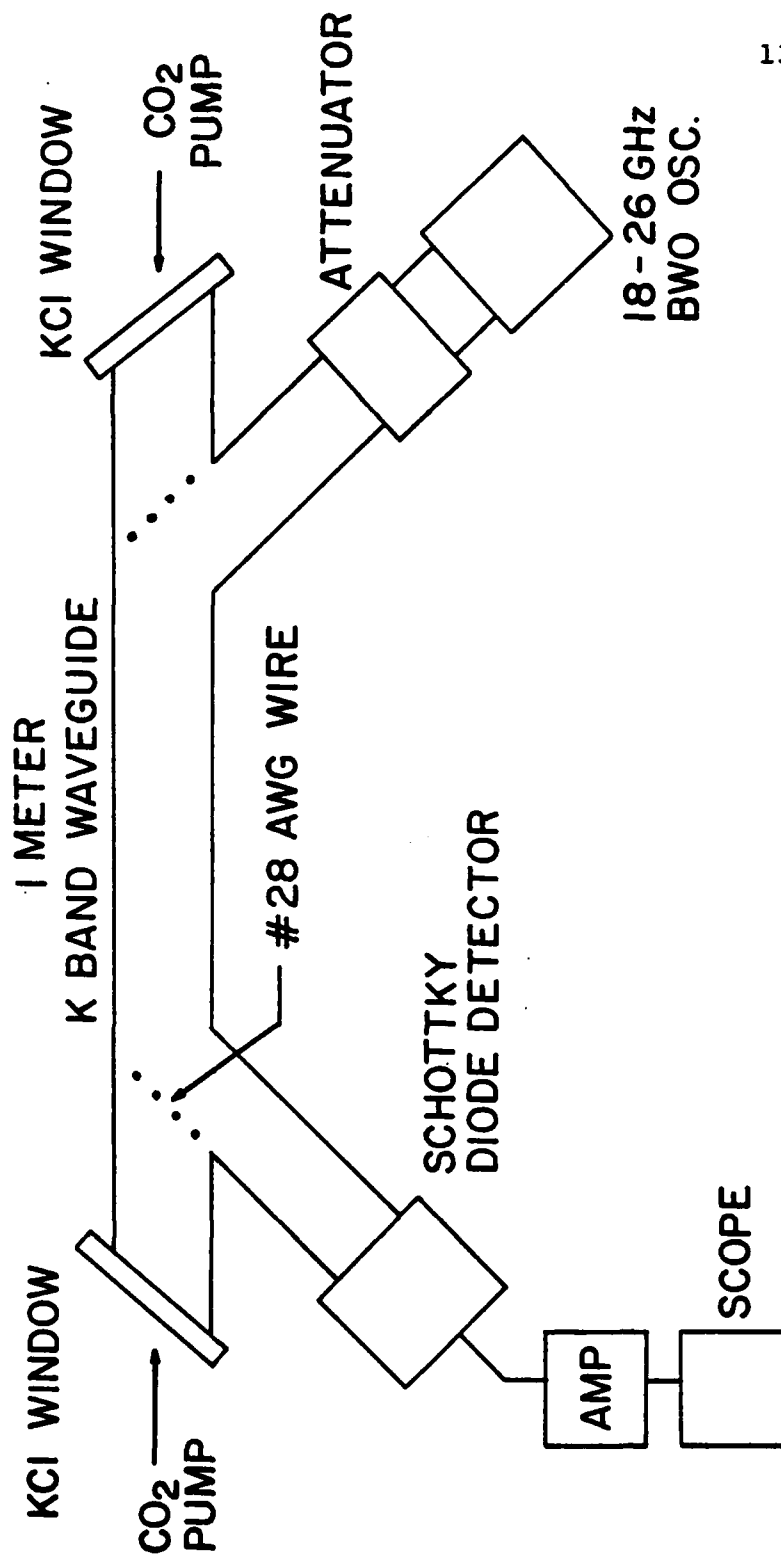


Figure 1. Schematic diagram of IR-MW apparatus for gain spectra measurements.

Two-Photon, Three-Level Gain Experiment $gs(5,4)$

The first two-photon, three-level gain experiment studied was that shown in Fig. 2a). Here the $gs(5,4)$ to $v_2a(5,4)$ transition in NH_3 is pumped by the $R(6)_{10}$ laser line of CO_2 , which is only 0.544 GHz off resonance, and the $gs(5,4)$ to $ga(5,4)$ transition probed with the microwave source.

The calculated gain spectra, for parallel and perpendicular pump-signal polarizations, are given in Figs. 3 and 4. The two peaked (with M-splittings) gain spectra curves are symmetric about the $(v_s - v_{21})$ values of 0 and -0.544 GHz. To a first approximation the frequency separation of the various M peaks is the Rabi frequency $\mu E/h$, i.e., for $|M| = 1$, the Rabi frequency is 0.63 GHz versus the calculated value (22.68-22.08) of 0.60 GHz. Above each M gain peak is written the calculated value of the frequency, which is to be compared to the experimental value.

Oscilloscope traces of the "Raman" signal at 22.03 GHz and "laser" signal at 22.72 GHz, along with the single mode $R(6)_{10}$ CO_2 signal, are displayed in Fig. 5 for the case of perpendicular polarization. Allowing for the 50 MHz amplifier used with the Schottky diode detector, the widths of the various signals are essentially equal with no time delays.

In Fig. 6 is plotted the calculated peak signal gain frequency versus the peak CO_2 $R(6)_{10}$ pump intensity in kilowatts/cm²

$$g_s = a(n_2 - n_1) + b(n_2 - n_3)$$

LASER

RAMAN

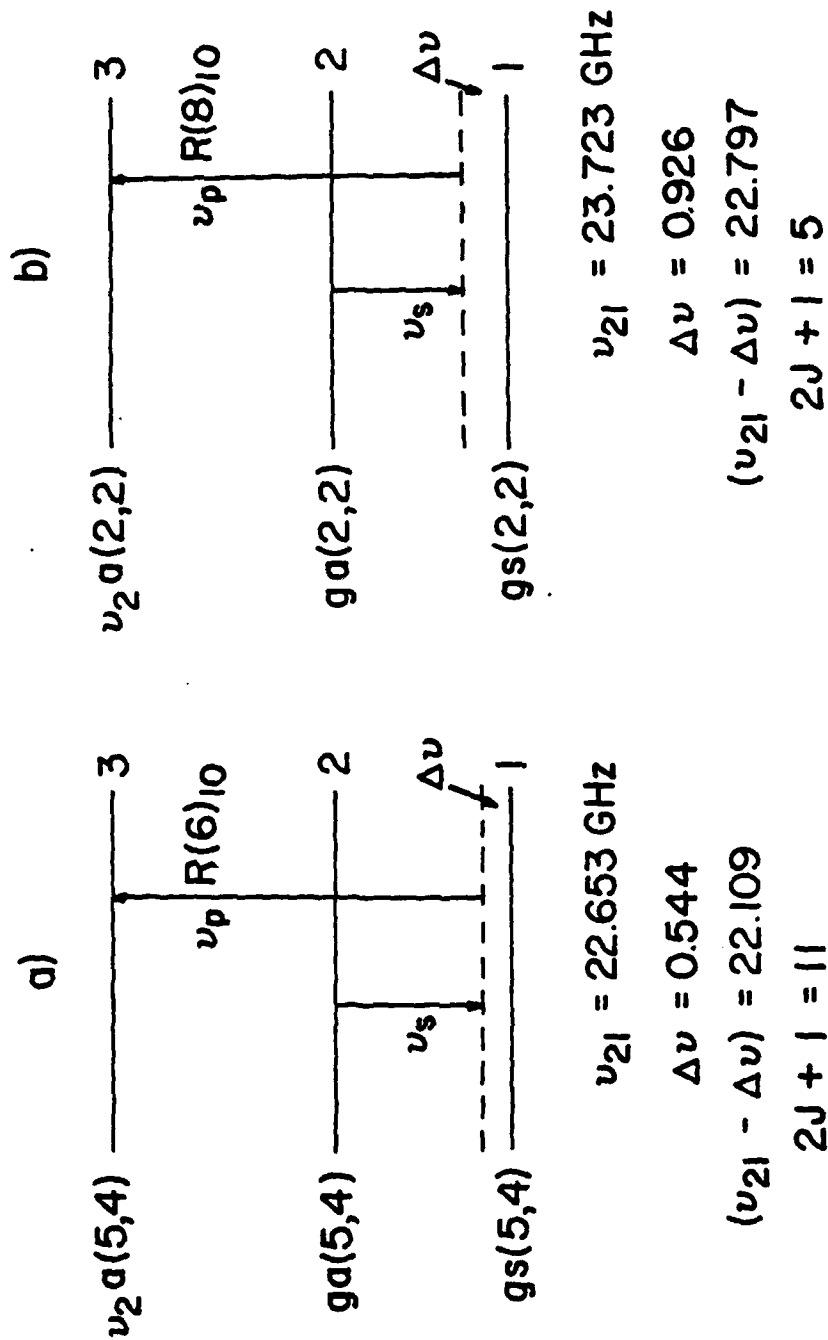


Figure 2. Two-photon, three-level experiments.

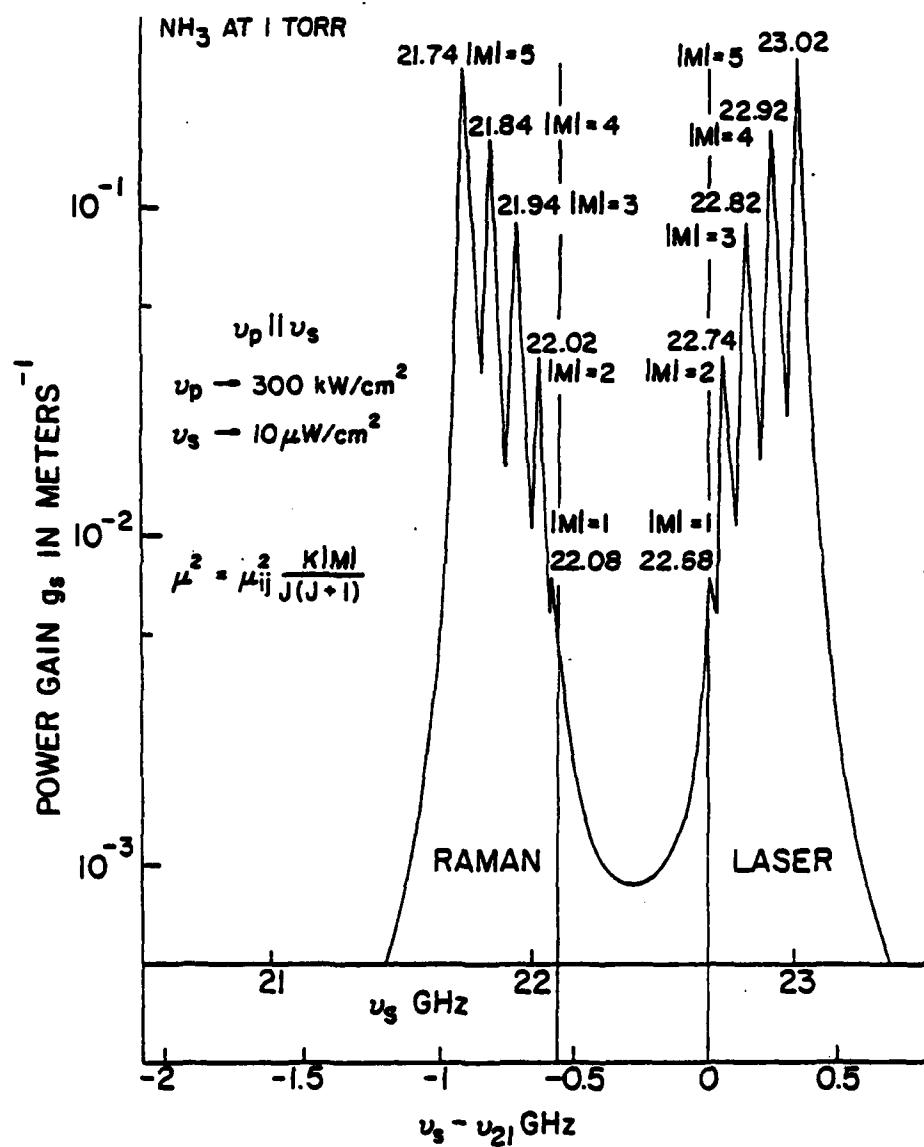


Figure 3. Calculated gain spectrum showing M-splitting (Experiment #1).

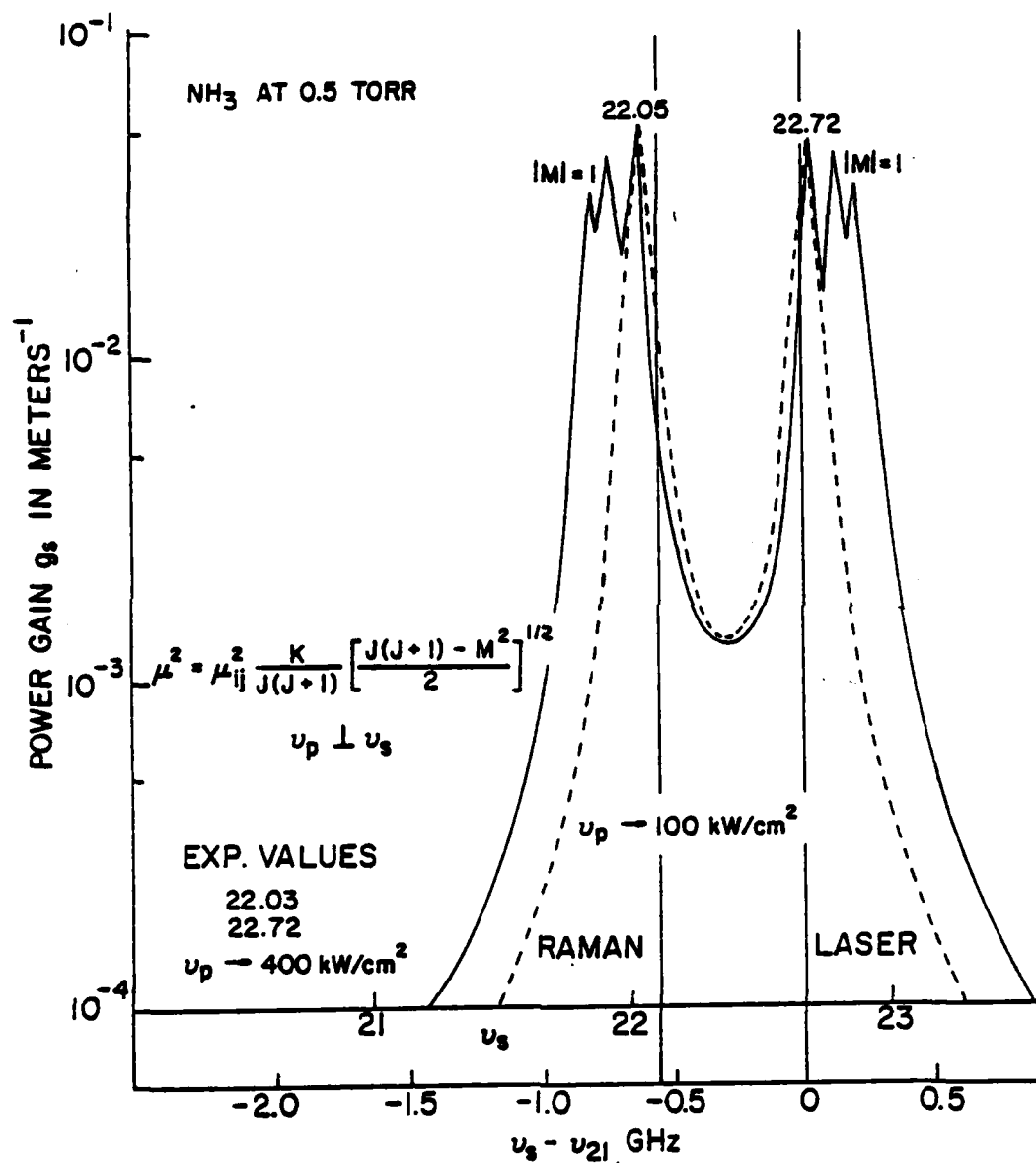
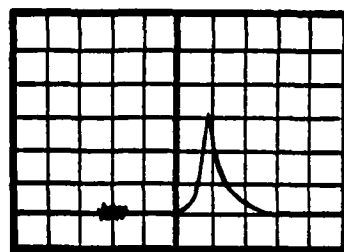


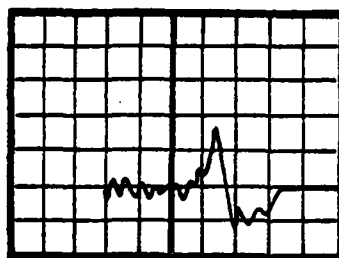
Figure 4. Calculated gain spectrum (Experiment #1).



CO₂ R(6)₁₀ SIGNAL

0.5 μ sec/div.

NH₃ at 0.5 torr

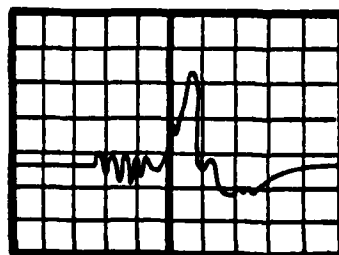


RAMAN SIGNAL
at 22.03 GHz

50 MHz AMP.

$\nu_p \perp \nu_s$

R(6)₁₀ $\sim$ 100 kW/cm²



"LASER" SIGNAL
at 22.72 GHz

Figure 5. Temporal characteristics of signals (Exp. #1).

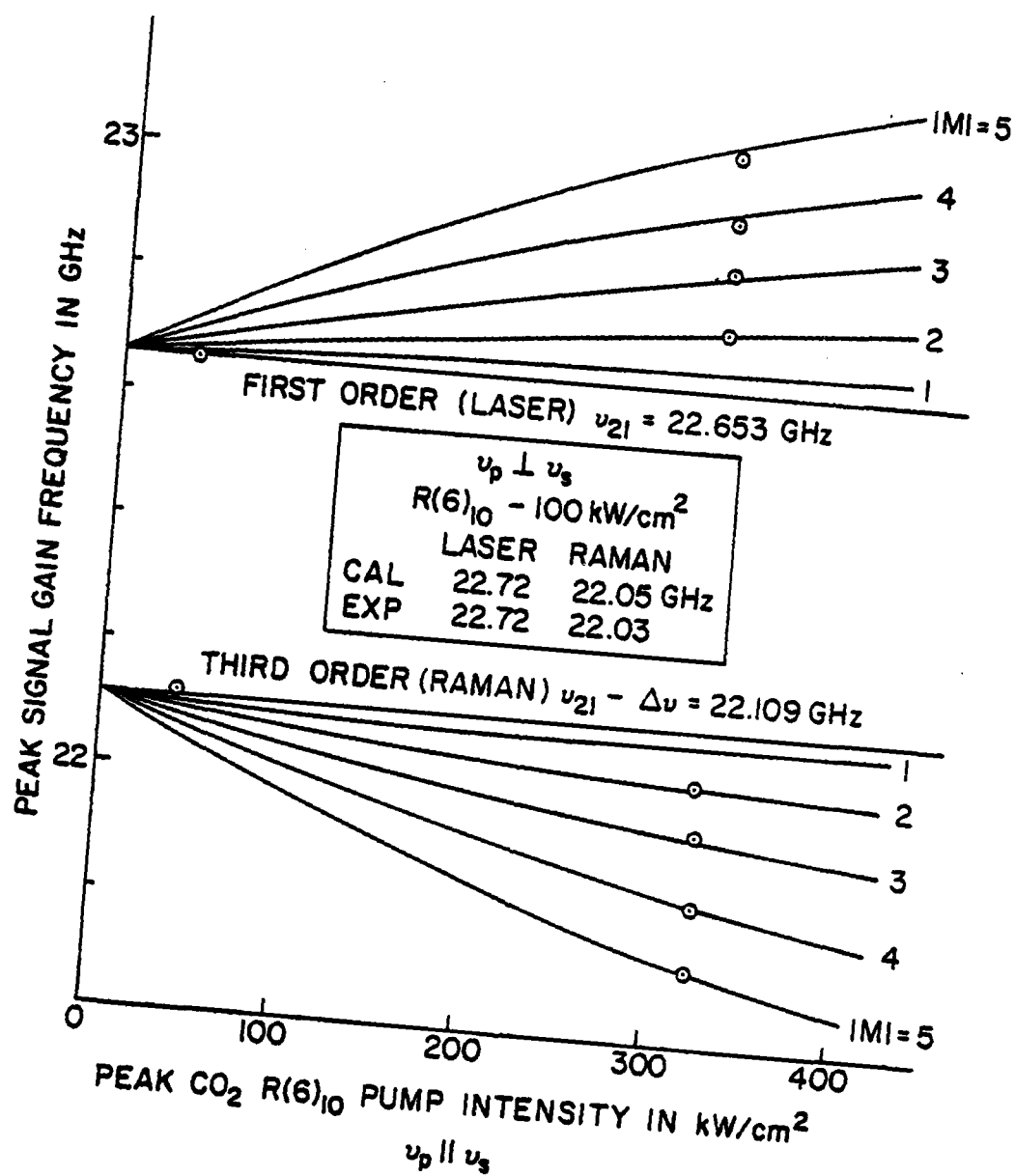


Figure 6. M-splittings of gain frequency peaks with pump intensity for gain experiment $gs(5,4)$.

for the various values of $|M|$ and the experimental data at fixed CO_2 pump intensity superimposed. It is seen that the agreement is excellent for a CO_2 pump intensity of 323 kW/cm^2 , with the exception of the two points for $|M| = 1$ which agrees well for a pump intensity of the order of 40 kW/cm^2 . The last two data points probably correspond to pump intensities in the tail of the CO_2 pump pulse.

The case of pump and signals fields perpendicularly polarized, the gain spectrum curves are not M-split for a pump intensity of 100 kW/cm^2 , but the gain peaks are displaced from 22.653 and 22.109 GHz, as seen from Fig. 4. The calculated values were 22.72 and 22.05 versus the measured values of 22.72 and 22.03 GHz shown in the insert of Fig. 6.

The gain peaks for the perpendicularly polarized case were not M-split to an appreciable extent for calculated pump intensities up to 400 kW/cm^2 and were difficult to resolve experimentally at the lower intensities that were used. Hence only two measured values are listed.

Two-Photon, Three-Level Gain Experiment (gs(2,2))

In this experiment, the two-photon, three-level system studied was that shown in Fig. 2b) where the gs(2,2) to $v_2a(2,2)$ transition in NH_3 is pumped by the $R(8)_{10}$ laser line of CO_2 , which is 0.926 GHz off resonance. These conditions lead to a calculated gain spectrum displayed in Fig. 7, where the gain peaks are M-split symmetrically above 23.723 and below 22.797 GHz.

The calculated peak gain frequencies versus CO_2 pump intensity curves are presented in Fig. 8 with the experimental data corresponding to a CO_2 pump intensity of 200 kW/cm^2 plotted on the curves.

The FWHM peaks of the M-split calculated gain peaks is 24 MHz, the $(\pi T_2)^{-1}$ value, while the experimental curves are much broader ($\sim 90 \text{ MHz}$), reflecting the Doppler broadened (FWHM) linewidth [17] of 90 MHz for NH_3 at 300°K and $10 \text{ }\mu\text{m}$ wavelength, which was neglected in the calculations. This Doppler broadening results in the M-split gain curves, in practice, not to be as sharp as depicted, have less deep "valleys" and probably not as large a peak gain. The experimental gain data was not absolute values but arbitrary units partially fitted to the curves.

The assumption of plane electromagnetic waves is not fulfilled in the microwave guide. Hence the transverse spacial variation of the various fields must also contribute to the broadening of the gain peaks. Considering these facts, the agreement of the data with calculations appears good.

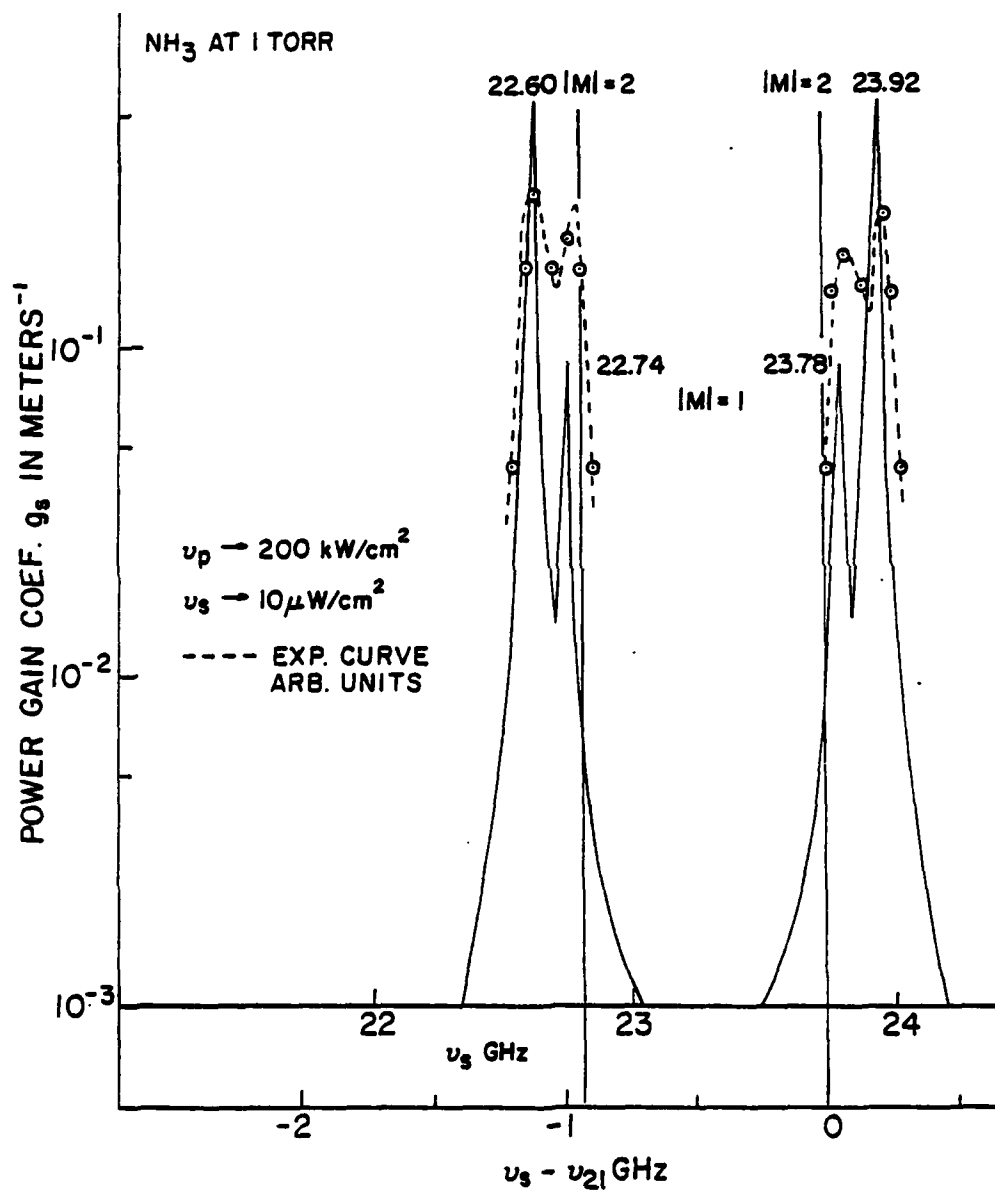


Figure 7. Calculated gain spectrum (Experiment #2).

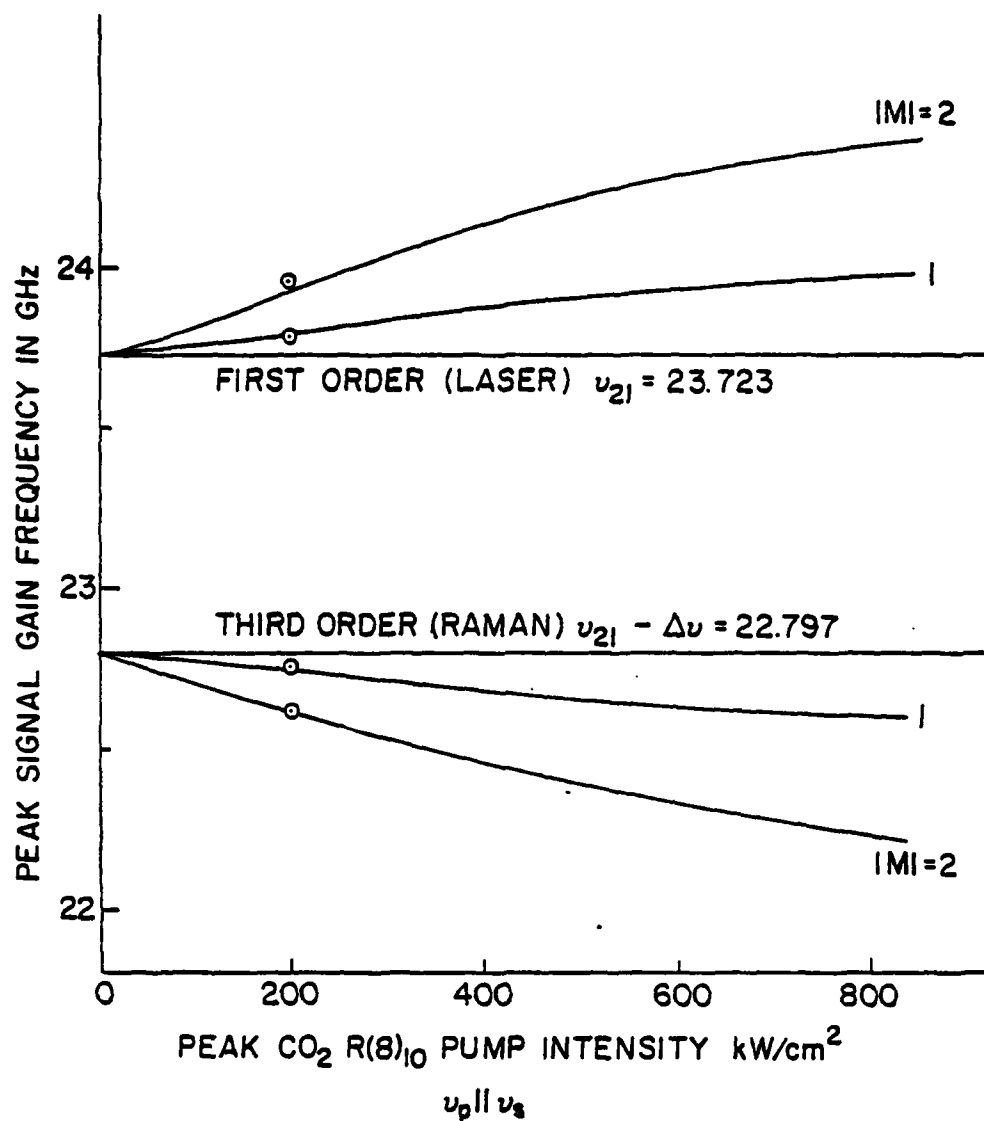


Figure 8. M-splittings of gain frequency peaks with pump intensity for gain experiment $gs(2,2)$.

Three-Photon, Four Level Absorption Experiment $gs(5,4)$

In this experiment two counter propagating CO_2 pumps $P(34)_{10}$ and $P(18)_{10}$ were used to pump the $ga(5,4) - v_2s(5,4)$ and $v_2s(5,4) - 2v_2a(5,4)$ transitions of NH_3 and the 22-23 GHz microwave signal used to probe the absorption of the $gs(5,4) - ga(5,4)$ transition. The counter propagating CO_2 pumps should reduce the Doppler broadening of the microwave absorption peaks and yield linewidths near the Lorentzian value.

The calculated absorption spectrum is shown in Fig. 9. In the case of two CO_2 pumps, the spectrum will have three absorption peaks (i.e., a triple resonance), associated with the first (Laser), third (Raman), and fifth (hyper-Raman) processes.

Only the first and fifth order absorption peaks are shown in Fig. 9, near the 22.653 and 22.947 GHz values. The Raman peak near 27.609 GHz was not accessible with the BWO source available and was weak because of the large 5.25 GHz frequency mismatch of the $P(34)_{10}$ CO_2 pump.

It is seen from the calculated absorption curves, very little M-splitting occurs even up to pump intensities of $P(34)$ 300 kW/cm^2 plus $P(18)$ 200 kW/cm^2 . The experimental absorption data, in arbitrary units, was scaled to be 0.0074 m^{-1} low on the 22.63 GHz peak and 0.0074 m^{-1} high on the 22.94 GHz peak. The FWHM values of the calculated and measured absorption peaks are 24 MHz, the Lorentzian $(\pi T_2)^{-1}$ linewidth. Accuracy of the measured width was the order of ± 2 MHz.

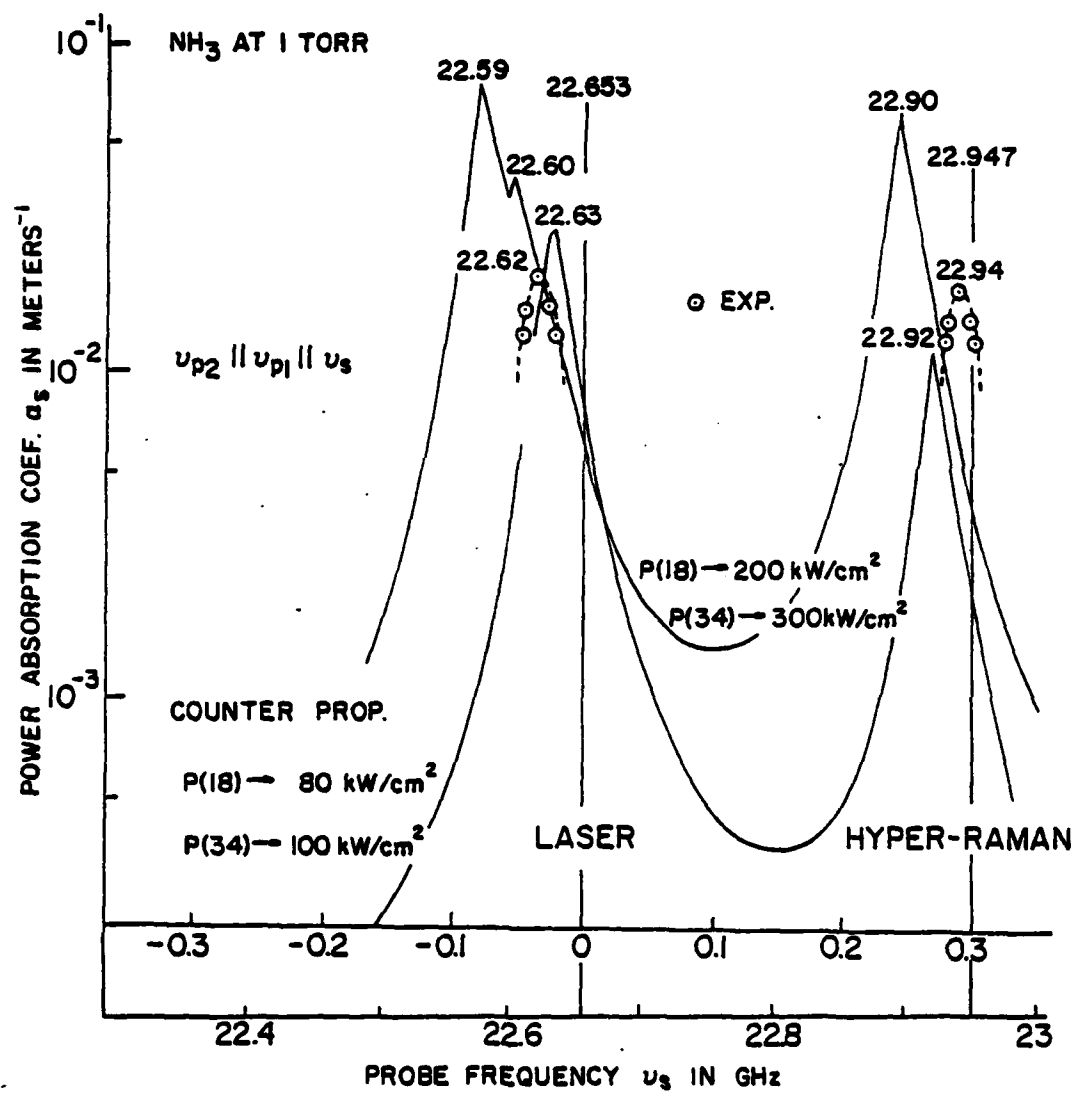


Figure 9. Calculated absorption spectrum (Experiment #3).

Conclusions

It has been experimentally demonstrated, by the measurement of the gain/absorption spectrum of an optically pumped molecular laser system, that a density matrix calculation, using the usual approximations, accurately describes the system in detail.

The measured gain/absorption peak frequencies in both a double and triple resonance spectrum agree with the calculated values to ± 10 MHz. The experimental values of the peak gain/absorption differ are a factor of 2-3 lower than calculated, mainly as a result of the assumptions of homogeneous line broadening and plane wave fields. The FWHM values of the individually M-split gain/absorption peaks reflect the Doppler broadened value of 90 MHz rather than the assumed 24 MHz Lorentzian broadening.

In the case of two counter propagating CO_2 pumps, the FWHM values of the gain/absorption peaks are near the 24 MHz Lorentzian linewidth.

A density matrix calculation, presented in a previous paper [10], which includes gain saturation was shown to yield excellent agreement on a two-photon pumped NH_3 system with respect to measured output intensity, optimum pressure, and saturated gain.

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IV. TUNABLE MASER EMISSION FROM $^{14}\text{NH}_3$ OPTICALLY PUMPED BY A CO_2 LASER - E. Malk

Introduction

Recently Kim and Coleman¹ presented results of calculated-experimental evaluation of some optically pumped NH_3 systems. Gain and emission at microwave frequencies were reported as a result of infrared pumping with a TEA- CO_2 laser in a traveling-wave cell. This paper will report observation of distinctly different results obtained in a high Q (~ 3000) microwave cavity using a lower power TE- CO_2 laser. Tunable microwave emission, attributed to a linear process, with excellent frequency stability has been observed and studied.

The energy level diagram relevant to this investigation is shown in Figure 1. Details regarding spectroscopic notation and data are the subject of Appendix A1. The near-resonant match (i.e., $\Delta\nu = 544 \text{ MHz}$ ⁶) of the CO_2 R(6)₁₀ ($\nu_p = 966.2504 \text{ cm}^{-1}$) laser line and the $^{14}\text{NH}_3$ G + ν_2 :sQ(5,4) ($\nu = 966.2660 \text{ cm}^{-1}$) absorption has been used to produce optically pumped far infrared (FIR) and infrared emission. The FIR transitions labeled 3 and 4 were reported by Fetterman, et al.² and Gullberg, et al.³ An additional FIR transition (i.e., G:sR(5,4) has been reported,⁵ but is not shown in Figure 1. The infrared transition labeled 4 was observed by Chang and McGee.⁴ The G:sQ(5,4) transition (labeled 5) occurs in the microwave range of the frequency spectrum at 22.653 GHz.⁷ The availability of

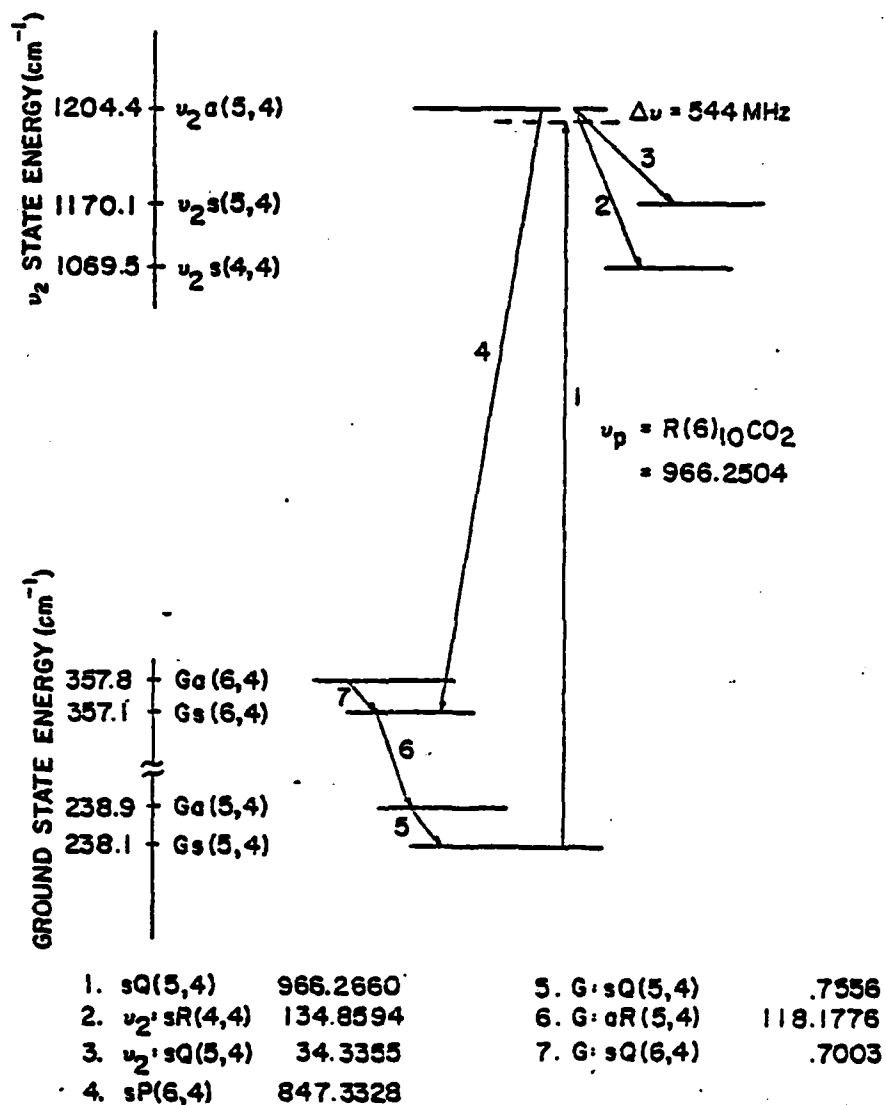


Figure 1. Energy level diagram for $^{14}\text{NH}_3$ relevant to the $^{12}\text{C}^{16}\text{O}_2 R(6)_{10}$ laser transition. The numbered transitions are identified and the frequencies (cm^{-1}) given.

tunable frequency sources in this range has led to investigation of this transition.

Kim and Coleman¹ recently reported results of the infrared-pumped microwave-probed G:sQ(5,4) system. Microwave frequency gain/absorption spectra were calculated using a two-photon three-level density matrix theory and compared to the experimentally obtained transmission spectra. The characteristic shape of the calculated spectra includes two distinct peaks near 22.653 GHz and 22.109 GHz. These peaks are designated the "laser" (linear order in field) peak and the "Raman" (third order) peak, respectively. Fine structure due to the AC Stark splitting of the M-level degeneracy is predicted for both peaks. The theoretical predictions for the laser and Raman frequency peaks are in excellent agreement with the experiment. The measured values of the gain magnitudes are within a factor of 3 when compared to the theoretical values. These results prompted further investigation in an experimental cell that could provide feedback for possible FIR radiation involved in yet higher order processes.

Cell Design

The cell used in the Kim experiment is a travelling wave device that provides no intentional feedback for infrared or FIR radiation. This design provides a relatively uniform infrared field to pump the $^{14}\text{NH}_3$ gas.

The cell designed for this investigation simultaneously provides feedback for the FIR and microwaves. The cell is a right cylindrical microwave transmission cavity operating in the lowest order linearly polarized TE_{11n} mode. The resulting FIR mode is the circularly polarized TE_{10n} . A similar cell has been used by Willenberg, et al.⁸ to produce a two-photon pumped CW laser. Further details regarding cell design and calibration are contained in Appendix A2. The infrared radiation is focused through a 1.5 mm coupling hole in a 0.1 inch thick copper mirror. The resulting infrared pump field is spatially non-uniform which causes the effective pumping field to be reduced, and the microwave gain fine structure to become unresolvable.

The compromise in the resonator cell design suggested by Willenberg⁸ that the circularly polarized FIR modes are not optimally excited by the linearly polarized pump field and the higher losses for the FIR are of little concern for the case of pumping with a pulsed high-power CO_2 laser. The point of resonantly enhancing and confining the microwave to a minimum volume is well taken, and the primary reason for choosing this design.

Experimental Apparatus

The experimental apparatus consists of four major parts. These include: 1) the infrared pump laser; 2) the optically

pumped FIR laser; 3) the microwave circuit; and 4) the pulse synchronization circuit. Each of these parts will be described in detail, with the experimental cell design features listed where they are important.

Infrared Pump Laser

The infrared pump laser is a single longitudinal mode TE-CO₂ laser capable of energies up to 150 mJ (stronger lines) at a 0.5 Hz repetition rate. The cavity consists of a gold-plated PTR 10m radius of curvature, 100 lines/mm, master diffraction grating blazed at 10.6 μ m and a flat germanium partial reflector (R=75%). The total cavity length is about 3m. The transverse discharge cell pressure was maintained at 300 torr while the longitudinal discharge gain cell pressure was at 15 torr. The premixed laser gas is flowed at a moderate rate and is a mixture of 12% CO₂, 14% N₂, and 52% He. Pulsed laser energies were measured with a GENTEC joule meter.

Far Infrared Laser

The FIR laser resonator is the TE_{11n} microwave transmission cavity resonator. The resonator consists of a non-precision 32in long 3/8 in. ID copper tube, a fixed circular (.355 in. OD) copper mirror with a 1.5 mm hole at its center, and a translatable circular (.355 in. OD) copper mirror. The only alignment adjustment is the cavity length. The remaining

alignment is determined by the machined accuracy individual components. Operating pressures of the $^{14}\text{NH}_3$ gas range from 0.1 to 20 torr and are easily maintained for many hours in the cell.

The optically pumped FIR radiation is coupled out the 1.5mm hole and deflected through a TPX vacuum window, similar to the arrangement used by Gullberg, et al.³ The signal is detected with a Si:P detector at 4°K. The detector is also sensitive to the infrared pump radiation, causing additional filters to be required for weak FIR signals.

The stable output of the optically pumped FIR laser and relatively ineffective cavity tuning indicate the FIR losses are low and the machined alignment is adequate for these experiments.

The Microwave Circuit

The microwave circuit used in the experiment was changed several times, but two similar circuits produce the best results. The basic circuit is shown in Figure 2. The klystron is an OKI 24V10 driven by an FXR Universal Klystron Power Supply. (Beam Voltage = 2000V @ 10ma, Reflector Voltage = -250V, Control Grid = -200V). Swept frequency operation is obtained by applying a 0-200 Volt ramp to modulate the reflector voltage. Quasi-fixed frequency operation is obtained by applying a square wave (0-200V) voltage to the reflector.

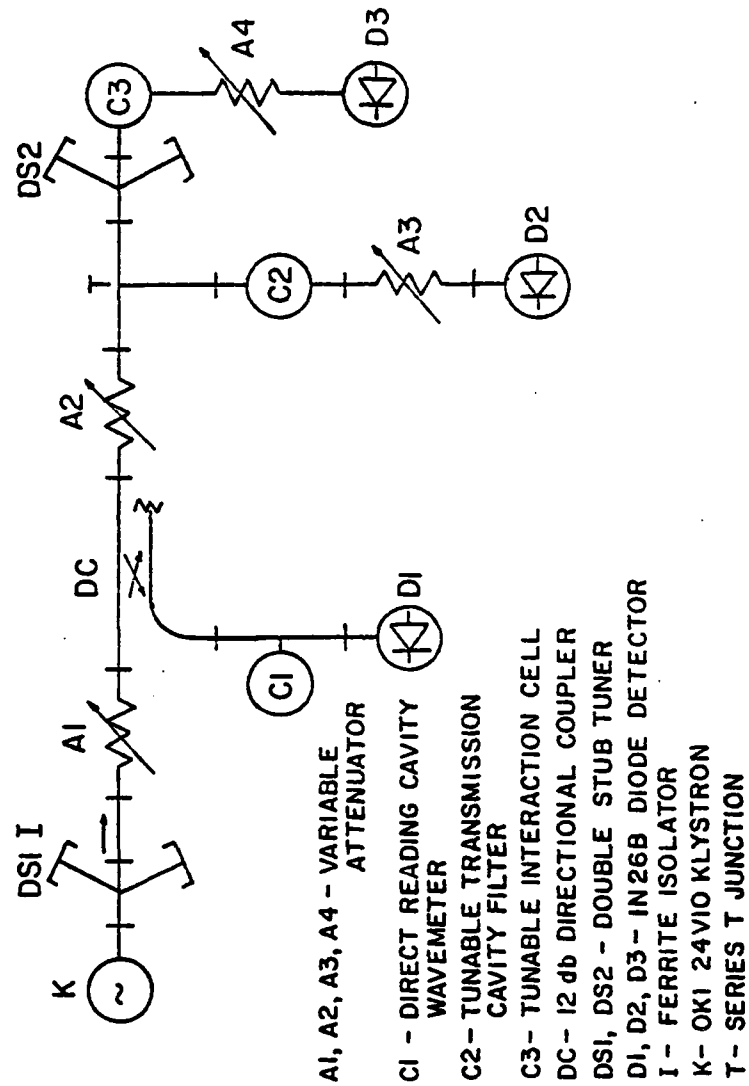


Figure 2. The microwave circuit.

DS1, I, and A1 serve to pad the Klystron from the rest of the mostly high Q circuit. DC, C1, and D1 serve to monitor the reflected microwave signal from C2 and C3. A2 controls the level of the microwave radiation. T is an E-PLANE (SERIES) T junction used to split the microwave radiation. The purpose of this junction is to facilitate setting of the microwave frequency. This will be considered in detail shortly. C2 is a high Q (≈ 7000) critically coupled tunable transmission cavity used as a frequency filter. A3 limits the level of microwave radiation incident on D2, a 1N26B diode. C3 is the designed cell (design details are in Appendix A2), a transmission cavity operating with the lowest order TE_{11n} mode. The measured Q of the cavity is about 3000 and the maximum coupling is less than 10%. The amount of coupling may be varied by tuning DS2. The transmitted microwave level is monitored on D3.

The setting of frequency in this circuit is somewhat tedious. The best results are obtained in the following manner. The klystron is operated in a swept frequency mode with the desired frequency located at or near the center of the sweep, as monitored with D1 (the maximum safe signal level from the 1N26B into $1M\Omega$ is 0.5V for < 1 msec pulse, for a duty cycle less than 0.1). DS2 is adjusted until a decrease of 5% or more is observed at D1. Careful examination of the change in signal level will demonstrate frequency sensitivity. The

change should be maximized at the desired frequency. D3 should now be monitored with a high gain amplifier. If no signal is present at D3 tune C3 until a signal is observed, taking care not to burn up D3. Additional adjustment of DS2 may be used to maximize the transmitted signal. For most applications this is all that is required.

For more precise frequency settings, C2 is set to a particular frequency. The critical coupling of C2 puts a sharp (high Q and more coupling) dip in the curve monitored at D1. This dip represents maximum transmission through C2 and results in dissipation of the microwave energy in A3 or D2. Following the procedure outlined previously a signal is then monitored at D3. When the cavity C3 is tuned such that the frequency of cavity C2 are the same, the same sharp dip will be observed in the transmitted peak at D3. This technique is important for investigating frequency-time behavior.

The second microwave circuit involves setting up a heterodyne detector. The klystron operating in the quasi-fixed frequency mode is used as the local oscillator. The basic circuit is modified as follows. The directional coupler (DC) is reversed so it splits a fraction of the incident microwave radiation to D1. The tunable transmission cavity filter is completely removed and A2 is placed between T and DS2. D2 now serves as the mixer for the heterodyne detector. This circuit

has been used to study microwave injection effects, frequency tunability, and frequency stability of the generated microwave signals.

Time Synchronization

Pulsed probe experiments require flexible, reliable triggering if meaningful data is to be obtained. The requirements for the experiments performed resulted in several different techniques being developed for triggering. The requirement peculiar to these experiments are caused by: 1) low repetition rate ($\sim 0.5\text{Hz}$) firing of the CO_2 laser and 2) time jitter of the reflector modulation power supply.

The low repetition rate firing of the CO_2 laser is required to get reliably stable pulses of infrared pumping radiation. The time jitter problem of the klystron reflector modulation could be solved by repairing or replacing the power supply, but was not practical at the time.

The only experiments performed where synchronization is required were microwave injection and heterodyne detection experiments. In both of these cases the klystron was operated in the quasi-fixed frequency mode (i.e., square wave modulation of the klystron reflector voltage). The triggering technique is shown in Figure 3.

The modulation output of the FXR universal klystron power supply is a 0 to 100V square wave with a period of T_1 . (T_1 is

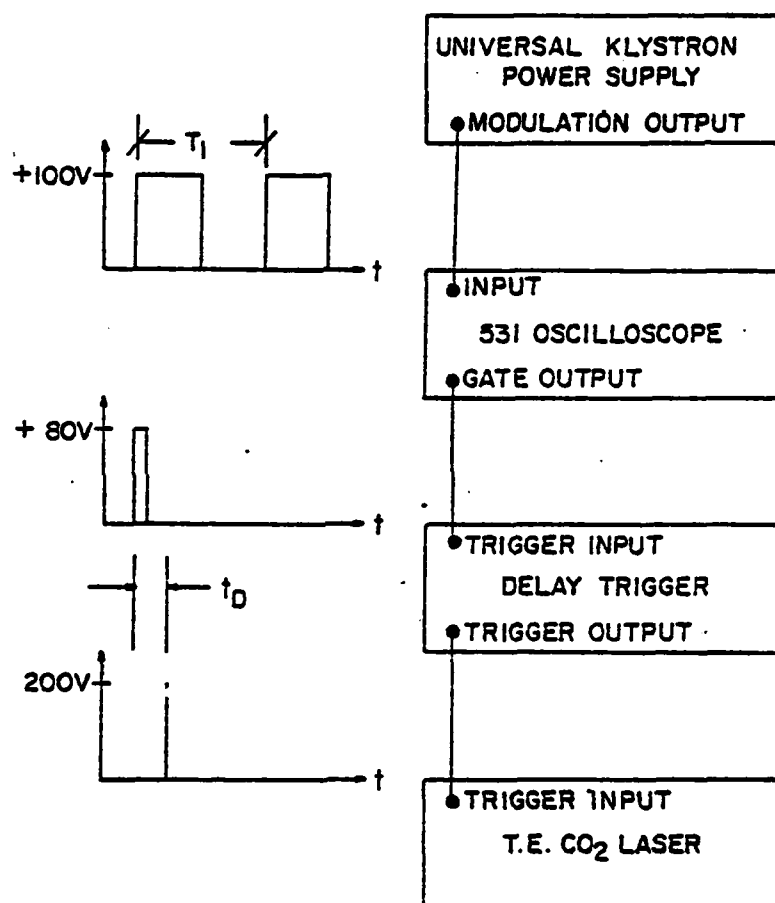


Figure 3. Time synchronization block diagram. The system allows synchronous firing of the TE-CO₂ laser with the klystron.

typically 1 msec). The square wave is monitored by a Tektronix 531 oscilloscope with a vertical sensitivity of 20 V/div. The time base is set at 0.2 sec/div and the scope is internally triggered by the square wave. The resulting gate output of the oscilloscope has a period determined by the time base of the oscilloscope (a 2 second period is typical), and is used to trigger a four channel delay trigger generator. The delay trigger ensures the laser trigger pulse occurs during the fixed frequency part of the klystron reflector modulation. This technique has produced the simplest synchronization of the infrared and microwave signals, and is least likely to be affected by jitter in the reflector modulation power supply.

The experimental details presented thus far are common to most of the performed experiments. Specific details peculiar to a given experiment will be discussed with the experiment.

Experimental Results

Optical pumping of $^{14}\text{NH}_3$ with a TE- CO_2 laser has produced strong, frequency stable microwave emission. The results to be presented include characterization of the microwave emission operating conditions, the emission bandwidth dependence on pressure, effects of microwave injection, and frequency stability observations.

Microwave Emission Characteristics

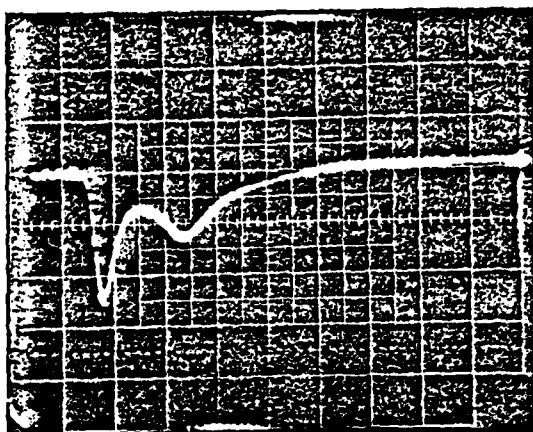
Microwave emission attributed to the G:sQ(5,4) inversion transition was observed following optical pumping of the $G \rightarrow v_2:sQ(5,4)$ transition with a TE-CO₂ laser tuned to the R(6)₁₀ ($\nu_p = 966.2504 \text{ cm}^{-1}$) line. The time synchronized photographs shown in Figure 4 show a typical infrared pump laser pulse ($E=60\text{mJ}$), the resulting FIR laser pulse, and the observed microwave emission. The conditions stated on the figure represent the near optimum conditions for the microwave emission. The emission is only observed over a relatively narrow pressure range from 0.3 to 2.2 torr, with stable amplitude behavior from 0.5 to 1.8 torr. Additional data is given in Figure 5. The pulse shapes are observed to change with pressure, becoming shorter with increased pressure. In all cases shown the cavity is set to the length that provides the maximum signal level at 1.13 torr.

To provide further understanding of the microwave emission, the frequency and emission bandwidth required investigation. The technique employed to obtain this information is performance of cavity tuning scans of the observed emission.

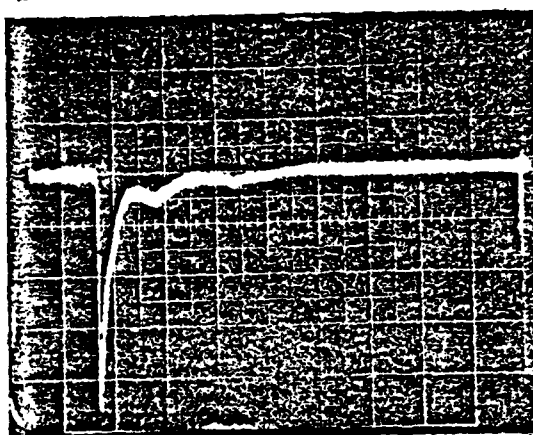
Cavity Scanning Results

A cavity scan is performed in the following manner. A motor drive is mounted to the micrometer tuning plunger of the experimental cell. The microwave emission is monitored

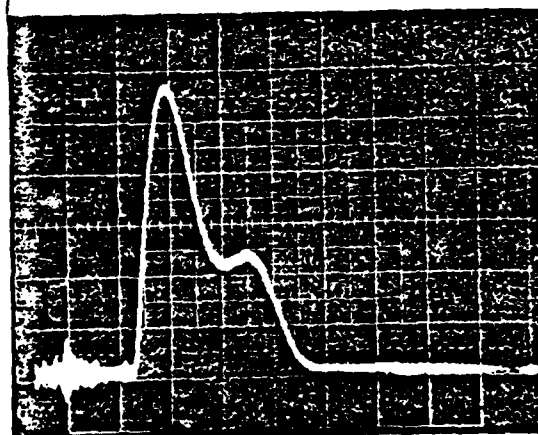
INFRARED
 $\text{CO}_2 \text{ R}(6)_{10}$
 $E \approx 60 \text{ mJ}$
 $\text{Si:P at } 4^\circ\text{K}$
 1 Volt/div



FAR-INFRARED
 $^{14}\text{NH}_3$ at 1.13 torr
 $\text{Si:P at } 4^\circ\text{K}$
 1 Volt/div



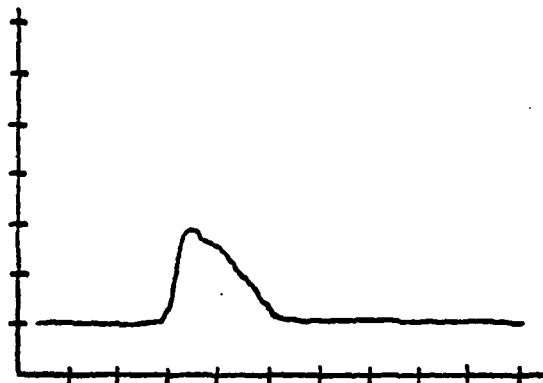
MICROWAVE
 $^{14}\text{NH}_3$ at 1.13 torr
 $\text{IN26B into } 1000\Omega$
 50 mV/div



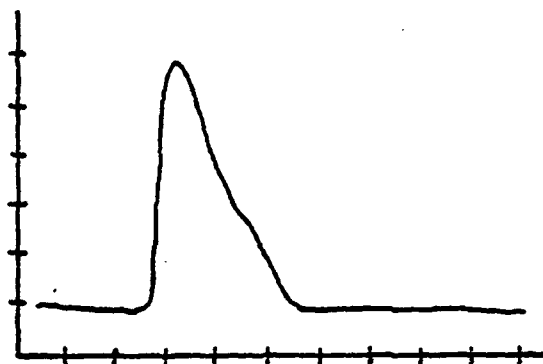
$t = 1 \mu\text{sec/div}$

Figure 4. Time synchronized oscilloscope traces showing the infrared pump pulse ($\text{CO}_2 \text{ R}(6)_{10}$), the optically pumped far infrared ($\nu_2:\text{sR}(4,4)$ at 134.86 cm^{-1} and $\nu_2:\text{sQ}(5,4)$ at 34.34 cm^{-1}) emission, and the resulting microwave emission attributed to the $\text{G:sQ}(5,4)$ at 22.653 GHz .

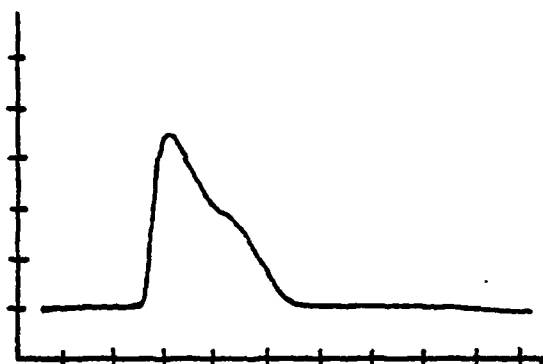
$P = .53 \text{ torr}$
 $y = 20 \text{ mV/div}$



$P = .71 \text{ torr}$
 $y = 20 \text{ mV/div}$



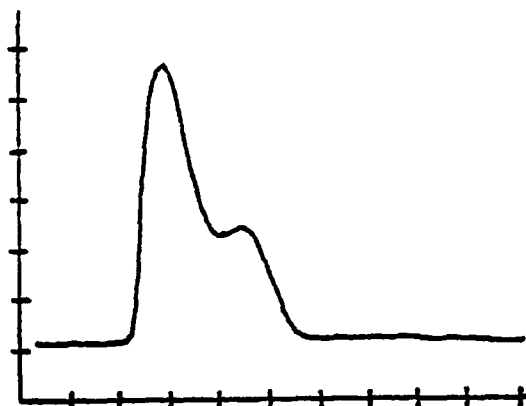
$P = .91 \text{ torr}$
 $y = 50 \text{ mV/div}$



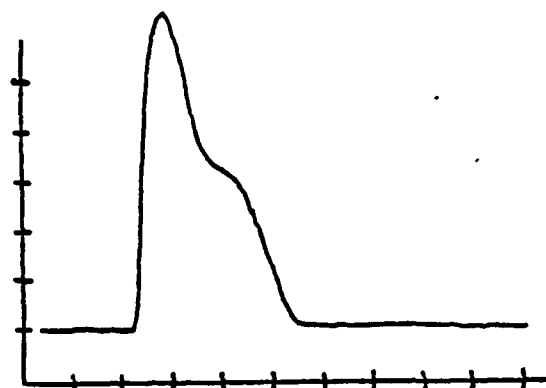
$t = 1 \mu\text{sec/div}$

Figure 5. Oscilloscope traces of the G:sQ(5,4) optically pumped emission.

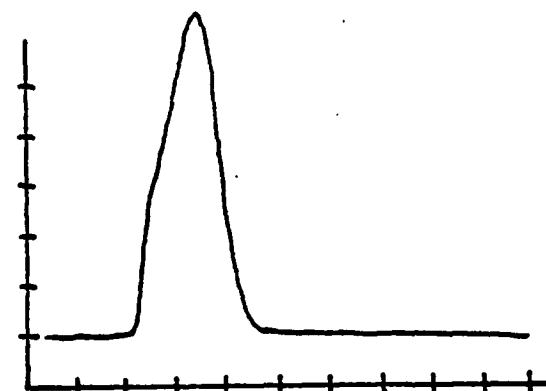
$P = 1.11 \text{ torr}$



$P = 1.31 \text{ torr}$



$P = 1.5 \text{ torr}$

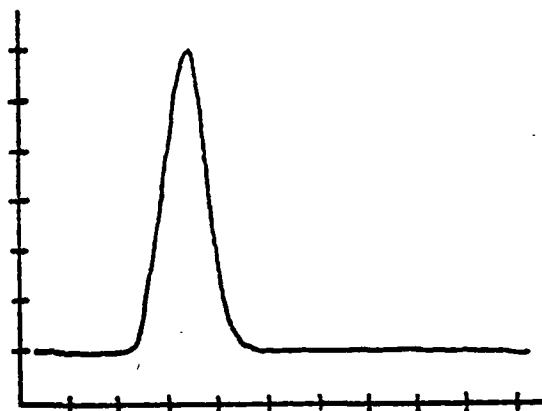


$t = 1 \mu\text{sec/div}$

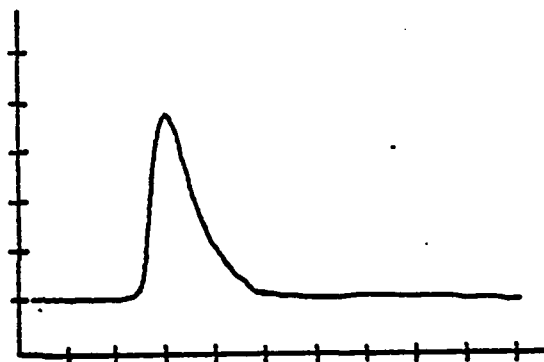
$y = 50 \text{ mV/div}$

Figure 5. Oscilloscope traces of the G:sQ(5,4) optically pumped emission.

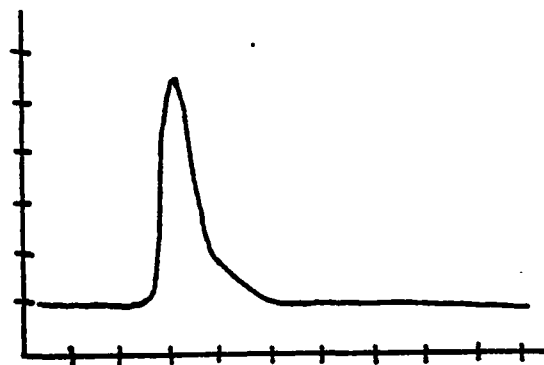
P = 1.71 torr



P = 1.90 torr
CO₂ MISFIRE



P = 1.90 torr
UNSTABLE
SIGNAL



$t = 1 \mu\text{sec/div}$

$y = 50 \text{ mV/div}$

Figure 5. Oscilloscope traces of the G:sQ(5,4) optically pumped emission.

P = 2.11 torr
UNSTABLE
SIGNAL

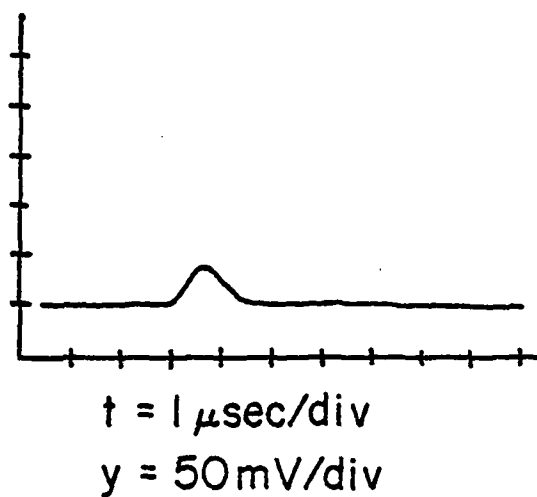


Figure 5. Oscilloscope traces of the G:sQ(5,4) optically pumped emission.

with a 1N26B diode (D3 in Figure 2) and input to a synchronized PAR Boxcar Integrator. The gate (i.e., integration window) of the Boxcar is set at 4 μ sec to allow for time jitter of the microwave emission pulse. The integration time of the Boxcar is set to the minimum value (i.e., 0.01 msec). The input is AC coupled to the 10k Ω Boxcar input with a shunt 1k Ω resistor to decrease the rise time of the detector. The signal output was used as the y input to an x-y recorder. The x was set to 100 seconds/inch scan rate. The combination of the motor drive with the x-y recorder produced 0.0452 inches of cavity scan per inch of graph paper. The initial and final cavity setting of the scan are placed on the graph for reference purposes. The upper curves in Figure 6 are the result of three consecutive cavity scans.

The lower curves give the absolute frequency calibration data for the upper curves. These curves are considerably more difficult to record. Detection of microwave absorption in a microwave cavity is a standard spectroscopic technique (see Townes and Schawlow,⁹ Section 15.11). The result of microwave absorption is increased loss at the resonant absorption frequency. The increased loss in the cavity reduces the Q of the transmitted microwave signal which is readily detectable at low pressures. At a pressure of 0.1 torr the homogeneous microwave absorption linewidth is about 2.5 MHz, thus a sizeable

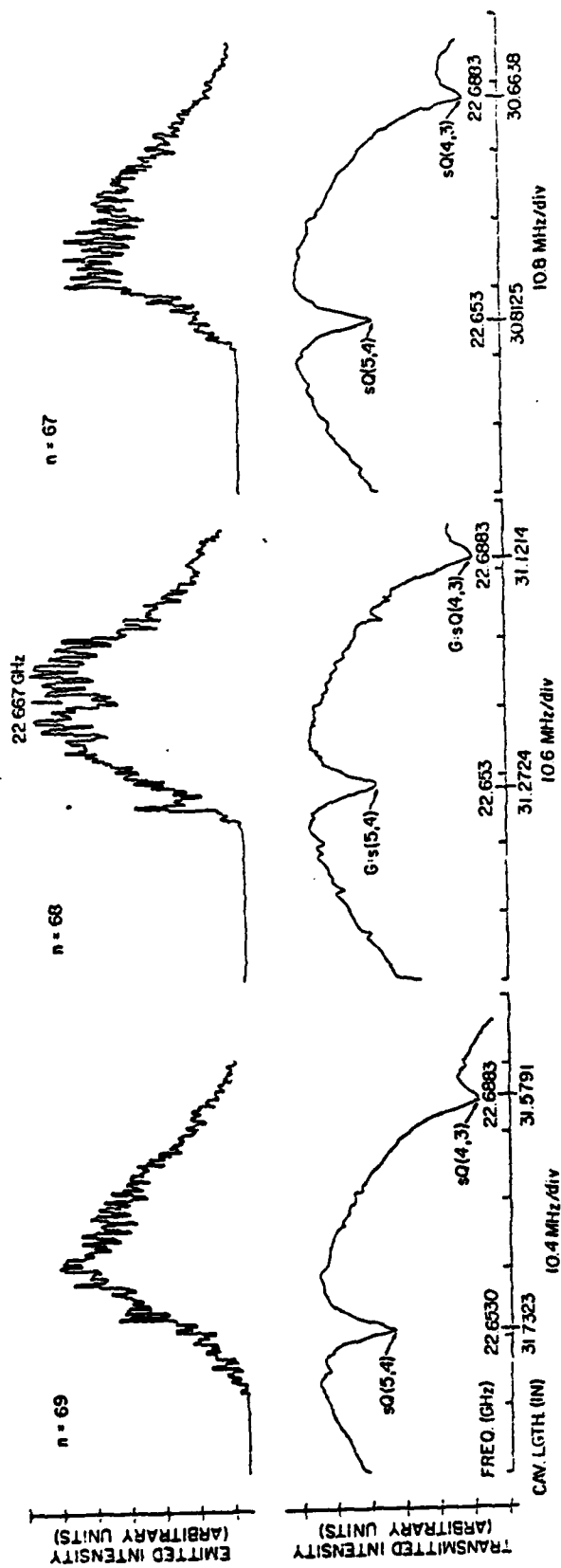


Figure 6. Cavity scans of the G:SQ(5,4) emission (upper curves) and microwave absorption calibration scans (lower curves) for the TE_{11n} ($n=67$, 68 and 69) modes. The cavity scan length is 0.0452 inches per division, $E_L = 60$ mJ, $^{14}NH_3$ pressure at 1.1 torr.

transmission dip would be observed if the cavity is scanned during microwave frequency sweep containing the resonant frequency. The $^{14}\text{NH}_3$ microwave absorption transitions are tabulated in Appendix A1 (see Ref. 7 for a more complete listing).

An absolute frequency calibration graph is recorded using the following method. The cavity wavemeter (C1 in Figure 2) is set to read the desired absorption frequency. For the calibration curves in Figure 6 the desired frequency is 22.653 GHz for the G:sQ(5,4) transition. The evacuated cavity is then set near the resonant frequency using the technique previously described (Section: The Microwave Circuit). Approximately 0.1 torr of $^{14}\text{NH}_3$ gas is added to the cell. The cavity tuning micrometer is adjusted to locate the dip in transmission monitored at D3 with a Tektronix 1A7A high gain differential amplifier having a $1\text{M}\Omega$ input impedance. The signal output of the 1A7A is then input to channel A of a Tektronix 475 oscilloscope and the $10\text{k}\Omega$ input of the boxcar integrator. The gate output of the triggered boxcar is input to Channel B of the 475 oscilloscope. The vertical display is set to "add" channel A and channel B. The gate of the boxcar is chosen to be much shorter in time than the transmission peak of the swept frequency klystron output. The time base of the boxcar is set to allow the gate to be delayed to any point of the frequency sweep. The cavity is adjusted to the desired starting

point and the gate output is adjusted to be at the resulting transmission peak. The cavity scan is then initiated, and manual feedback is used to keep the gate, by varying the delay of the boxcar, at the transmission peak. If the resulting graph exhibits excessive structure (i.e., noise) increase the integration time and/or aperture time. Care must be exercised to ensure there is no significant detection lag time in an accurate frequency calibration graph.

The cavity wavemeter (C1) calibration was verified to be within 5MHz of all the measured absorption frequencies. (For more details, see Appendix A2).

Cavity scans performed at different pressures and fixed input power provide information regarding emission bandwidth, saturation, and optimal operating conditions. Figure 7 shows the resulting cavity scans at various pressures. The emission bandwidth numbers are obtained by measuring the full width at half maximum length on the graph and multiplying it by the length to frequency conversion factor and scan rate factor

$$\Delta f(\text{FWHM}) = L \times \underset{\substack{\text{SCAN} \\ \text{FACTOR}}}{0.0452} \times \underset{\substack{\text{LENGTH} \\ \text{FREQUENCY} \\ \text{FACTOR}}}{\left| \frac{f_2 - f_1}{L_2 - L_1} \right|} \quad (1)$$

$\Delta f(\text{FWHM}) \rightarrow \text{GHz}$

$L \rightarrow \text{GRAPH PAPER INCHES}$

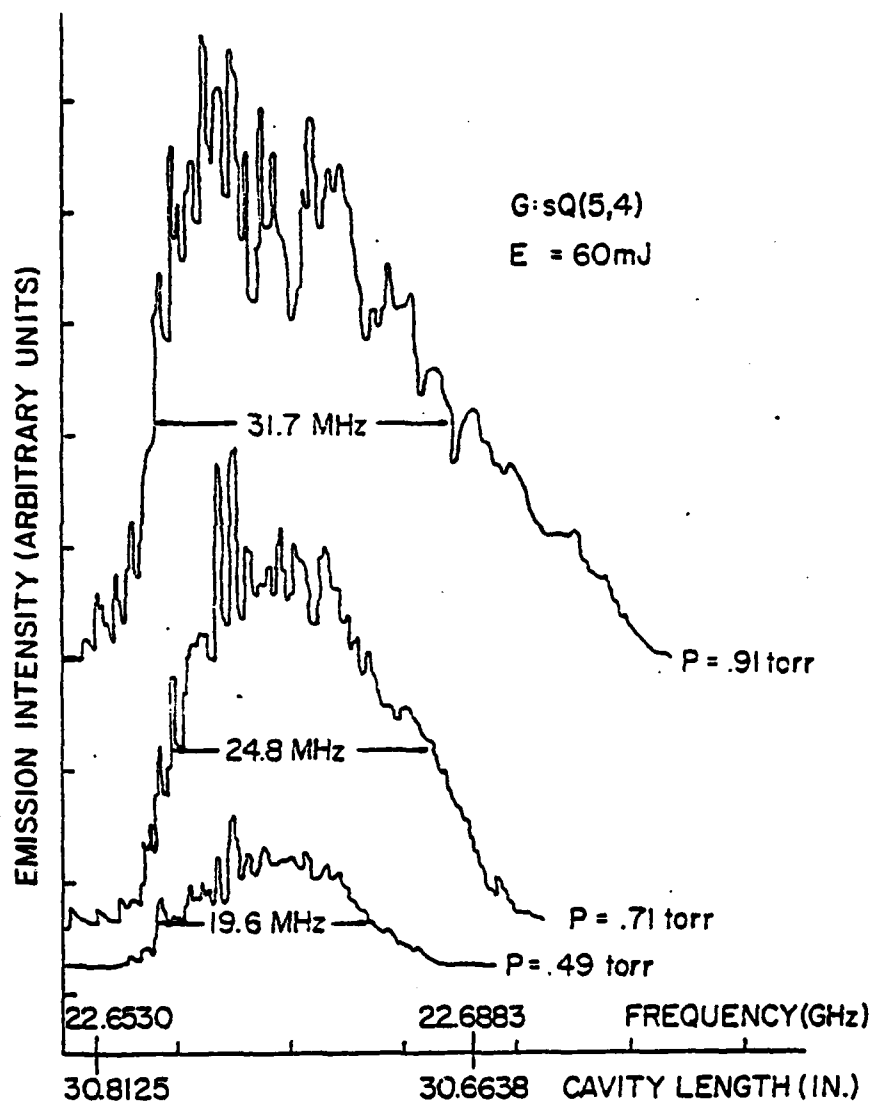


Figure 7. Cavity scans at different pressures for the G:sQ(5,4) emission. (TE_{11n} , $n=67$ mode) cavity length is 0.0452 inches/div., frequency scan is 10.8 MHz/div.

$0.0452 \rightarrow (\text{CAVITY SCAN INCHES}) / (\text{GRAPH PAPER INCHES})$

$f_2, f_1 \rightarrow \text{ABSOLUTE FREQUENCY CALIBRATION POINTS}$

$L_2, L_1 = n \frac{\lambda_{g2}}{2}, n \frac{\lambda_{g2}}{2} \rightarrow \text{ABSOLUTE LENGTH AT THE FREQUENCY CALIBRATION POINTS.}$

The accuracy of the measured emission bandwidth is limited by the emission structure observed in the cavity scans. Cavity scans at higher $^{14}\text{NH}_3$ pressures have been recorded but the structure observed makes it nearly impossible to measure the full-width half-maximum with any certainty.

Microwave Injection Effects

Microwave injection effects have been investigated with very limited success. The experiments were performed in hopes of producing information regarding magnitude, time, frequency, and saturation behavior of the emission gain. The difficulties in obtaining this information are multiplied by the high Q frequency characteristics of the interaction cell. To obtain reliable experimental data it is believed the cell used in the Kim¹ experiment would be better. Several interesting qualitative observations have been made and will be presented here.

The qualitative observations resulting from microwave injection mentioned above include: 1) change of the delay time for the gain switched microwave emission, 2) increased pressure

range operation of emission, 3) observation of the transmitted signal frequency beating with observed emission frequency, 4) increased emission bandwidth, 5) the microwave emission dependence on level of injection indicates the emission is saturated, and 6) time dependent gain is present in the microwave emission. The majority of these observations are not particularly surprising. A feature common to all of the observations is the dependence on injected microwave signal frequency.

Microwave injection effects are only observed when the injected microwave signal frequency is between 22.645 and 22.725 GHz. This is not symmetric with respect to G:sQ(5,4) transition at 22.653 GHz, but is consistent with the data observed in the cavity scans. Injection of signals at and around the Raman frequency peak at 22.109 GHz produced no obvious effects.

The most interesting observations are the indication of gain saturation and the time dependent gain of the emission. The gain saturation is observed by varying the input level of injection at various pressures. At pressures less than 1 torr the delay time decreases, the pulse length increases, but the peak amplitude remains very constant. The level of injection to produce these effects is not detectable at the transmission monitor diode (D3 in Figure 2). Increasing the level of injection an amount so as to be detectable at D3 (~ 10 db in power)

produces the identical result. This was observed near the peak emission cavity tuning. Tuning the cavity and microwave frequency to a point beyond the emission bandwidth half-power points produced similar results with more (but not much) dependence on signal level injection. The most obvious result is increased amplitude stability of the microwave emission. Tuning the cavity and injection frequency 15 MHz beyond the frequency where emission stops produces no effect.

At pressures greater than 1.5 torr, the emission bandwidth is observed to be decreasing. This is attributed to higher losses. Microwave injection can be used to increase the emission bandwidth. Stable amplitude pulses of emission can be observed at frequencies 30 MHz beyond the point where self-oscillation stops. At pressures greater than 3 torr no signals are observed. The particularly interesting feature of higher pressure (i.e., > 1.8 torr) injection experiments is the time behavior of the emitted signals.

The signal is observed to consist of two distinct pulses separated in time. The multi-pulse observation varies from pulse to pulse and cannot be reliably reproduced. The pulse occurring first is slightly delayed but overlaps in time with the infrared pump laser pulse. The later pulse amplitude and delay is relatively constant and is believed to be the usual microwave emission. The frequency dependence of the earlier

pulse on the injected microwave signal was observed to be shifted toward the higher frequency end (i.e., ~ 22.69 GHz) of the emission bandwidth. The observation of the earlier pulse is consistent with the results of Kim,¹ and will be considered in the discussion of results section.

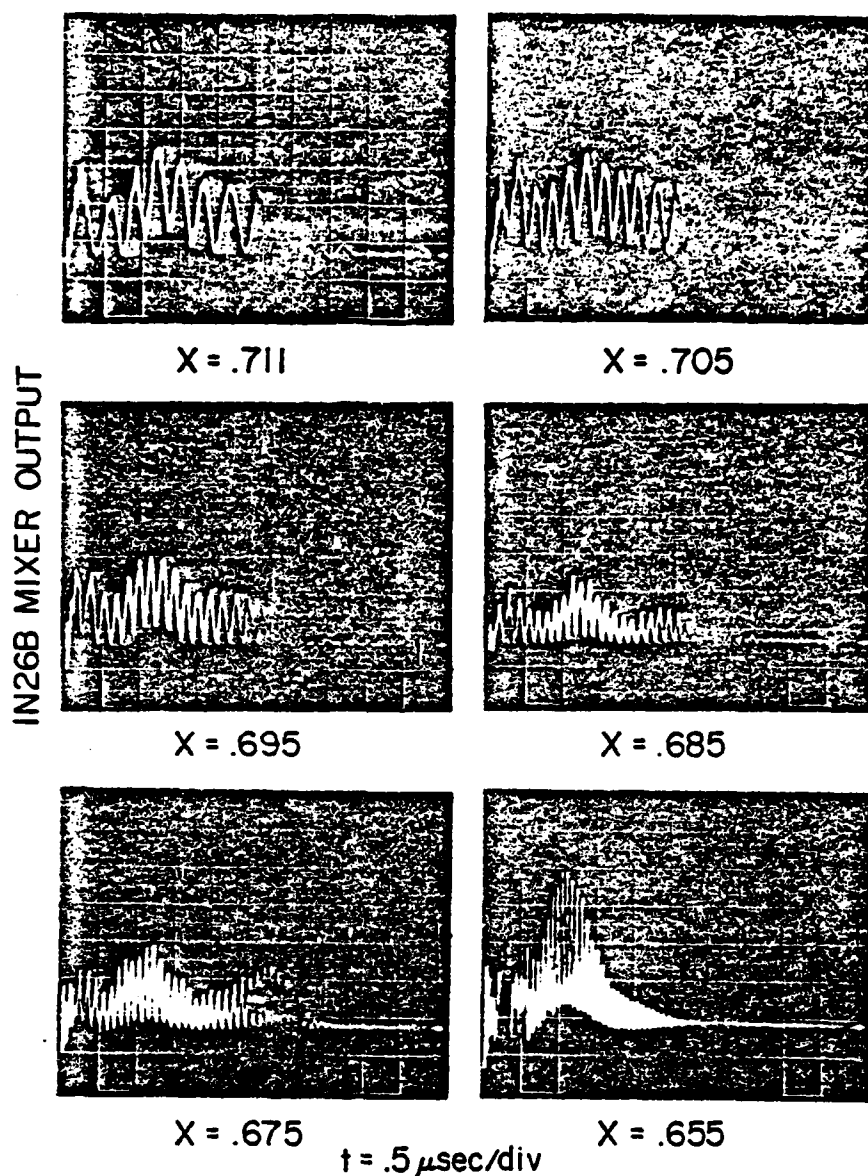
The injection of single frequency microwave radiation into the optically pumped $^{14}\text{NH}_3$ has produced results that could be studied more effectively using a different cell. An investigation of more importance to this study is tunability and stability of the optically pumped microwave emission.

Heterodyne Frequency Measurements of Tunability and Stability of the Optically Pumped Microwave Emission

Heterodyne frequency measurements provide a straightforward method of determining if a signal is tunable. The equipment required for a heterodyne detector¹⁰ are a mixer, and a local oscillator. The OKI klystron is used as the local oscillator and a 1N26B diode is used as the mixer (D2 in Figure 2). The klystron is operated in the fixed frequency mode and the cavity is tuned until a beat note is observed on the 200 MHz bandwidth TEKTRONIX 475 oscilloscope. Care was taken to avoid injection effects during the heterodyne measurements. This was achieved by padding the cell with considerable attenuation A2 and adjusting DS2 for minimal coupling. No injection effects were observed at D3.

Some observed beat frequencies are shown in Figure 8. The oscilloscope photographs were taken at different cavity micrometer settings (X). An interesting feature observed during the first 0.5 μ sec is the obviously different period of the beat frequency. Careful examination of this is inconclusive at best, the beat is reproducible but not understood. Figure 9 is a slightly different presentation of the data in Figure 8. The number of beat frequency peaks were counted and divided by the time interval (neglecting the first 0.5 μ sec) to obtain an approximate beat frequency and plotted as a function of cavity setting. The resulting curve is linear to within the accuracy of the measurement in agreement with the expected result. (See Appendix A1 for details on linearity of cavity tuning).

The method used above is a quick and dirty technique to demonstrate tunability. Stability of the microwave emission was examined and surprisingly stable reproducible beats were observed. The stability of the beat note is surprising because no attempt has been made to frequency stabilize the experiment. Recently, Fetterman, et al.¹¹ performed "real-time spectral analysis for FIR laser pulses" using a surface acoustic wave (SAW) reflective array compressor (RAC) device. Bob Miller, a member of this laboratory, is currently working on a similar project. The optically pumped microwave emission observed and the heterodyne detection system already being used suggested



G:sQ(5,4) $^{14}\text{NH}_3$ at .54 torr
 LOCAL OSCILLATOR FREQUENCY 22.670 GHz

Figure 8. Oscilloscope trances of observed beat notes at different cavity length settings. G:sQ(5,4) emission in TE_{11n} ($n=68$) mode.

easy implementation of a spectral analysis system. The system used was set up with the help of Bob Miller.

A block diagram of the resulting real-time spectral analysis data acquisition system is shown in Figure 10. The specifications for the Raytheon RAC device are:

$$f_0 = 60 \text{ MHz}$$

$$\text{Bandwidth} = 6 \text{ MHz} \equiv B$$

$$\text{Dispersion Time} = 20 \text{ } \mu\text{sec} \equiv T$$

$$\text{Number of Resolvable Frequencies } 11$$

$$\text{Frequency Resolution } 0.55 \text{ MHz}$$

$$\text{Minimum Pulse Width } 0.667 \text{ } \mu\text{sec}$$

$$\text{Maximum Pulse Width } 1.217 \text{ } \mu\text{sec}$$

The RAC device acts as a linearly dispersive delay line with the center frequency (f_0) being delayed $T/2$. The bandwidth divided by the dispersion time (i.e., B/T) gives the dispersion rate ($= 0.3 \text{ MHz}/\mu\text{sec}$). Thus if one were to apply a single frequency pulse with the correct frequency (f_0) and pulse width ($t_{\min} < t_p < t_{\max}$), the Fresnel transform of the pulse will be the output of the RAC device. (For further details, see Refs. 11, 12 and 13). The advantage of using the RAC device to measure the frequency tuning is the linearity of the delay with respect to frequency. Frequency stability measurements become much more quantitative than the observations mentioned previously.

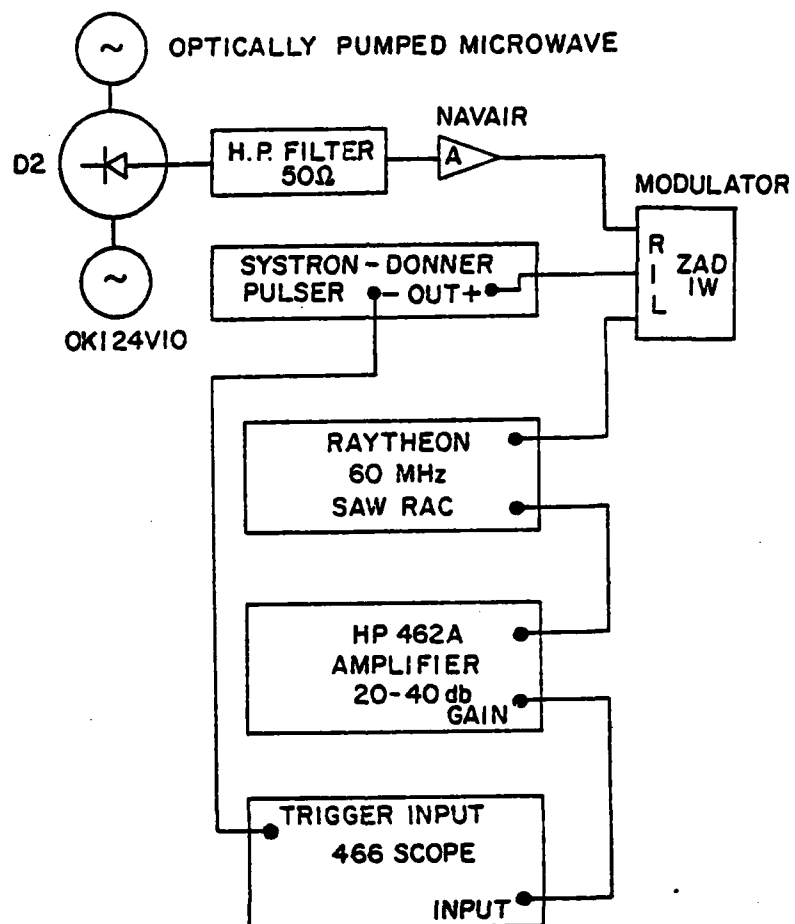


Figure 10. Real-time spectral analysis of the optically pumped microwave emission block diagram.

Cavity tuning of the optically pumped emission demonstrated a linear dependence of frequency with length in agreement with Figure 9 and Appendix A2. The study of cavity tuning length actually requires a much wider bandwidth RAC device than the 6 MHz bandwidth device used. A 6 MHz bandwidth corresponds to tuning the cavity length approximately 0.025 inches for the 22.66 GHz TE_{11n} ($n=67$) mode. The measured change in cavity length was 0.028 inches, in good agreement with expected value.

The most impressive results obtained with the 60 MHz RAC device are shown in Figure 11. The microwave emission was gated by a 1 μ sec pulse from the triggered SYSTRON-DONNER pulser applied to the modulator in Figure 10. The gate was delayed past the initial 0.5 μ sec of the pulse. The photographs shown are the amplified output of the 60 MHz RAC with a local oscillator frequency of 22.605 GHz and a fixed cavity length setting (micrometer reading = 0.305). Each photograph in Figure 11 is a recording of the tenth consecutive pulse. The pulses not recorded exhibit the same stability. The shape of the curves resembles the $(\sin x)/x$ frequency distribution expected for square wave pulse input.¹³ The results indicate frequency stability of the optically pumped microwave emission, to well within 1.5 MHz over 60 consecutive shots. This is indeed impressive because no attempt to frequency stabilize any part of

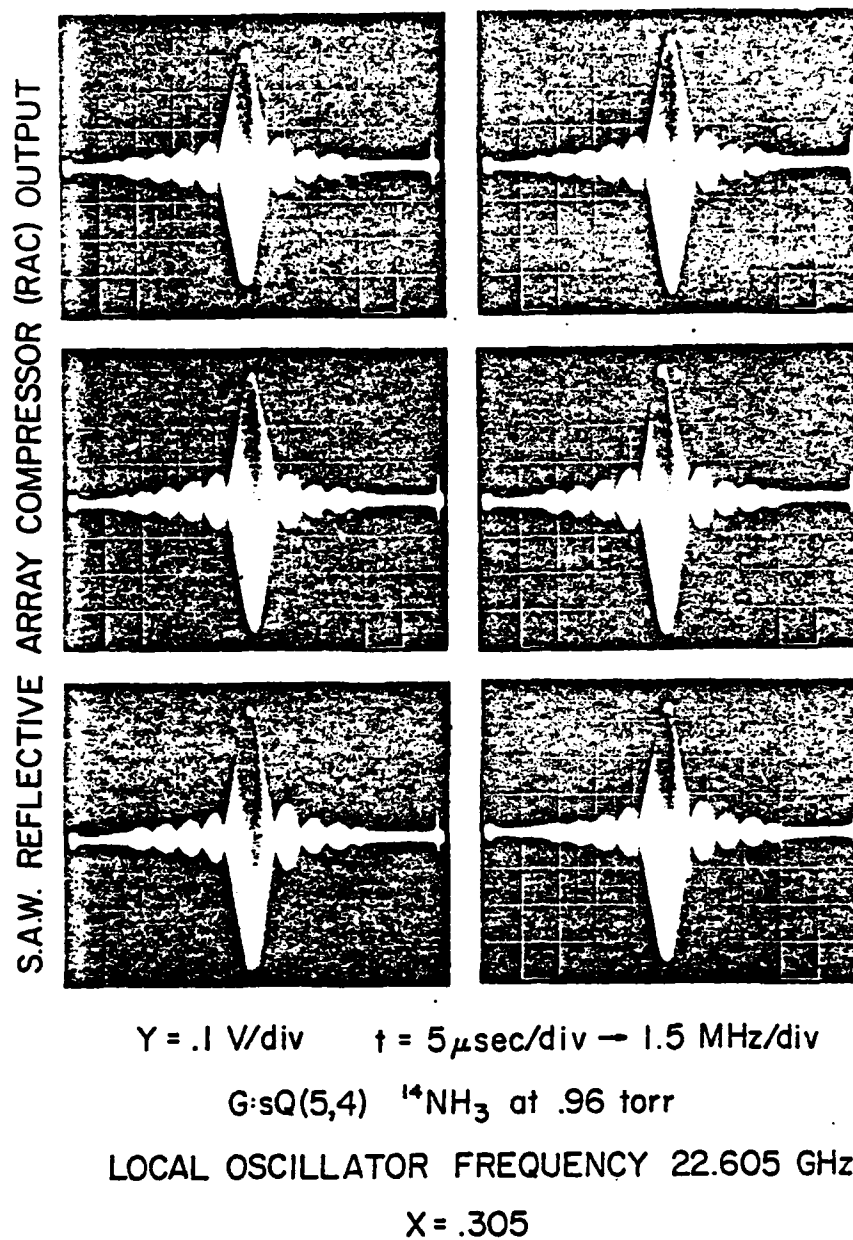


Figure 11. Oscilloscope traces of real-time spectral analysis of the optically pumped microwave emission. Each photo represents the tenth consecutive pulse.

the system, including the OKI 24V10 klystron was made. Changing the pump laser power and cell pressure affected the envelope of the resulting real-time spectra, but did not change the observed beat frequency.

It was initially hoped that the index of refraction effects could be measured with the RAC device, however, the index changes are so small that no frequency shift larger than the possible experimental error could be observed over the emission operating pressure range. A much longer cell length may be required to obtain a measurable frequency shift.

The surface acoustic wave RAC device has been used to demonstrate the high level of frequency stability of the optically pumped microwave emission. The use of a wider bandwidth (i.e., 100 MHz bandwidth) RAC would provide more detailed information regarding the emission bandwidth and linearity in cavity tuning of the pumped emission. The power of real-time spectral analysis using this technique cannot be overrated.

Discussion of Results

The results observed in these experiments, present an alternative method to generate NH_3 maser emission. Similar results have been obtained for the $\text{G:sQ}(2,2)$ transition pumped by the CO_2 $\text{R}(8)_{10}$ laser line. Cavity scans for this system are shown in Figure 12. The emission is attributed to the same type of process.

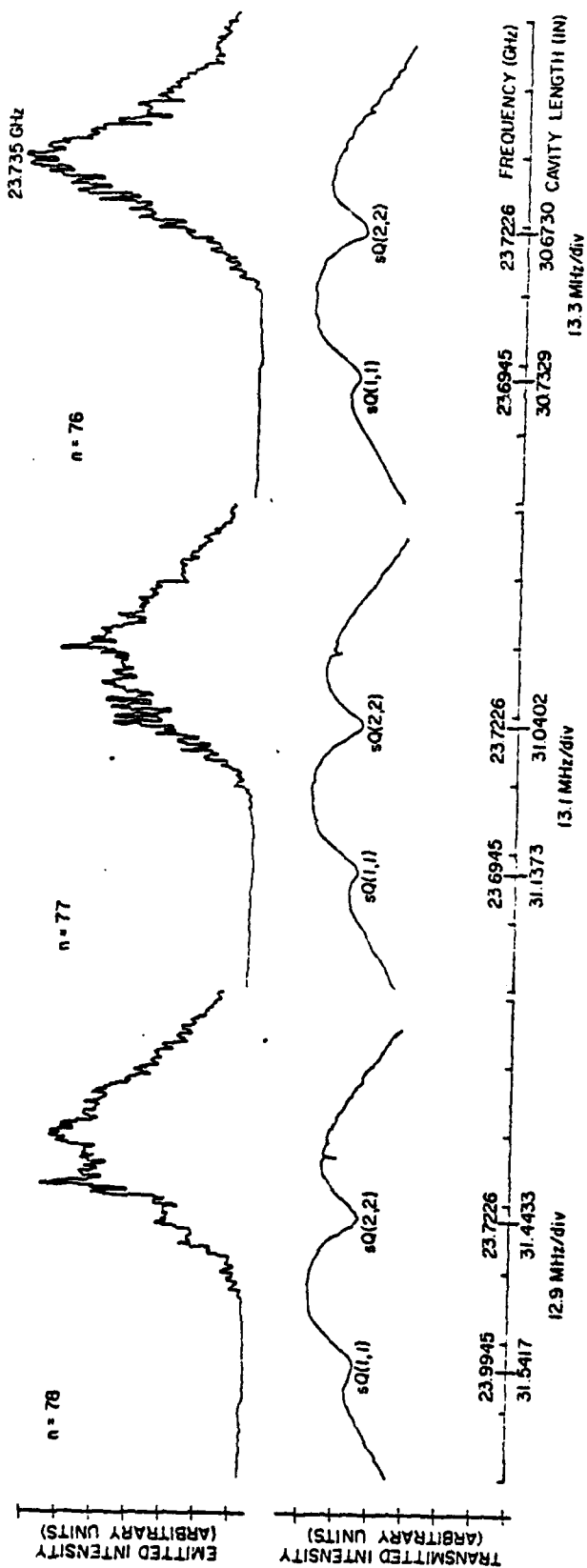


Figure 12. Cavity scans of the $G:sQ(2,2)$ emission (upper curves) and microwave absorption calibration scans (lower curves). The cavity scan length is 0.0452 in/div. The cavity emission modes are TE_{11n} ($n=76, 77, 78$). The pump laser is $CO_2 R(8)_{10}$, $E_L = 80mJ$, $^{14}NH_3$ pressure is 1.1 torr.

The microwave emission is attributed to a linear cascade lasing process. The data supporting this includes: 1) the distinctive time delay between the pump laser and the observed emission; 2) the observed emission bandwidth; 3) the frequency stability of the microwave emission; and 4) decoupling of the microwave emission from the FIR emission.

The distinctive delay associated with the initiation of the gain switched microwave emission is a characteristic of cascade emission. The delay has a very weak dependence on cell pressure as can be observed in the time synchronized photos (traced) of Figure 5. The frequency stability of the emission is partially caused by the decoupling of the infrared pump laser pulse. The emission center frequency would exhibit dependence on the infrared pump power. Observations made during several different power runs indicate decreased amplitude stability by lowering the pump power. The location of the emission center frequency does not change.

The microwave emission and FIR emission were simultaneously monitored during several cavity scans. No obvious correlation was observed between the microwave and FIR. The observed decoupling further supports the linearity of the emission.

The bandwidth of the observed microwave emission is saturated and homogeneously broadened. The CW two-photon pumped FIR laser observed by Willenberg⁸ exhibits the Doppler

broadened width of the two-photon pump transition. The same behavior would be expected for a single photon optically pumped emission. No evidence of non-linear behavior has been observed for the G:sQ(5,4) emission so the emission is believed to be linear.

The linear emission is different than that observed by Kim and Coleman,¹ but their results provide additional understanding needed to explain some of the observed results.

The microwave emission can be theoretically modeled using a single-photon two-level density matrix formalism. The density matrix theory treats the coherence between the energy levels coupled by the maser field. For a comprehensive explanation of density matrix theory, see Refs. 14, 15 and 16. The detailed derivation of the complex susceptibility is outlined in Section 8.1 of Ref. 16. Two differences in the G:sQ(5,4) system and the single-photon two-level calculation assumptions should be noted. The treatment in reference 16 assumes only two levels are involved in the interaction, the experimental system actually consists of degenerate energy levels. There are eleven degenerate M values (i.e., $2J+1$, $J=5$) for the upper and lower levels. The presence of the G:sQ(4,3) transition may also effect the two level assumption. The remaining assumptions are consistent with the experiment. The imaginary and real parts of the susceptibility are given in Equations (2) and (3).

$$\chi''(\omega) = \frac{\mu^2 T_2 \Delta N_0}{\epsilon_0 \hbar} \frac{1}{1 + (\omega - \omega_0)^2 T_2^2 + 4\Omega^2 T_2 T_1} \quad (2)$$

$$\chi'(\omega) = \frac{\mu^2 T_2 \Delta N_0}{\epsilon_0 \hbar} \frac{(\omega - \omega_0) T_2}{1 + (\omega - \omega_0)^2 T_2^2 + 4\Omega^2 T_2 T_1} \quad (3)$$

ΔN_0 - Population difference at zero field

$$T_2 = T_1 = 1.326 \times 10^{-8} \text{ sec-torr}$$

$\Omega = \mu E_0 / 2\hbar \equiv$ Precession (Rabi) frequency

The absorption/gain can be calculated from the imaginary part of the susceptibility and the index of refraction may be calculated from the real part. The importance of equations (2) and (3) is the resulting Lorentzian line shape of the absorption/gain. This width is 23 MHz/torr for $^{14}\text{NH}_3$ ground state inversion transitions. A consequence of saturation is broadening of the Lorentzian line shape given by Equation (4)

$$\Delta\nu_{\text{SAT}} = \Delta\nu \sqrt{1 + \frac{\mu^2 E_0^2 T_2 T_1}{\hbar^2}} \quad (4)$$

The problem with using this model is that the frequency shift of the microwave emission observed in the cavity scans is not explained.

The emission frequency shift observed in the cavity scans is believed to be the result of the time dependent gain observed during the microwave injection experiments. The

results of Kim indicate strong gain occurring during the presence of the infrared pump pulse. Figure 13 (reproduced from Kim's paper) gives the AC Stark shifted laser and Raman frequencies as a function of the laser power density. The laser frequency peak is always shifted to a higher frequency for the G:sQ(5,4) system. If the emission level occurring during the laser pulse was lower than the noise level (i.e., non-detectable), injection locking of the observed emission by the non-detectable emission could occur. The large delay and gain switched pulse shape of the microwave emission would tend to disprove this explanation.

The cavity scans produce emission bandwidth greater than the homogeneous linewidths. Equation (4) can be used to determine the Rabi frequency and hence relative field strengths of the microwave emission. The calculation results are:

<u>PRESS(torr)</u>	<u>$\Delta\nu_H$ (MHz)</u>	<u>$\Delta\nu_{SAT}$ (MHz)</u>	<u>$\frac{\mu E}{h}$ (MHz)</u>	<u>$\frac{\mu E}{h} \Delta\nu_H$</u>
.49	11.27	19.6	31.77	2.819
.71	16.33	24.8	38.56	2.36
.91	20.93	31.7	49.23	2.35

Using the measured emission linewidth at 0.91 torr and neglecting the M degeneracy, a circulating power density of 0.54 watts/cm² is calculated. The ratio of the Rabi to the homogeneous linewidth is the measure of saturation. The results

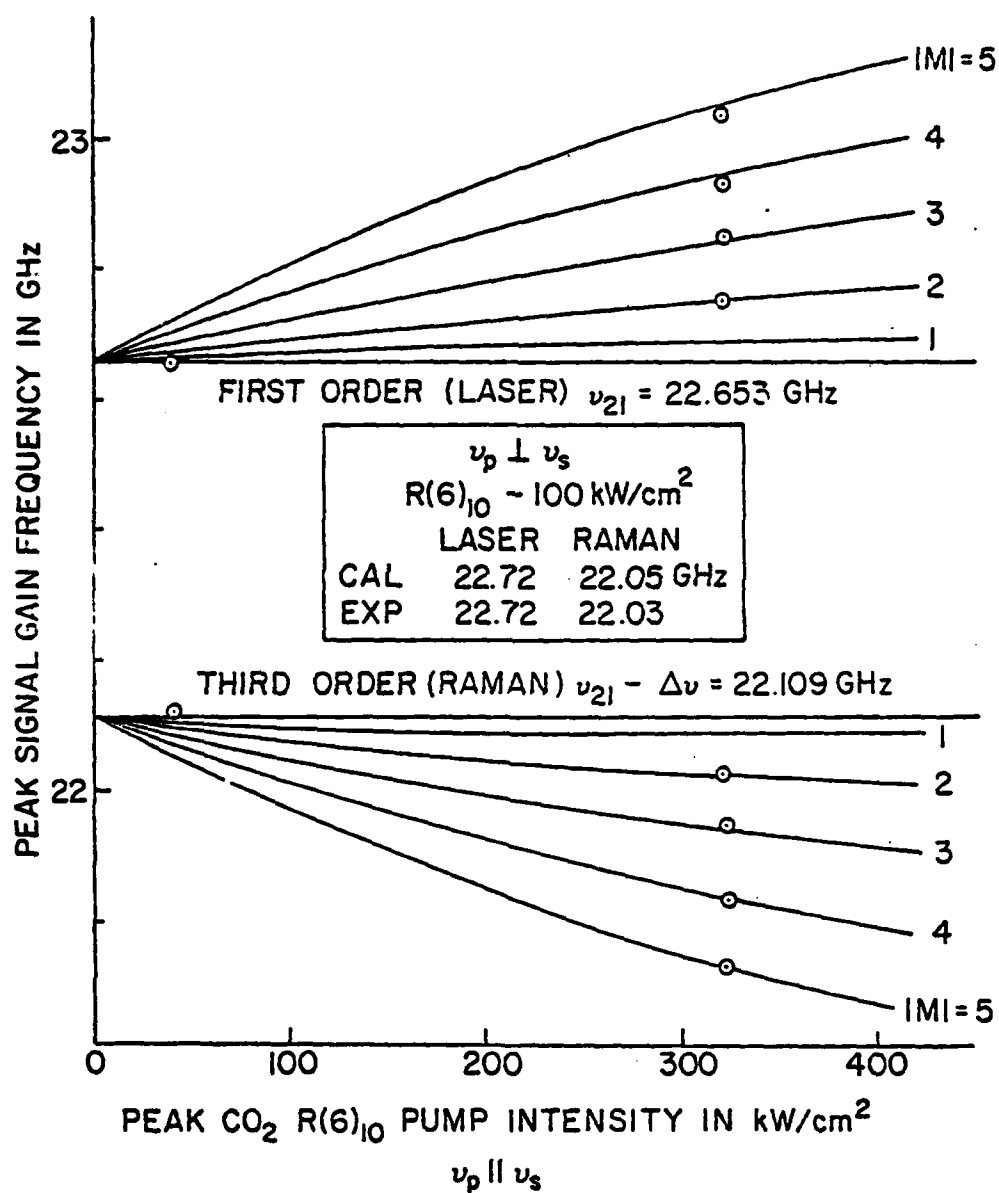


Figure 13. M-splittings of gain frequency peaks with pump intensity for gain experiment G:sQ(5,4).¹

of microwave injection experiments concerned with saturation agree with the cavity tuning results in that the degree of saturation decreases with increasing pressure. The saturation, tunability, and frequency stability suggest the observed emission may be a valuable tool as a source to study other processes in $^{14}\text{NH}_3$.

Conclusions

Microwave emission attributed to a linear cascade effect has been observed from $^{14}\text{NH}_3$ optically pumped by a TE- CO_2 laser. The emission is tunable over the saturated homogeneous linewidth (i.e., $> 24 \text{ MHz/torr}$) and exhibits a high degree of frequency stability. The output power density determined from the saturated emission bandwidth is 0.54 watts/cm^2 at 0.91 torr . The observed emissions are assigned to G:sQ(5,4) and G:sQ(2,2) ground state inversion transitions.

There are many other candidate systems for which this type of microwave emission should be observed. The criterion for a candidate system is: 1) a laser- $^{14}\text{NH}_3$ absorption match with a frequency mismatch less than 1.5 GHz , 2) the lower level of the NH_3 absorption must be the symmetric energy level of the inversion doublet, 3) the inversion doublet exists (i.e., $K \neq 0$). The obvious candidates are the laser-absorption matches that produce optically pumped FIR emission. Appendix A1 includes

a "match list" to be examined for possible candidates. Only $^{14}\text{NH}_3$ has been considered in this investigation, further study should produce similar results for other molecules with inversion symmetry.

V. INTERACTION BETWEEN MULTIPLE GENERATED LASER SIGNALS IN OPTICALLY PUMPED FAR IR SYSTEMS - W. Lee

Introduction

Single-photon pumping of gaseous molecules to generate IR or FIR radiation has been analyzed usually by the density matrix calculation of a two-wave three-level system.¹ The processes being studied consisted of one-photon (lasing) and two-photon (Raman) interactions. For multi-line emission, however, the simple model becomes inadequate. As shown in Figure 1, the pump P generates emissions E_1 and E_2 either directly or by a cascade process. When E_1 and E_2 are weak, there is negligible interaction between them and the system can be considered as two independent, two-wave, three-level systems. As the signals E_1 and E_2 increase, the emissions will affect each other through two-photon and three-photon processes. To study the coupling between the signals, a density matrix calculation has been applied to a three-wave four-level system in NH_3 .

Emission Coupling in Optical Triple Resonance

In triple resonance systems, studies have been reported on the hyper-Raman^{2,3} and Raman⁴ processes. The nonlinear effects on the emission was investigated with fixed detuning of the other two waves. When there are two emissions, the detuning of one of them will be affected by the detuning of the

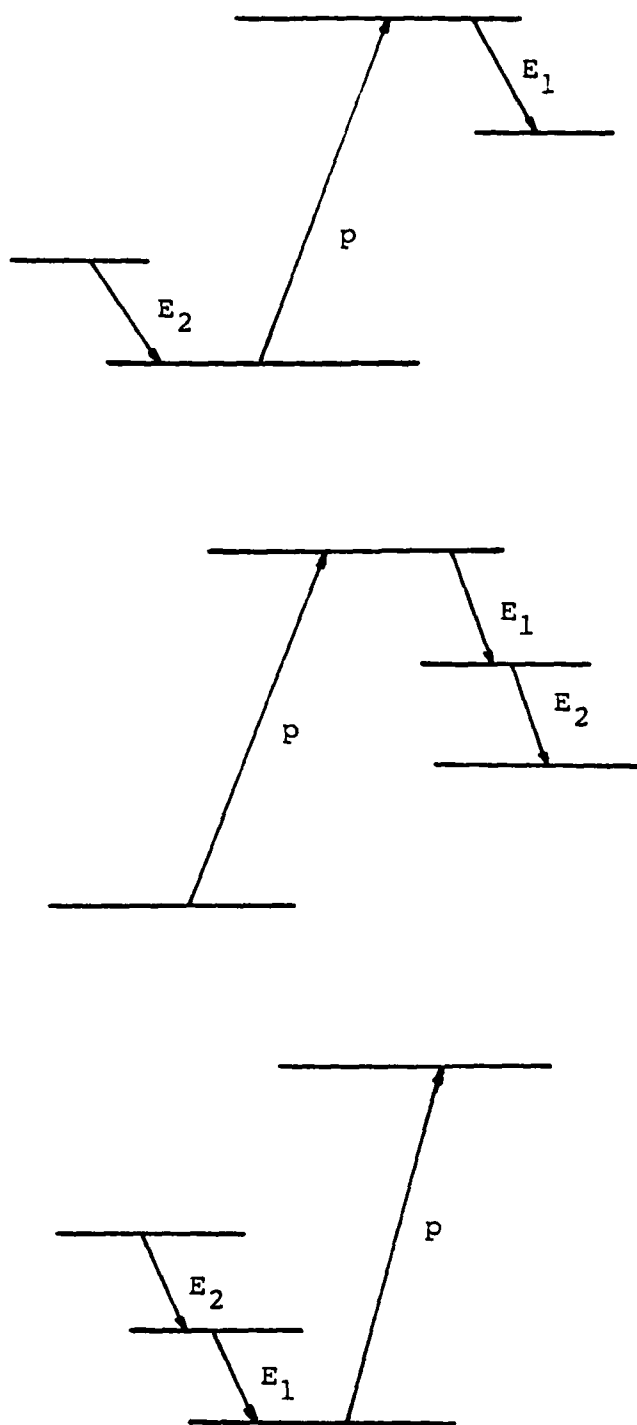


Figure 1. Triple resonance by single-photon pumping.

other one and vice versa. Because there is no direct way to determine the detuning of any one of the emissions when they are both strong, the problem becomes very tedious to solve. That is, the detuning of Δ_1 of Emission E_1 as a function of detuning Δ_2 of emission E_2 , i.e., $\Delta_1 = \Delta_1(\Delta_2)$ has to be found, and similarly for $\Delta_2 = \Delta_2(\Delta_1)$. A self-consistent calculation of $\Delta_1(\Delta_2)$ and $\Delta_2(\Delta_1)$ will be given the coupling frequencies of the two emissions.

FIR-Microwave Emission Coupling System in $^{14}\text{NH}_3$

Because the spectroscopy of NH_3 is well-known⁵ and a tunable microwave source in the 18-26 GHz region is readily available, NH_3 is a good candidate for emission coupling studies.

The triple resonance system considered here is shown in Figure 2. The $R(14)_{10}$ line from a CO_2 TEA laser pumps the $\text{Ga}(1,1)$ state to generate the FIR (256.7 μ) emission,⁶ which then induced the cascade emission of the 23.1 GHz microwave signal.⁷ A tunable backward oscillator provides the microwave signal to probe the energy shifts of states $G(1,1)$ and $G_s(2,1)$ so that the detuning Δ_1 and Δ_2 can be determined.

M-Splitting and Polarization

For the pumping transition $\text{Ga}(1,1) \rightarrow v_2s(2,1)$, the change of the angular momentum ($|\Delta J| = 1$) implies that the preferable direction of the quantization axis J_z is perpendicular to the polarization direction of the pump. Since the pump is linear

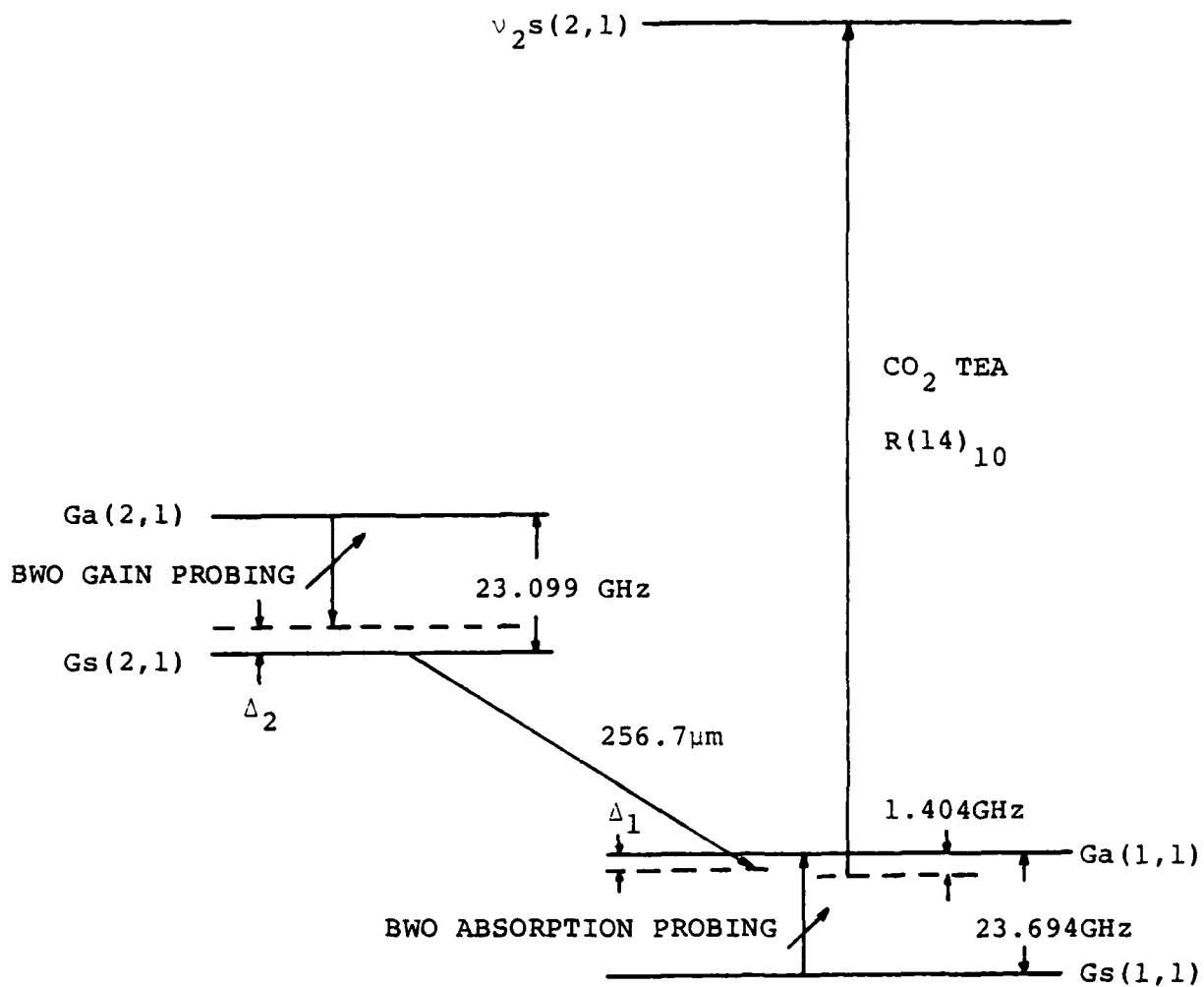


Figure 2. Infrared, far infrared and microwave triple resonance system for emission coupling study.

polarized along $\hat{x}$ or $\hat{y}$ direction, in terms of the raising and lowering operator $J_x \pm iJ_y$, the selection rule for the M-sublevel will be $\Delta M = \pm 1$. Similarly, the same rule applies to the FIR transition $Gs(2,1) \rightarrow Ga(1,1)$. Due to the cell design (Section III), the microwave will be polarized along the same direction as the other two waves.

Using the selection rule $\Delta M = \pm 1$ for all three transitions, it is seen that twenty transitions will be involved as listed in Table 1. The transition matrix element between two M-sublevel can be calculated by the Wigner-Eckart theorem.⁸

Result of Calculations

The calculations were based on the density matrix equations for a three-wave four-level system as described in Section III.

1) Threshold and Saturation Intensities of the Pump

Small signal gain for the FIR was plotted as a function of its detuning from line center. The intensities of the microwave and the FIR signals were set at $1 \mu W/cm^2$, while the intensity of the pump was changed from $1 kW/cm^2$ to $400 kW/cm^2$, as shown in Figures 3 through 8. The negative gain peak around zero detuning is the linear contribution. The threshold intensity of the pump for generating the FIR was shown to be about $10 kW/cm^2$ as a Raman peak appeared about 1.4 GHz detuned from the line center in Figure 4. The Raman gain kept on increasing with the pump intensity until the pump reached about $200 kW/cm^2$,

Table 1. Twenty combinations of three M-sublevel transitions.

Ga(2,1)	Gs(2,1)	Ga(1,1)	$\nu_2s(1,1)$
$M_1 \longleftrightarrow M_2 \longleftrightarrow M_3 \longleftrightarrow M_4$			
2	1	0	1
2	1	0	-1
1	2	1	2
1	2	1	0
1	0	1	2
1	0	1	0
1	0	-1	0
1	0	-1	-2
0	1	0	1
0	1	0	-1
$M_i \longrightarrow -M_i$			

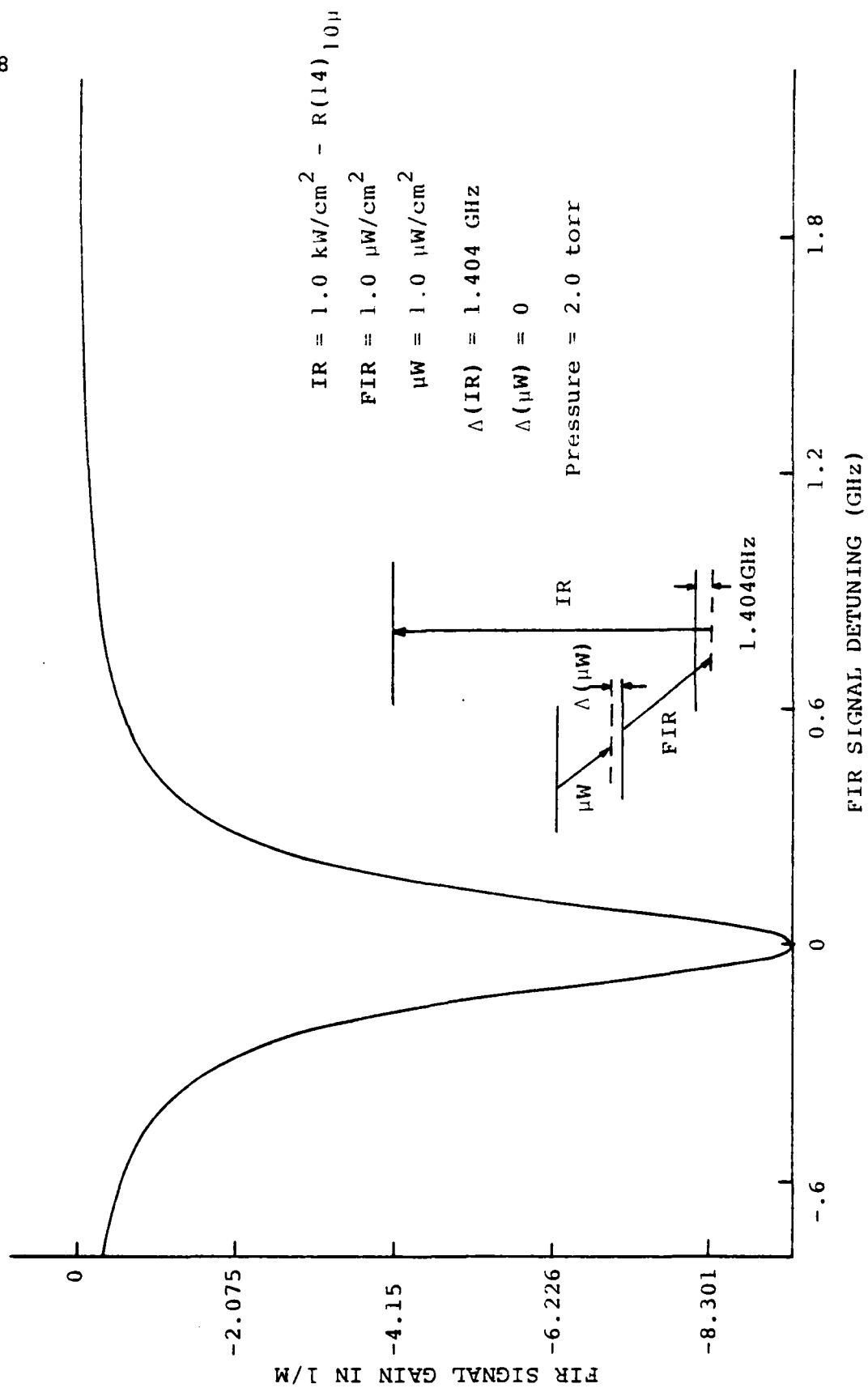


Figure 3. Gain curve for FIR pumped by $R(14)_{10}$ of 1 kW/cm^2 intensity.

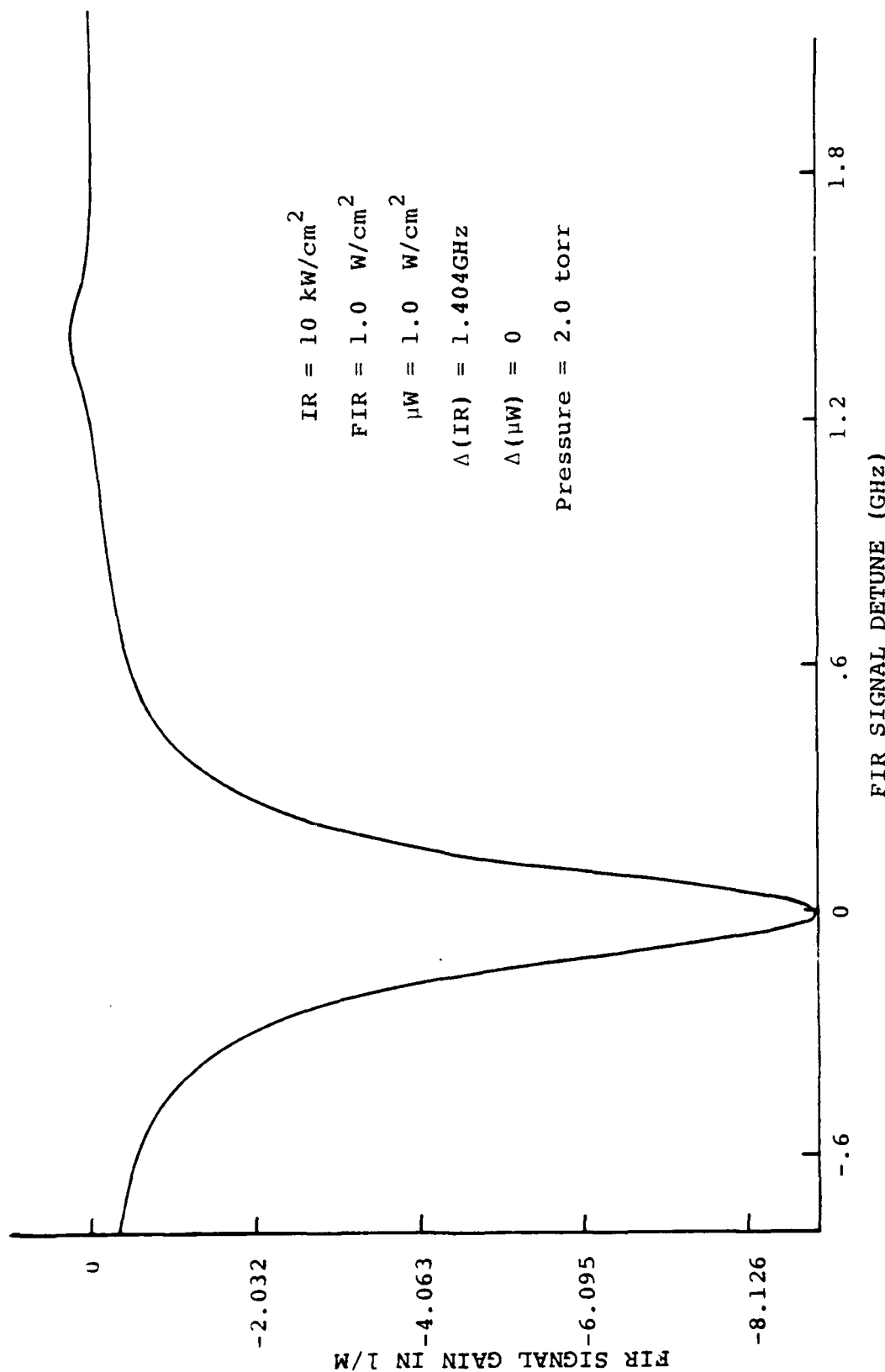


Figure 4. Gain curve for FIR pumped by R(14)₁₀ of 10 kW/cm² intensity.

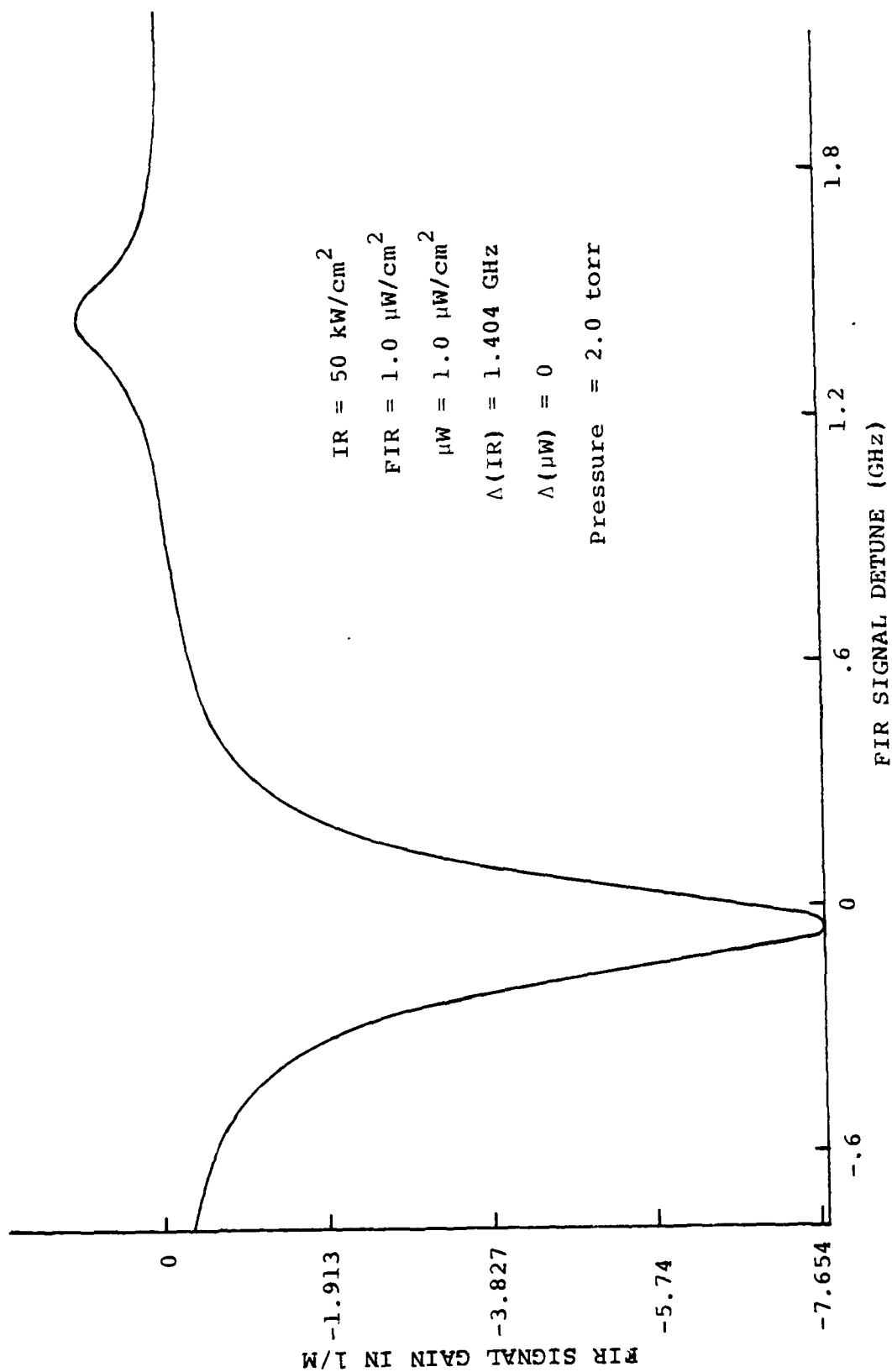


Figure 5. Gain curve for FIR pumped by R(14)₁₀ of 50 kW/cm² intensity.

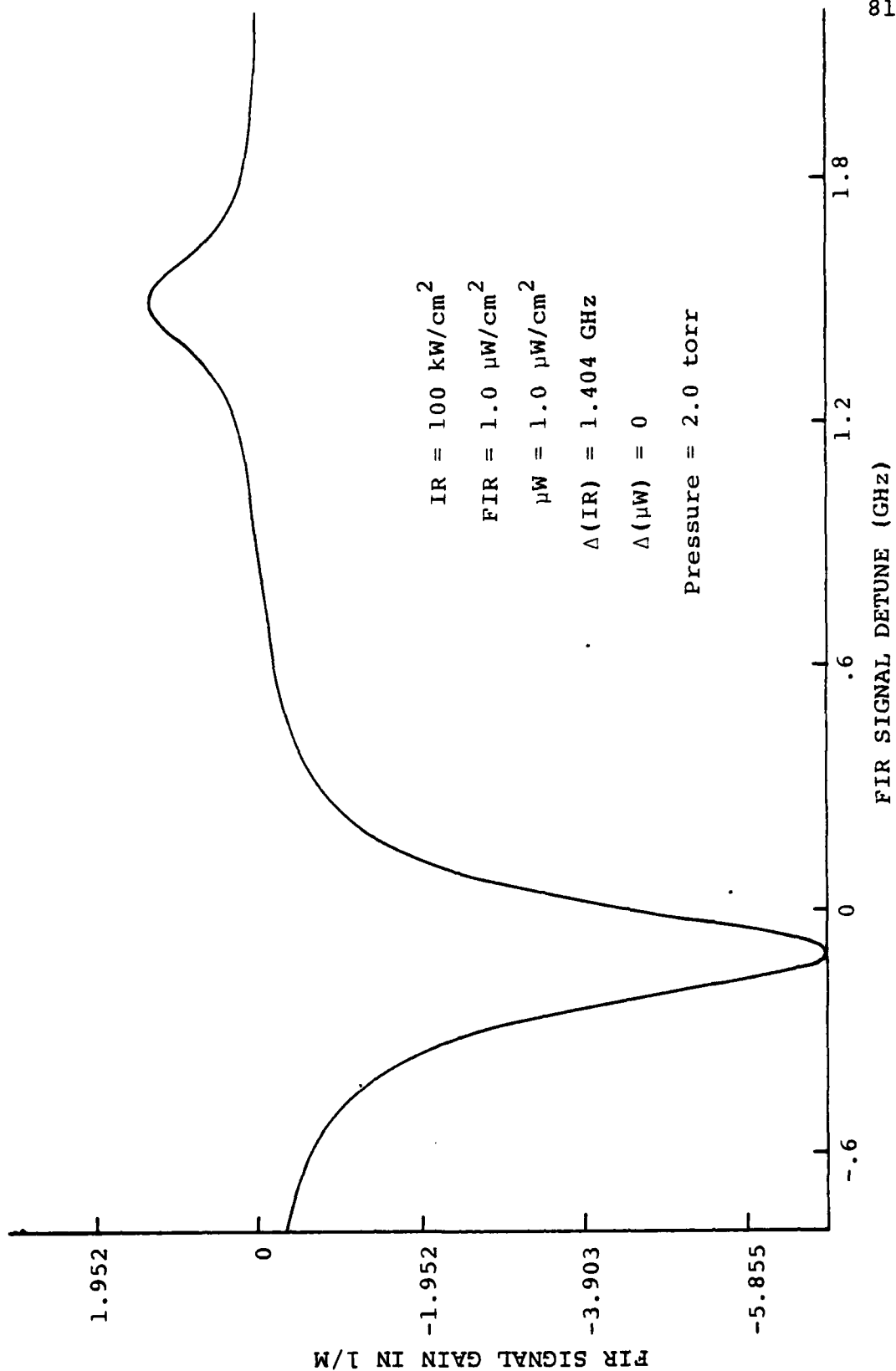


Figure 6. Gain curve for FIR pumped by R(14)₁₀ of 100 kW/cm² intensity.

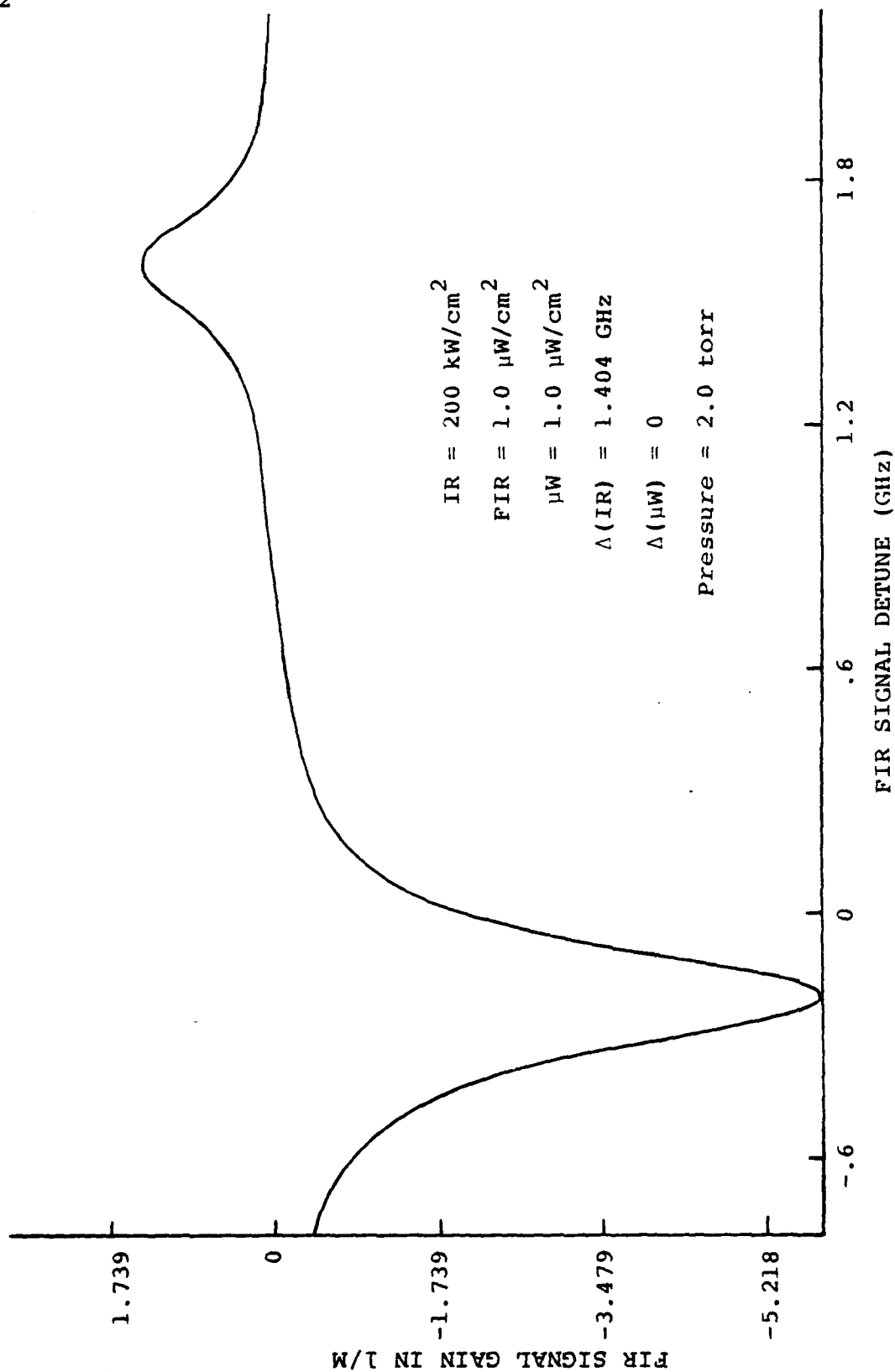


Figure 7. Gain curve for FIR pumped by R(14)₁₀ of 200 kW/cm² intensity.

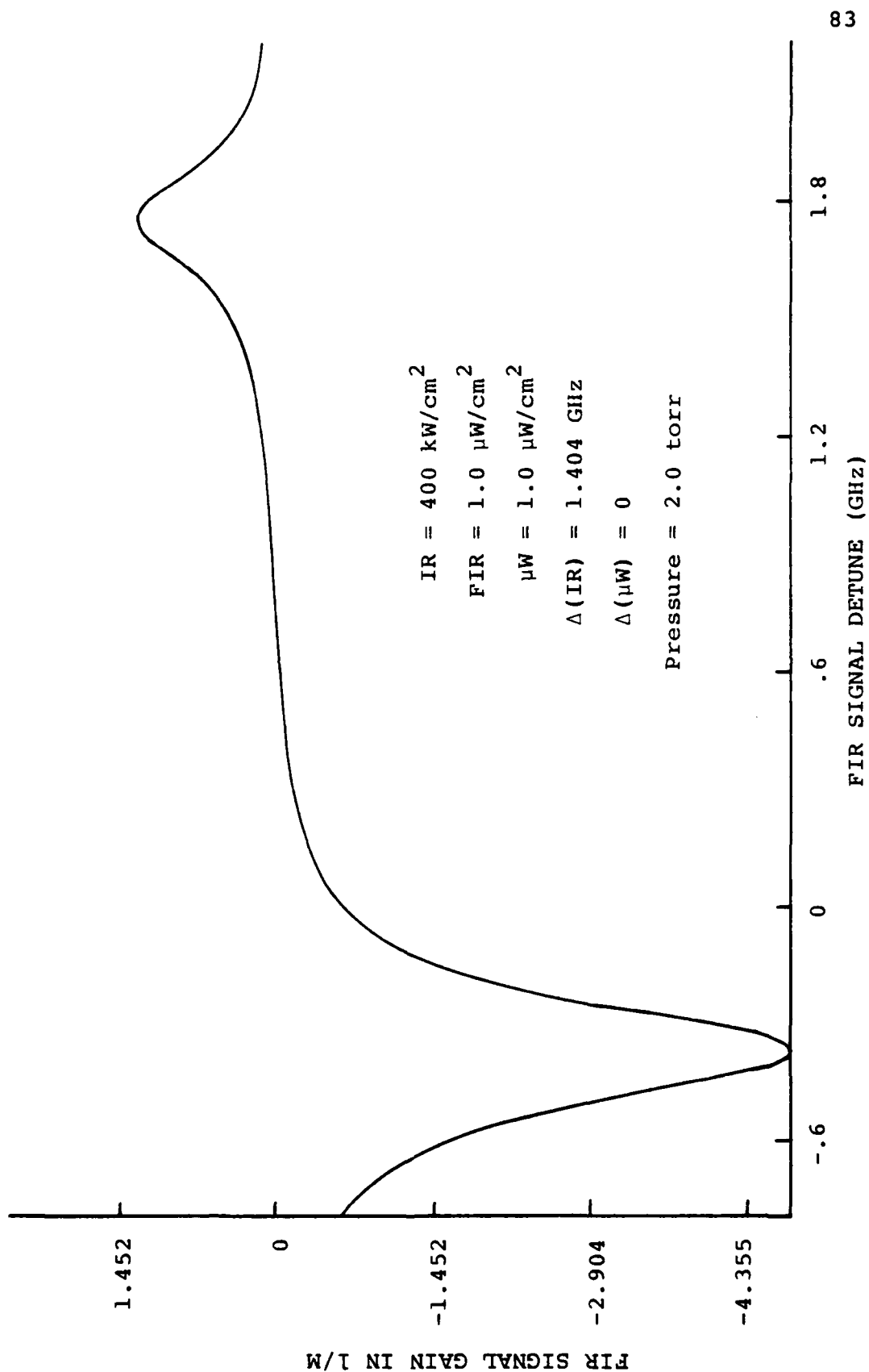


Figure 8. Gain curve for FIR pumped by R(14)₁₀ of 400 kW/cm² intensity.

which would be the saturation intensity.

2) Saturation Intensity of the FIR

Fixing the pump intensity at 200 kW/cm^2 , changing FIR intensity from $1 \text{ }\mu\text{W/cm}^2$ to 100 kW/cm^2 (Figure 7, Figures 9-12), showed appreciable drop of the gain of FIR from intensity 1 kW/cm^2 to 10 kW/cm^2 . With pump depletion, optical cell losses and limit of quantum efficiency, the FIR generation would be difficult to reach more than 10 kW/cm^2 .

3) Microwave Spectra

Gain curves for microwave signals were plotted for three different microwave intensities (Figures 13-15). The absorption peak at 0.9 GHz detuning is the linear contribution while the one on the other side is the Raman contribution. The positive gain peak at -0.07 GHz is the hyper-Raman contribution.

4) FIR and Microwave Frequency Coupling

The microwave detuning was plotted as a function of the FIR detuning shown in Figure 16 as $\Delta_{\mu\text{W}}(\Delta_{\text{FIR}})$. The same was done for $\Delta_{\text{FIR}}(\Delta_{\mu\text{W}})$. The frequency offsets were found to be 1.60 GHz for FIR, and -0.006 GHz for the microwave signal.

Conclusion

The emission coupling of a triple resonance system has been analyzed. A method of calculation, based on density matrix equation, has been developed to reveal Raman and hyper-Raman contribution to each of the emissions. The calculation also

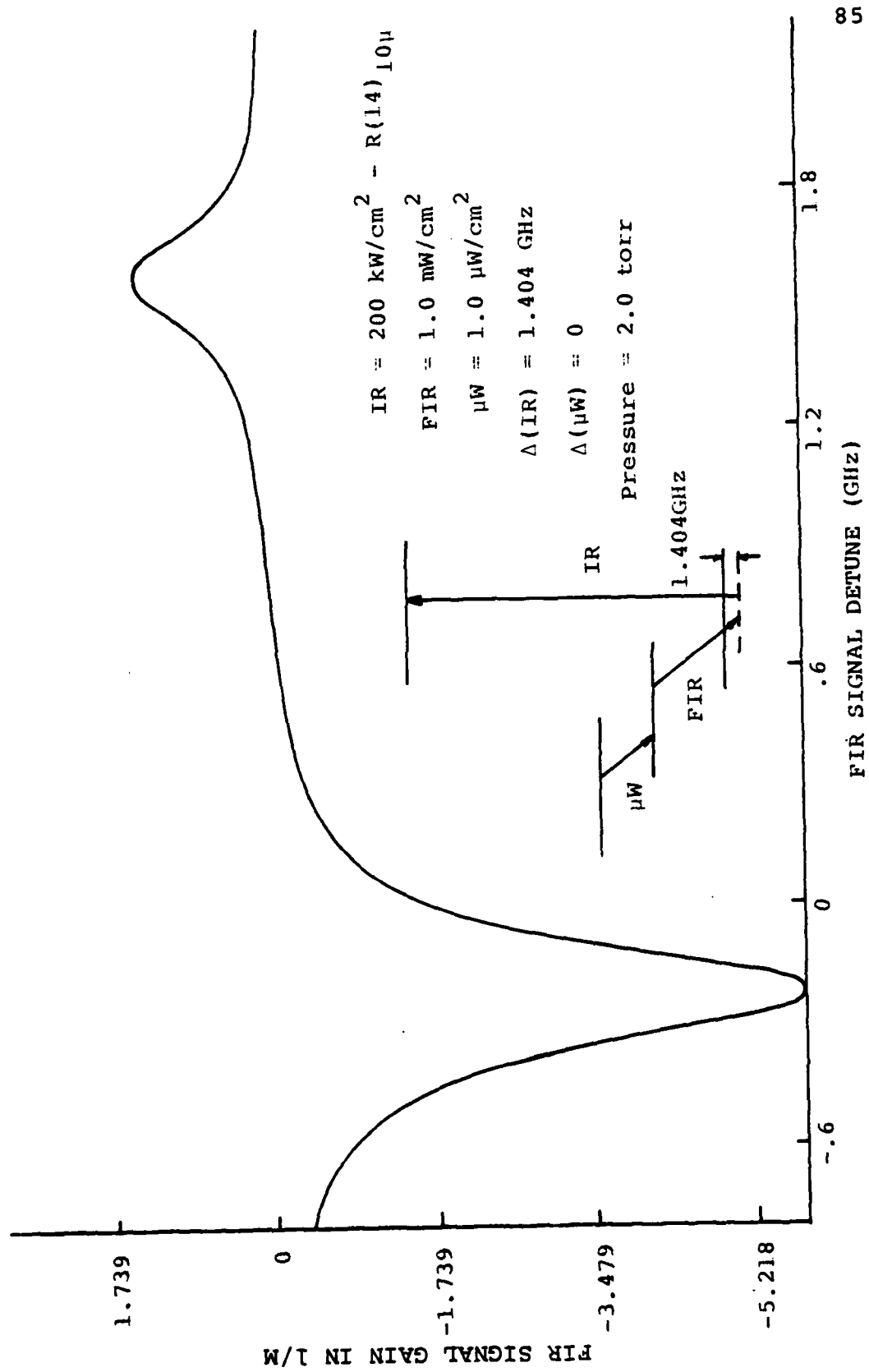


Figure 9. Gain curve for FIR of 1.9 mW/cm^2 intensity.

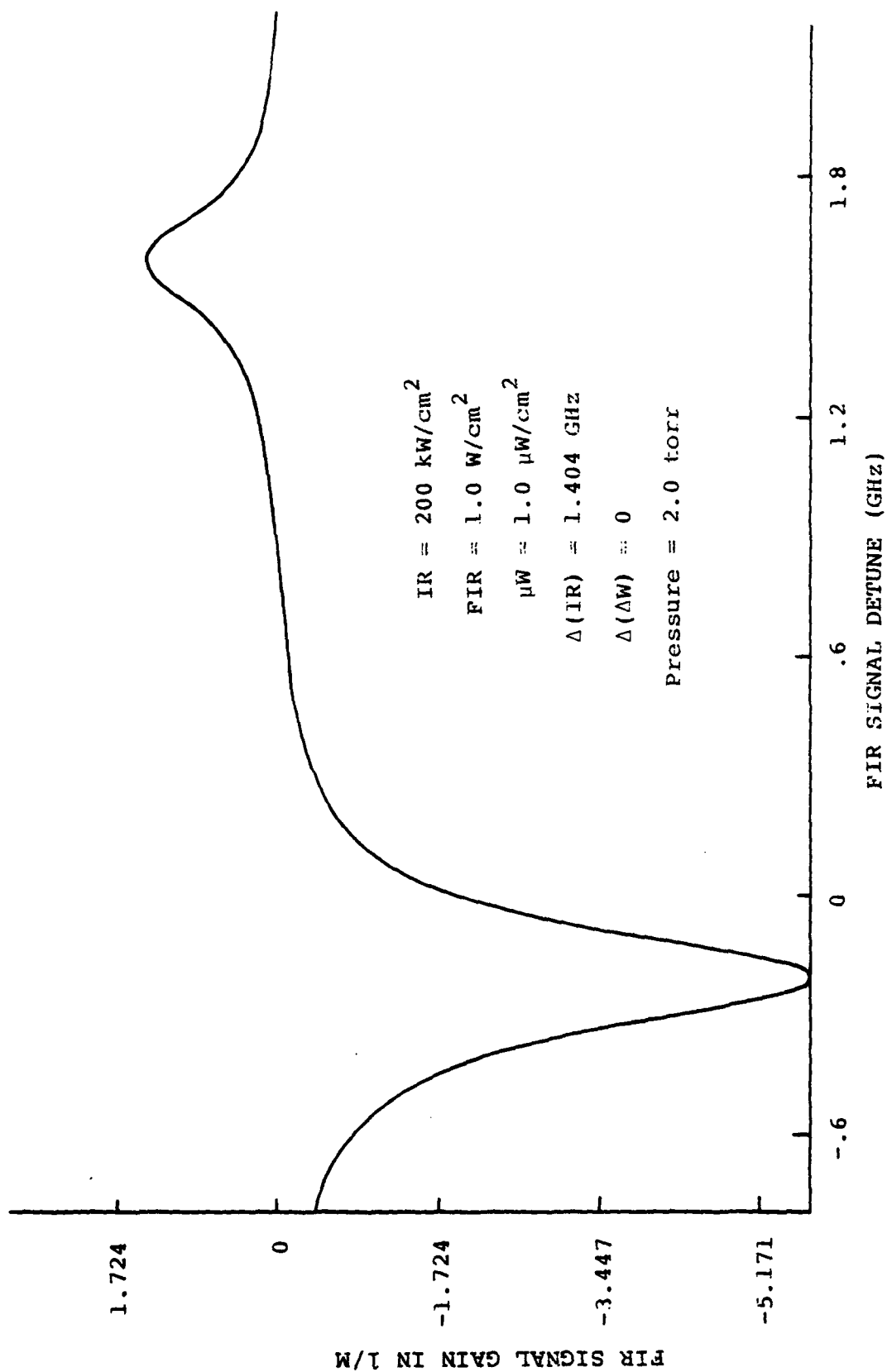


Figure 10. Gain curve for FIR of 1.0 W/cm^2 intensity.

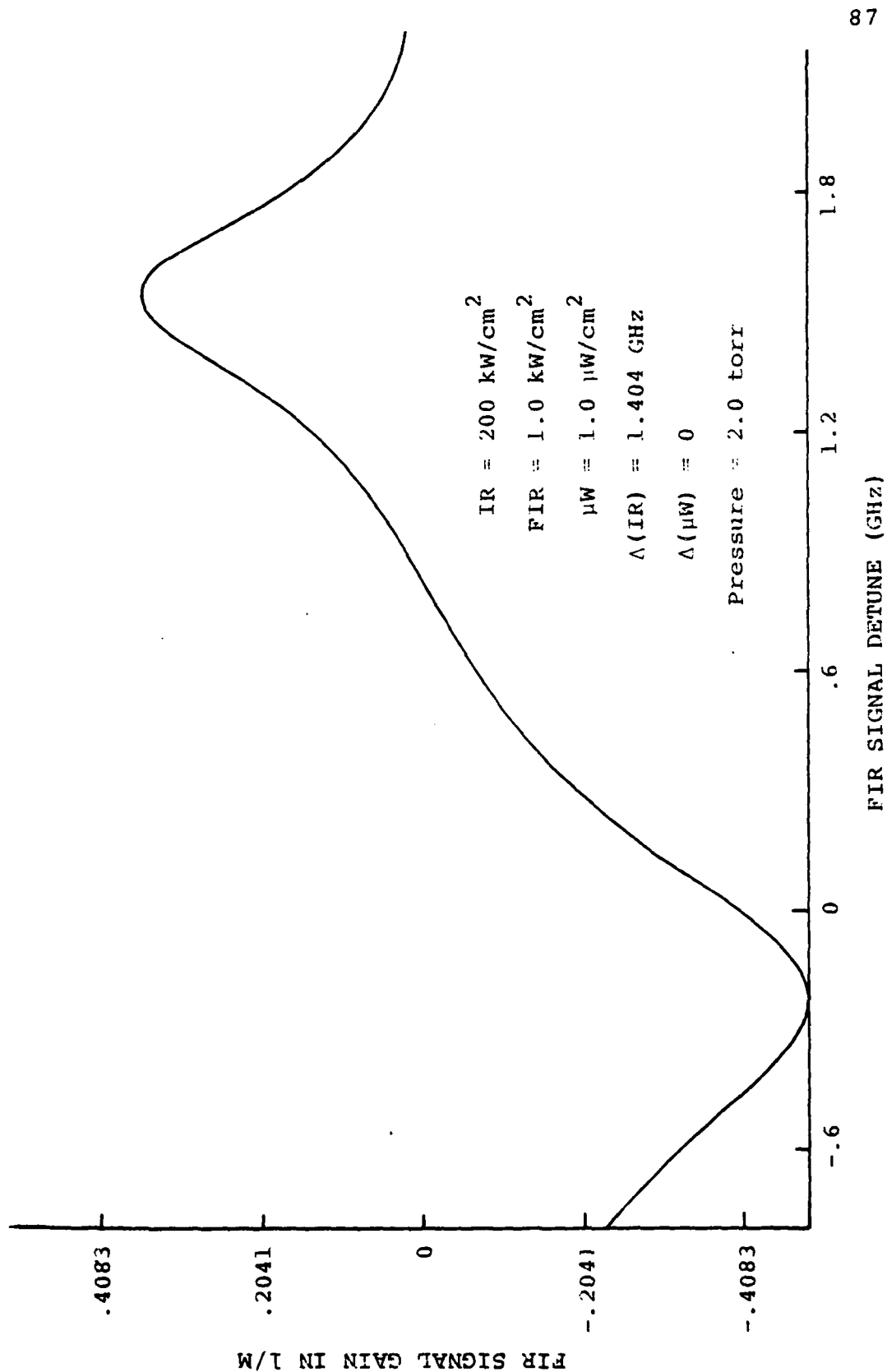


Figure 11. Gain curve for FIR of 1 kW/cm² intensity.

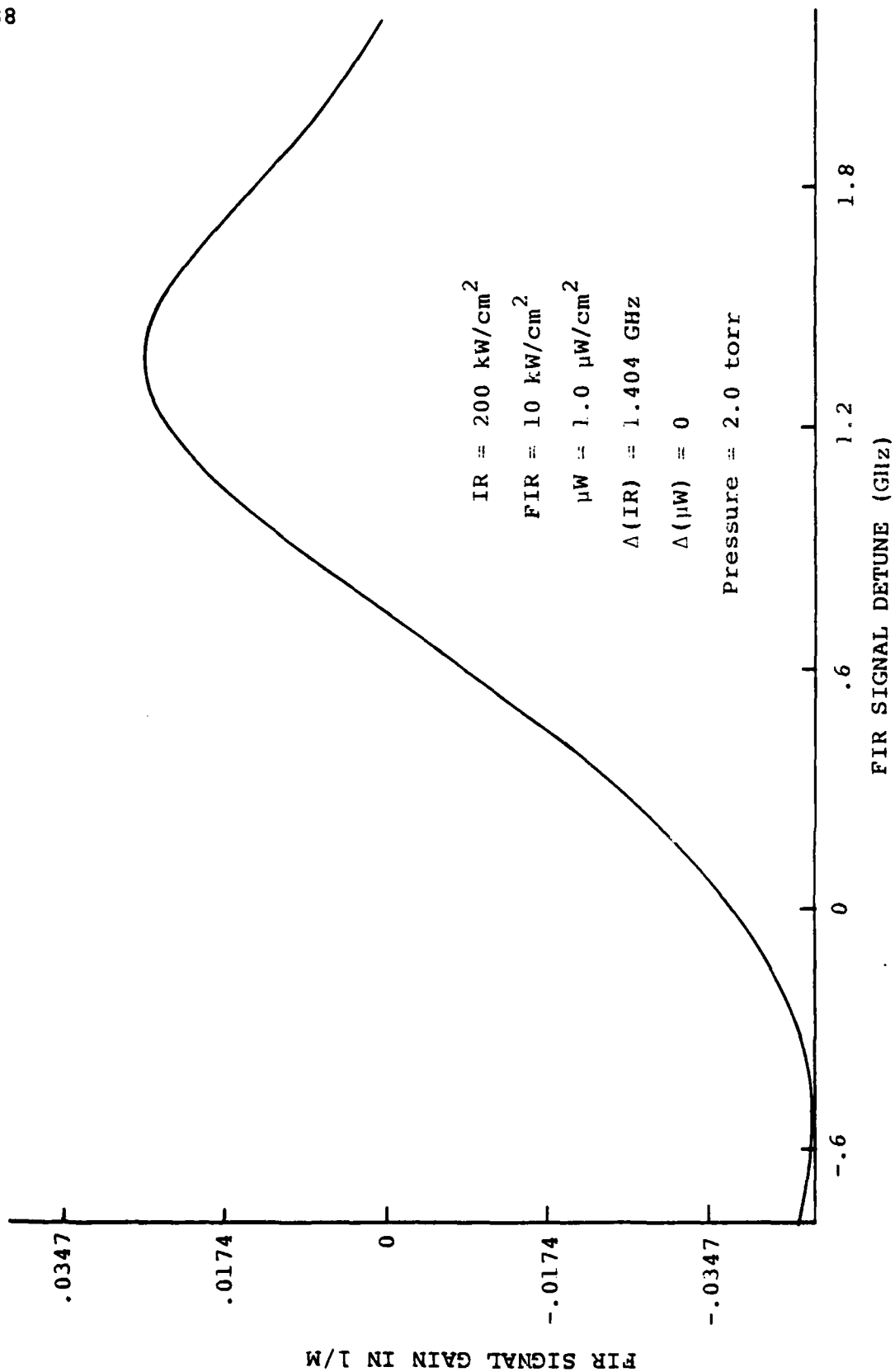


Figure 12. Gain curve for FIR of 10 kW/cm^2 intensity.

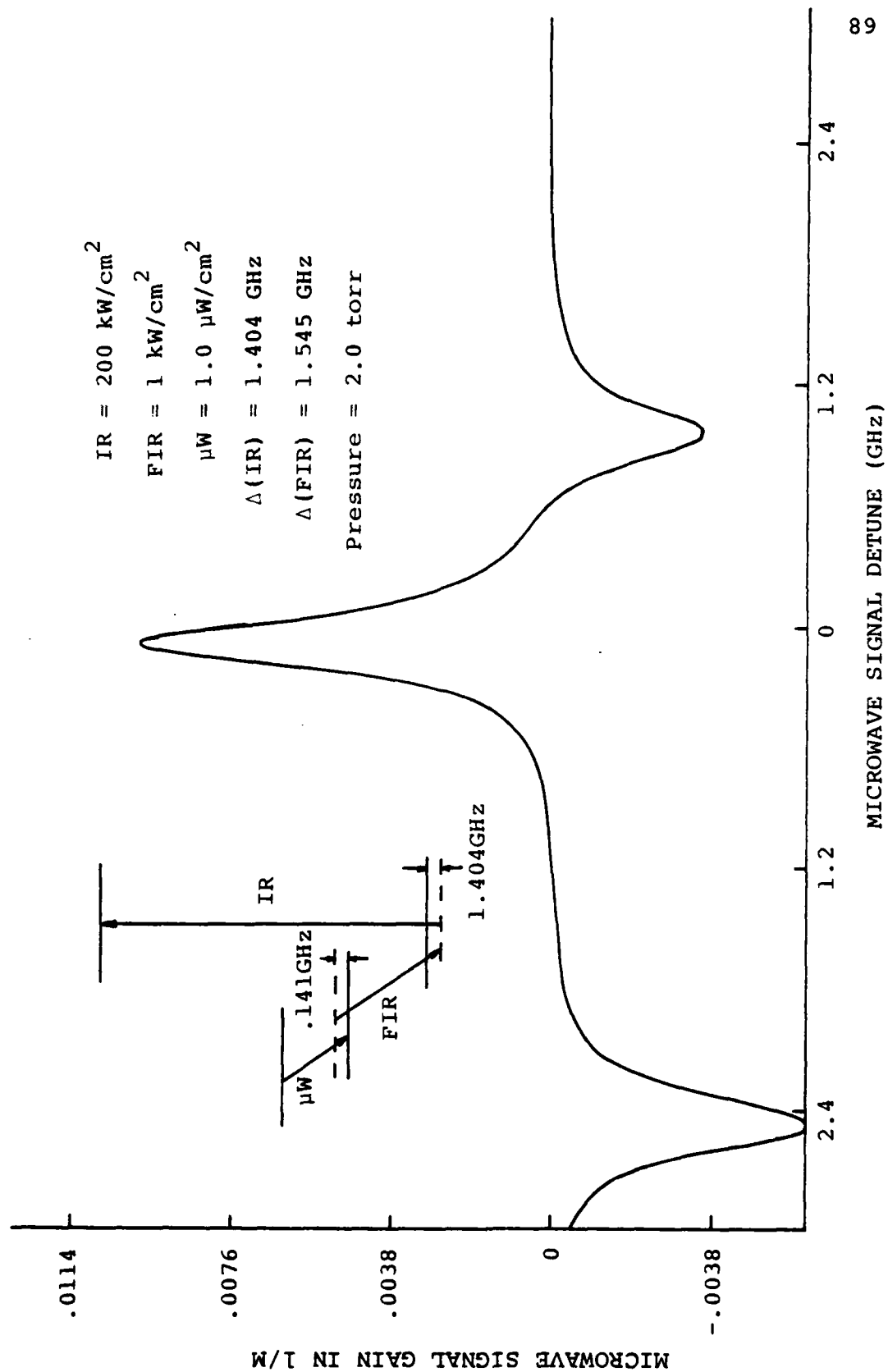


Figure 13. Gain curve for microwave of 1.0 $\mu W/cm^2$ intensity.

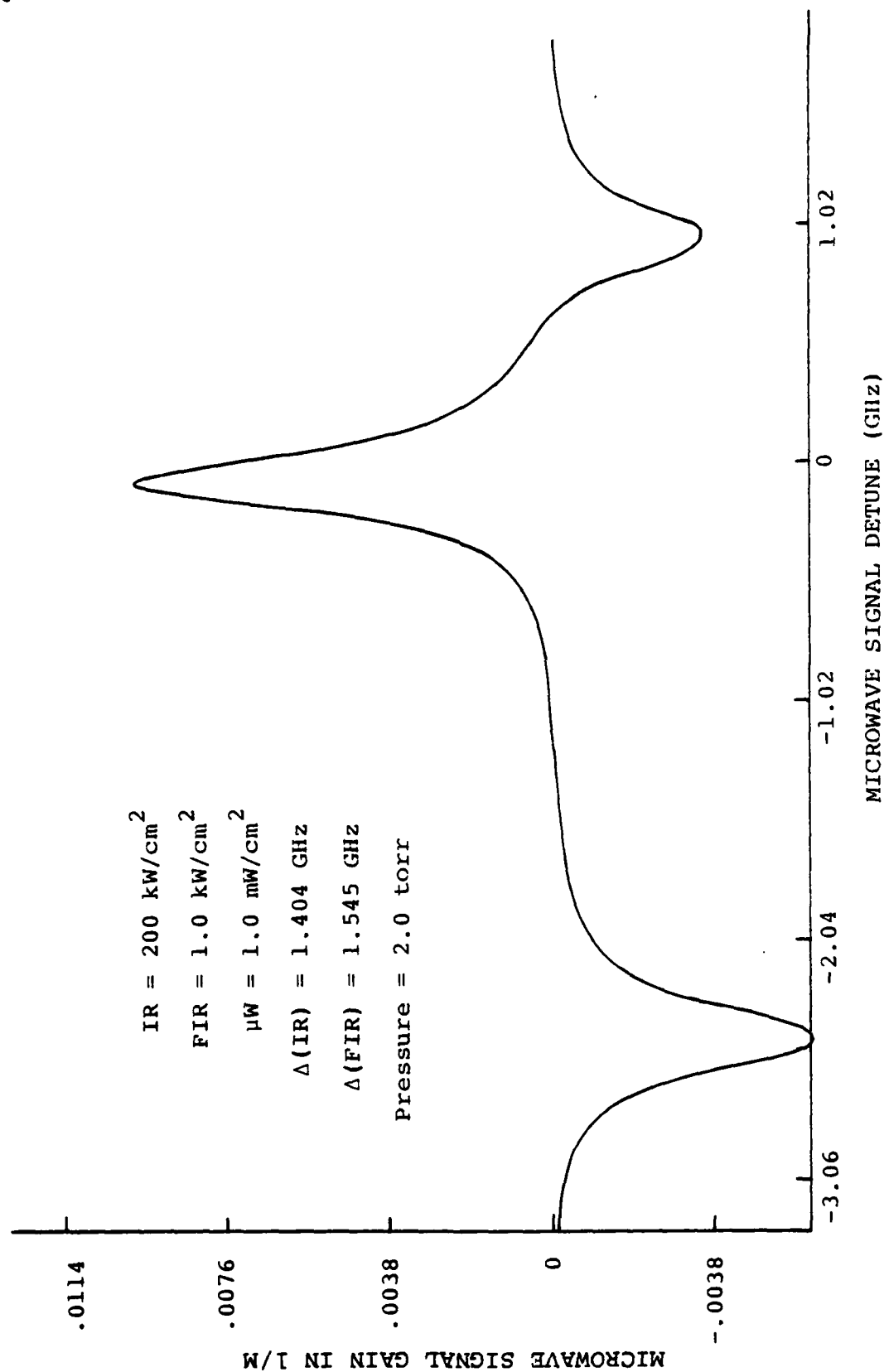


Figure 14. Gain curve for microwave of 1.0 mW/cm² intensity.

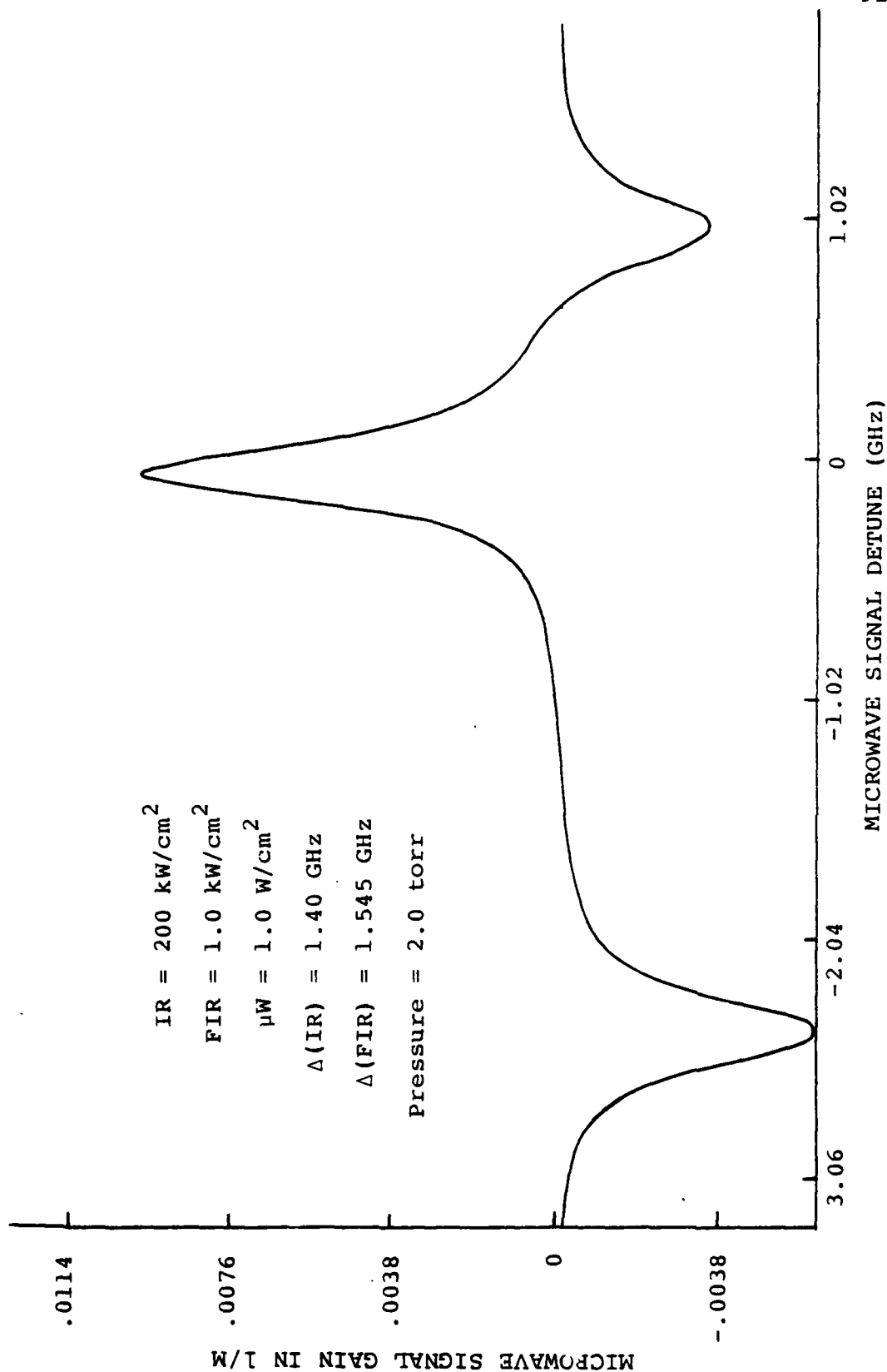


Figure 15. Gain curve for microwave of 1 W/cm² intensity.

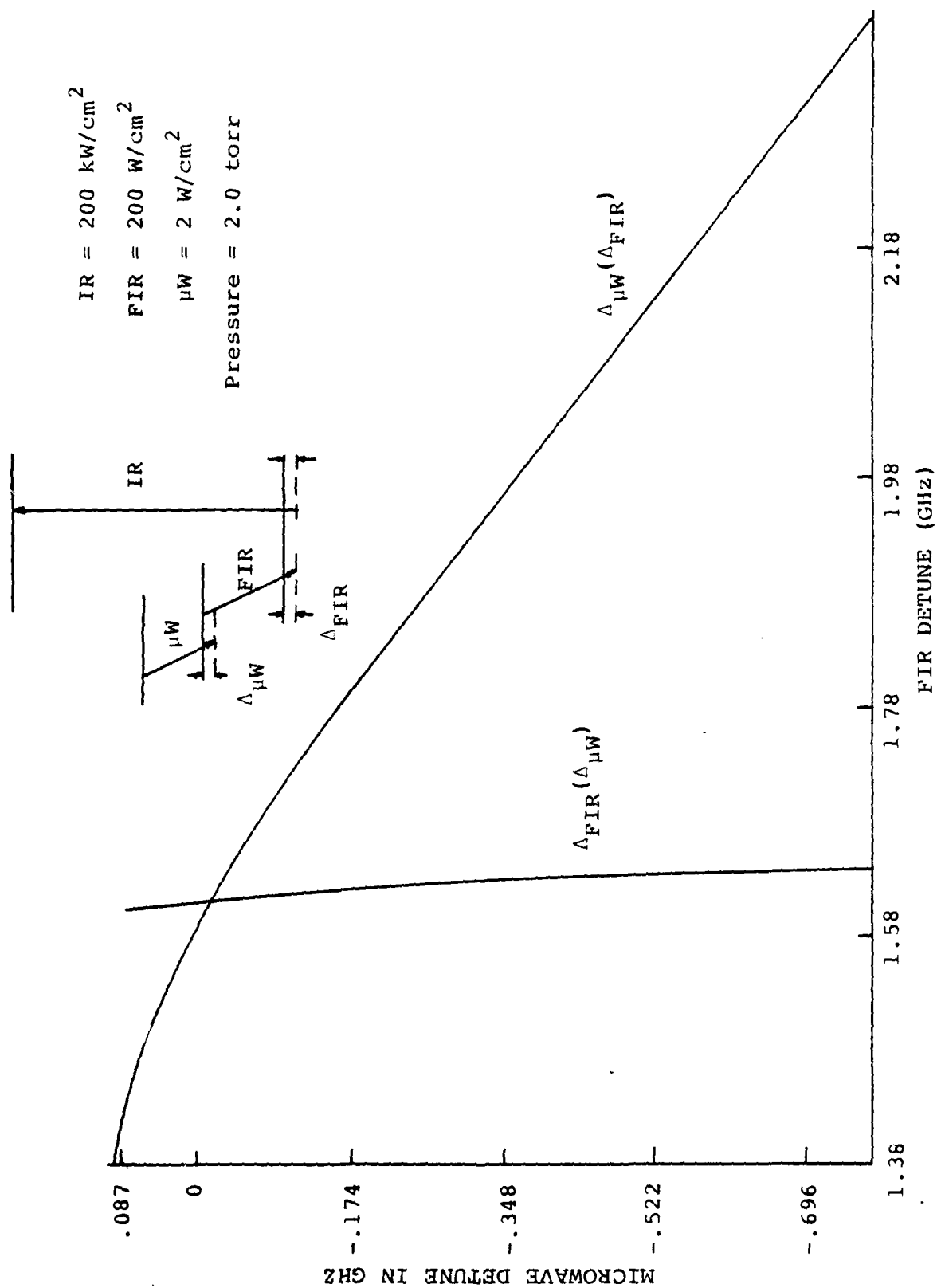


Figure 16. Microwave detune dependence of FIR detune and vice versa.

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includes the polarization dependent M-sublevel transition. Relevant values, such as threshold intensity, signal detuning of each nonlinear process and offset frequency has been obtained which will be most helpful in an experiment.

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VI. REAL TIME, SINGLE-PULSE SPECTRUM ANALYSIS OF FAR IR LASER SIGNALS USING SAW CHIRP TRANSFORMS - Robert Miller

Introduction

An important property of any coherent radiation source is its spectral characteristics. While it is believed that optically pumped molecular gas lasers yield high quality spectral signals, few measurements and papers have appeared on this subject. There is good reason for this: such measurements are difficult to do, especially for pulsed FIR lasers. Yet the potential use of such lasers on applications such as laser radar systems, where both range and velocity information is desired from the return signal, makes spectral characterization of these lasers of practical interest. Quantitative knowledge of such things as pulse-to-pulse frequency stability, amount of frequency chirping during a pulse, variability of spectral content of the output with changes in various system parameters, would be of great usefulness to system designers.

The researcher also stands to gain from such measurements. Detailed knowledge of the spectral content of laser signals can give valuable insights into the lasing mechanisms involved. For example, if the frequency of an optically-pumped laser is linearly related to pump frequency, a Raman process is suggested.^{1,2}

Approaches to Spectrum Analysis

The low repetition rate and narrow pulse widths of pulsed FIR lasers make spectral measurements difficult. Moreover, most spectrum analysis techniques are only capable of determining an average spectrum of many pulses.

Purely optical methods either suffer from poor spectral resolution, or, in the case of Fabry-Perot resonator techniques, spectral mode-matching and mechanical stability problems which make measurements tricky and tedious. In order to obtain a spectral display, one of the mirrors of the Fabry-Perot resonator is usually moved (scanned). As will be shown below, the type of display which would be obtained from passing a low duty-factor pulse through such a scanning filter is not a true frequency domain display, but one which contains a combination of frequency and time information.³ It is not possible to obtain the spectrum of a single pulse using a Fabry-Perot resonator; many pulses are needed.

Optical heterodyne methods followed by electron spectrum analysis of the resulting infrared signal offer some advantages with regard to resolution and convenience. However, the intermediate-frequency signal is also of low repetition rate and narrow pulse width, which can cause severe problems with some electronic spectrum analysis techniques.

Figure 1 shows a greatly simplified block diagram of a conventional electronic spectrum analyzer. It consists of a

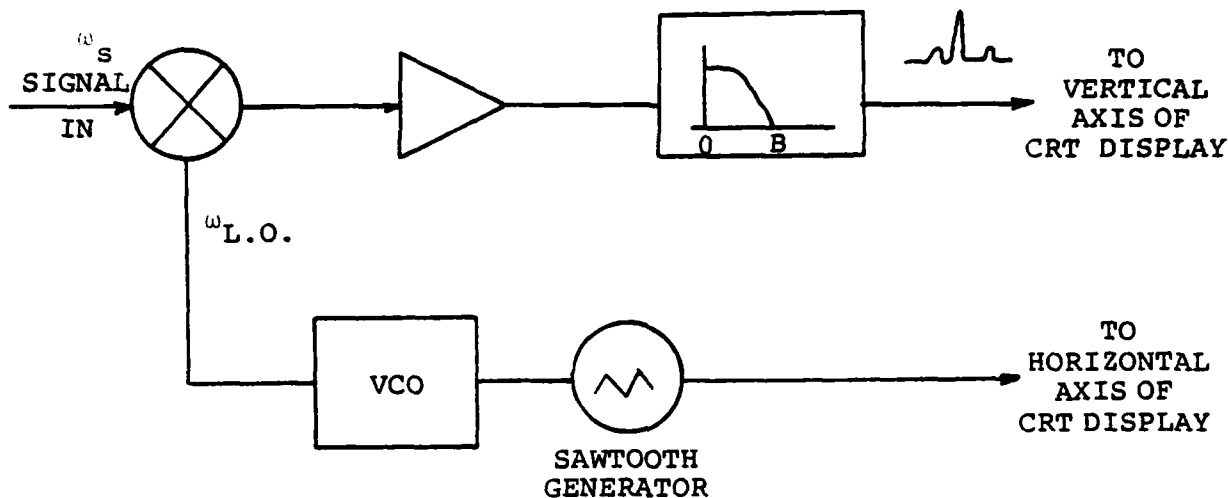


Figure 1. Highly simplified block diagram of conventional electronic spectrum analyzer.

swept local oscillator at frequency $\omega_{L.O.}(t)$, a mixer, and a baseband filter of bandwidth B . For CW signals, the L.O. and mixer translate these signal components in the range $\omega_{LO} - B \leq \omega_s \leq \omega_{LO} + B$ down to baseband, where they are passed by the baseband filter and sent to the vertical axis of a CRT display. The same sawtooth which causes the L.O. to sweep is also used to drive the horizontal axis of the CRT. For CW signals, this results in a true display of the signal's spectral content, if baseband filter B is narrow enough.

For pulsed signals, though, the situation will be quite different if the filter bandwidth B is greater than $1/T$, the pulse repetition frequency. (This will probably be the case

for low duty-factor pulses obtained from pulsed FIR sources). In this case, the vertical output will be non-zero only when the input signal is non-zero. It will consist of narrow pulses separated in time by T . The amplitude of each pulse will be the amplitude of the envelope of the pulse spectrum $G(\omega)$, evaluated at the particular frequency of $\omega_{L.O.}$ when the pulse occurred.

Thus the output of a conventional spectrum analyzer would be misleading since it would look like a line spectrum, but the line spacing would actually be the repetition time T of the pulses. (For very low repetition rates, this would hardly be a useful display unless some storage were used). The envelope of the spectrum would clearly be the average envelope of the pulse spectrum. The same type of display would be obtained with a scanning Fabry-Perot resonator; the only difference there is that the filter is scanned past the signal.

A very powerful method of analyzing signals, which is now becoming more practical, is based on digital techniques. The infrared signal pulse from an optical heterodyne experiment is A/D converted in its entirety, and sent to a computer, which can then apply a whole arsenal of signal averaging techniques, can Fourier transform all or any part of the signal, and perform whatever calculations may be needed. The only problem with applying this technique to FIR signals is that of the high data rates required, which require very fast A/D converters

able to perform a conversion in a few nanoseconds. A/D converters of this speed do exist, but they tend to be limited in the number of bits of resolution. This resolution problem can be cleverly circumvented by signal averaging techniques: a number of low resolution samples, each with some random noise added to it, are digitized and accumulated by the computer. As the number of samples summed together increases, the random noise not only cancels out, but the statistics of the process of digitizing samples plus noise effectively fills in the coarse resolution of the digitizing process. Once again, though, the technique is unable to obtain a high resolution spectrum of a single pulse -- only averages can be obtained.

There is one method of spectrum analysis which can perform a high-resolution Fourier transformation of a single pulse, and in real time: chirp transform techniques, based on Surface Acoustic Wave (SAW) technology. A surface wave device known as a Reflective Array Compressor (RAC)⁴ was developed for just this sort of problem in the radar community. Recently, Fetterman, et al.¹ at Lincoln Labs were the first to report application of this technique to the measurement of IR laser signals.

A RAC (shown in Figure 2) is a linearly dispersive delay element; two superimposed pulses of different frequencies put into the device will appear separated at the output by a time difference proportional to their frequency differences. In

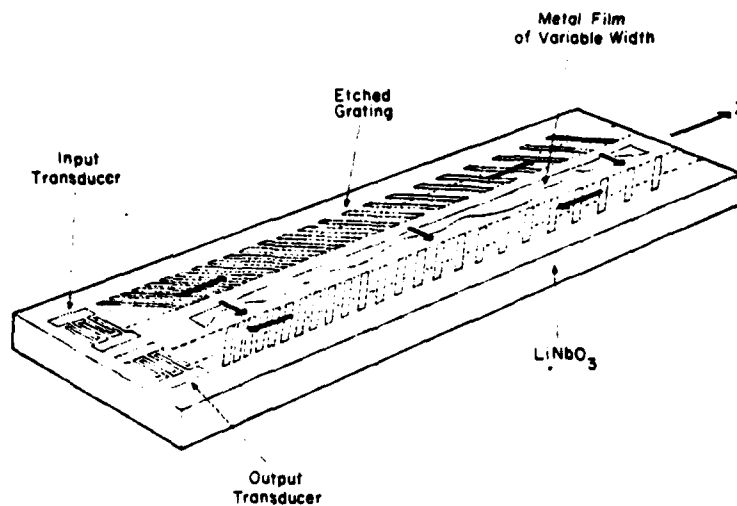


Figure 2. Reflective array compressor vs. reflections of surface acoustic waves from etched grating of linearly varying pitch to provide long dispersive delays and wide bandwidth. (From Ref.8).

the next section, we shall show that under certain conditions the output will be a nearly exact Fourier transform of an input pulse, allowing real-time spectrum analysis of FIR sources to be performed with the experimental set-up shown in Figure 3.

SAW devices, having a range of characteristics, were kindly supplied by Raytheon, Hughes and Lincoln Labs to us in the latter part of the contract year for study and evaluation. These are described in the section on "Short Description of Donated SAW Devices."

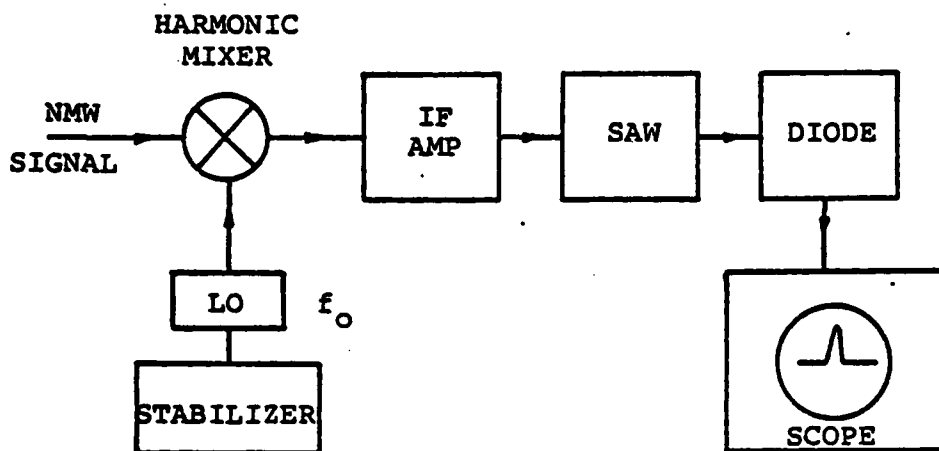


Figure 3. Experimental arrangement for pulsed Fourier transform analysis of NMW sources.

The problems involved in applying the SAW technique to far IR laser signals are: 1) the development of an optical heterodyne system (i.e., a suitable mixer and a stable local oscillator) to produce an infrared signal of the right frequency for the RAC, and 2) making the pulse width of this infrared signal compatible with the particular SAW device being used. The section, "Experimental Measurements" will describe a number of experiments in spectrum analysis.

Application of these methods to the spectral measurement of the 22.65 GHz maser signal generated in NH_3 is also reported elsewhere in this report, Section IV by E. G. Malk.

Fourier Analysis with SAW Device

If a signal $s(t)$ is put into a SAW dispersive delay line which has an impulse response $h(t)$, the output response $r(t)$ is given by the convolution integral:

$$r(t) = \int_{-\infty}^t s(\tau)h(t-\tau)d\tau \quad (1)$$

For a physically realizable RAC device, the impulse response is idealized by a linear chirp:

$$h(t) = \begin{cases} \cos[\omega_s(t-t_d) + \mu(t-t_d)^2], & t_d \leq t \leq t_d + T \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

where: ω_s = starting frequency

t_d = initial delay

T = dispersion time

μ = chirp slope

The instantaneous frequency of this linear chirp is

$$\omega(t) = \frac{d\phi}{dt} = \omega_s + 2\mu(t-t_d)$$

or

$$f(t) = f_s + \frac{\mu}{\pi} (t-t_d) \quad (3)$$

We can simplify the ensuing discussion, however, by ignoring the initial delay t_d , the starting frequency ω_s , and expressing $h(t)$ as a complex impulse response:

$$h(t) = e^{j\mu t^2} + cc$$

Equation (1) then becomes

$$r(t) = \int_{-\infty}^t s(\tau) e^{j\mu(t-\tau)^2} d\tau + cc \quad (4)$$

Equation (4) is in the form of a Fresnel transform,⁵ not a Fourier transform. However, we shall show that for small enough input pulse widths, the Fresnel transform is a good approximation to a Fourier transform.

Since

$$(t-\tau)^2 = t^2 - 2t\tau + \tau^2$$

Equation (4) can be written

$$r(t) = e^{j\mu t^2} \int_0^t s(\tau) e^{j\mu\tau^2} e^{-j(2\mu t)\tau} d\tau \quad (5)$$

where the lower limit of the integral has been changed to reflect the assumption that signal $s(t)$ starts at $t=0$.

The integral in Equation (5) is almost a Fourier integral, with kernel function

$$e^{-j(2\mu t)\tau}$$

implying the transformation of variables

$$\omega' \leftrightarrow 2\mu t \quad (6)$$

relating the time scale of the output pulse to frequency.

However, the integrand of Equation (5) is multiplied by a chirp. If the input pulse duration t_p is small enough though, this chirp is not highly different from a CW burst of the same duration. We may say that this is true if the phase of this chirp differs from that of a CW pulse by not more than $\pi/2$ in the interval t_p or:

$$\mu t_p^2 < \pi/2 \quad . \quad (7)$$

For a RAC having total dispersion time T and bandwidth ΔF , Equation (3) shows that

$$\mu \equiv \pi \frac{\Delta F}{T} \quad (8)$$

Combining Equations (7) and (8) tells us that the output of the RAC will be sufficiently close to a Fourier transform if the input pulse length t_p is shorter than

$$t_p \lesssim \frac{2}{3} \sqrt{\frac{T}{\Delta F}} \quad . \quad (9)$$

Experimental verification is shown in the next section below.

Equation (6) thus shows that, for short enough input pulses, the magnitude of the RAC will be proportional to a Fourier transform. The exponential term in front of the integral is a unit amplitude chirp just like the impulse response $h(t)$ of the RAC. If we are only interested in the magnitude

of the spectrum of our pulse signal, we need do nothing more than pass it through the RAC, and look at the envelope of what comes out.

If our pulsed signal has a duration t_p which is larger than the limit given in Equation (9) above, or if we desire a more exact Fourier transformation, we may pre-multiply $s(t)$ before the RAC by a chirp of opposite slope, and post-multiply the output of the RAC by a similar chirp of opposite slope as that of the RAC (See Figure 4). In general, if

μ_1 = pre-multiply chirp slope

μ_2 = RAC chirp slope

μ_3 = post-multiply slope

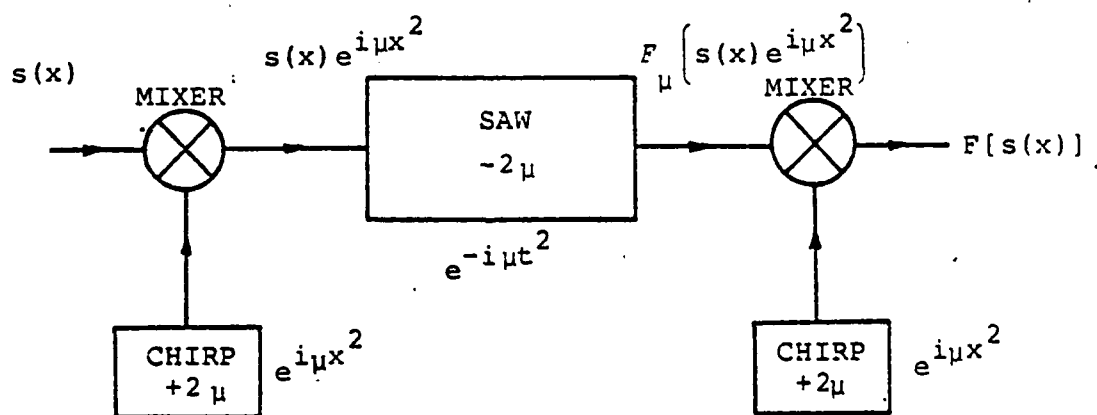


Figure 4. Chirp Fourier transformation using SAW RAC. Input signal is pre-multiplied by chirp of opposite slope as RAC, passed through RAC.

then

$$r(t) = e^{j(\mu_2 - \mu_3)t^2} \int_0^t s(\tau) e^{j(\mu_2 - \mu_1)\tau^2} e^{-j(2\mu t)\tau} d\tau \quad (10)$$

$$= [r(t)] \quad \text{if } \mu_1 = \mu_2 = \mu_3.$$

This multiply-convolve-multiply mode of operation^{6,7} will be referred to hereinafter as the chirp Fourier transform mode, as opposed to the Fresnel transform mode which merely involves passing a signal through the RAC.

Equation (10) clearly shows the result of mismatch between pre-multiply chirp slope μ_1 and device chirp slope μ_2 . If the two do not exactly cancel, the integral in Equation (10) is still of the Fresnel transform type, but with reduced chirp slope $(\mu_2 - \mu_1)$. If the input pulse duration is small enough the arguments leading to Equation (7) apply, but the remanent chirp slope $(\mu_2 - \mu_1)$ leads to a larger allowable pulse width t_p . This will be discussed further in the section below.

It should be pointed out that, although narrow input pulses are needed to assure an accurate Fourier transformation, the finite bandwidth of the SAW device places a lower limit on pulse width as well. This lower limit is harder to define, since the output of the device will just look like a truncated spectrum. Clearly the lower pulse width limit is determined by how much of the spectrum we need to see in a single shot. (If the input pulses are reproducible, on the other hand, then a

wide spectrum can be reconstructed from small pieces of it, obtained by changing the local oscillator each time).

The usual criterion given in the literature for a non-deformed spectrum output⁷ is that the time-bandwidth product of the RAC be at least four times that of the input signal. This leads to a lower limit on the pulse width of

$$t_p \geq \frac{4}{\Delta f} \quad (11)$$

which, by the reasons given above, may be relaxed if one is content with viewing only a portion of the spectrum at a time.

In summary, in the Fresnel mode of operation, a signal pulse is simply passed through a SAW dispersive delay line or RAC. The output pulse will be an accurate representation of the Fourier transform of the input signal if the duration t_p of the input signal falls within the limits

$$\frac{4}{\Delta f} \leq t_p \leq \frac{2}{3} \sqrt{\frac{T}{\Delta f}} \quad (13)$$

For longer signal durations, it is necessary to either pre-multiply the signal by a chirp of opposite slope as that of the RAC (chirp Fourier transform mode of operation), or to gate out a small portion of the input pulse and look at its spectrum as a function of position in the signal pulse. The latter procedure has interesting possibilities as will be shown in the next section.

Short Description of Donated SAW Devices

We are very grateful to the Raytheon Corporation, Hughes Industries, and MIT Lincoln Laboratories for their donation or loan of surface wave devices for this work. These are state-of-the-art devices in some cases, employing ion-etched grooves of precisely controlled depth (depth variation along the grating array is one of the design parameters) as well as width. At least in the case of the Lincoln Labs device, additional phase correction is determined for and fabricated on each individual device, to make the phase response closer to exactly parabolic.⁸ (Some of the other devices may employ this technique as well, but we are sure that the MIT device does).

Table 1 summarizes the important parameters of these devices, such as bandwidth, dispersion time, and frequency resolution. Figures 5 through 8 show frequency response curves.

Table 1. Summary of operating characteristics of SAW RAC devices donated or lent to The University of Illinois Electro-Physics Lab.

MANUFACTURER	CENTER FREQUENCY (MHz)	BANDWIDTH F (MHz)	DISPERSION TIME T (μsec)	T-B PRODUCT	NUMBER OF RESOLVABLE FREQUENCIES	FREQUENCY RESOLUTION (MHz)	MINIMUM PULSE WIDTH (μsec)	MAXIMUM PULSE WIDTH (μsec)
RAYTHEON	60	6	20	120	11	0.55	0.667	1.217
RAYTHEON	120	24	3	65	8	2.98	0.167	0.224
HUGHES	500	150	3	450	21	7.07	0.027	0.094
MIT	420	100	16	1600	40	2.50	0.040	0.267

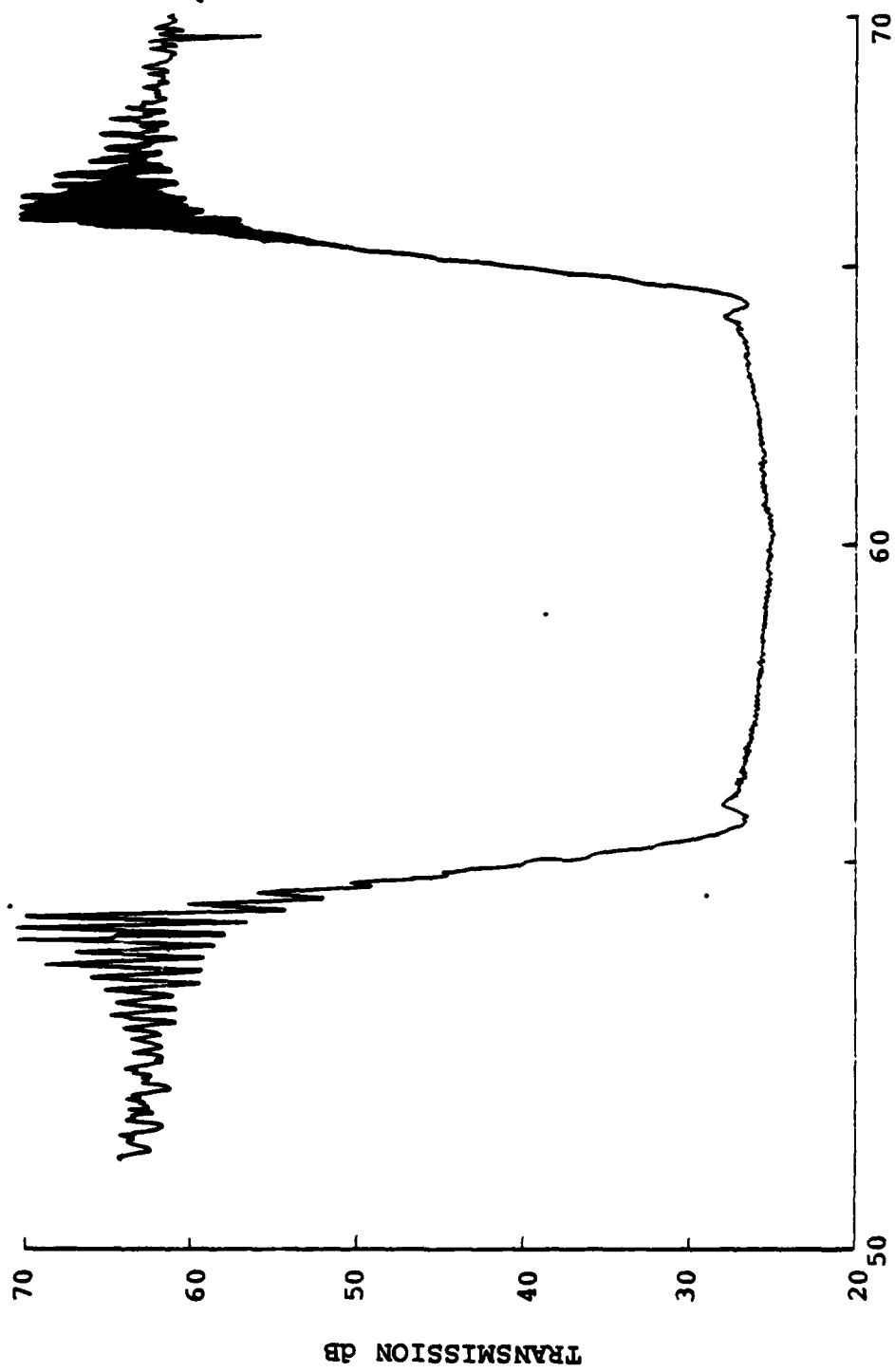


Figure 5. Frequency response of Raytheon 60 MHz RAC.

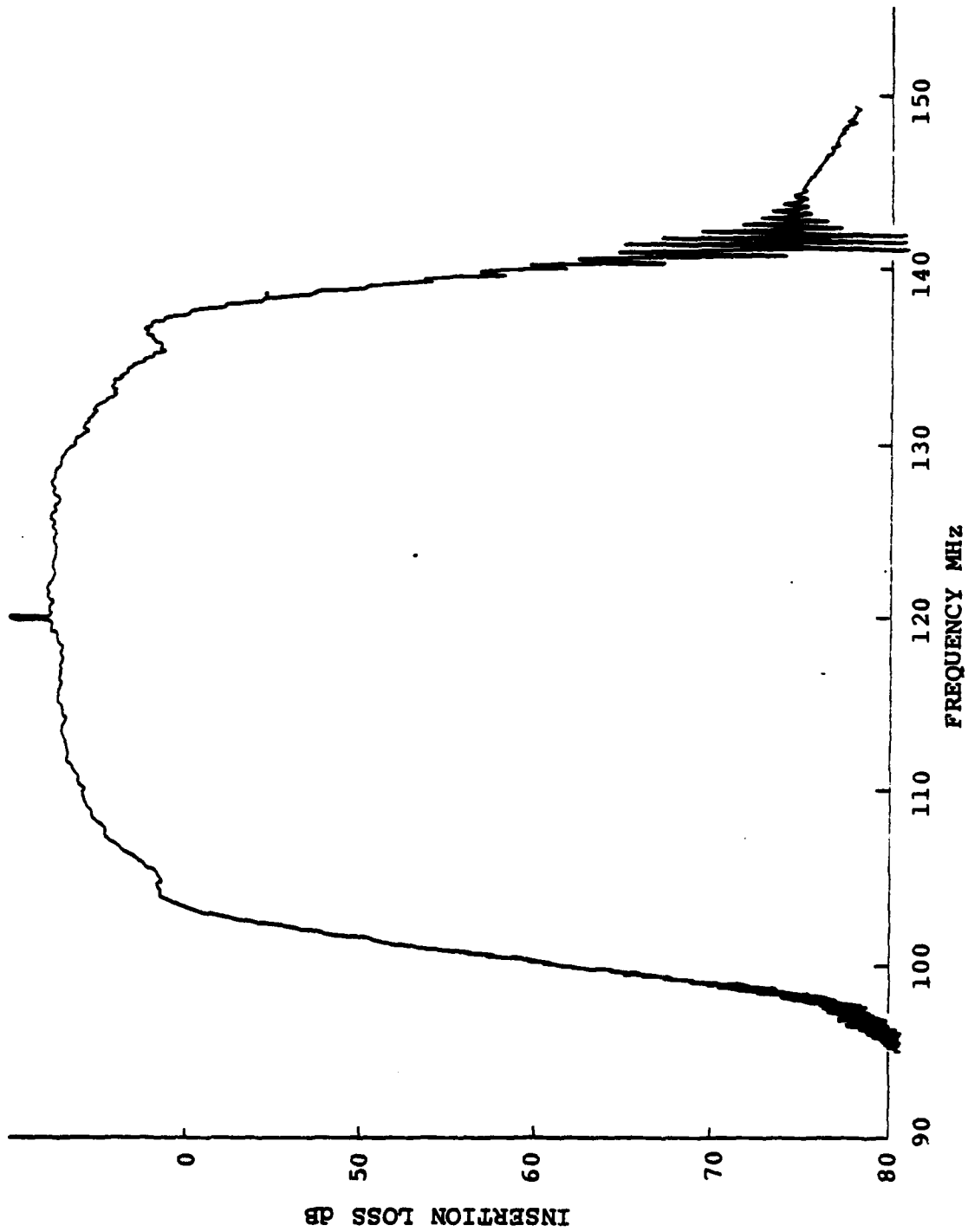


Figure 6. Frequency sources of Raytheon 120 MHz RAC.

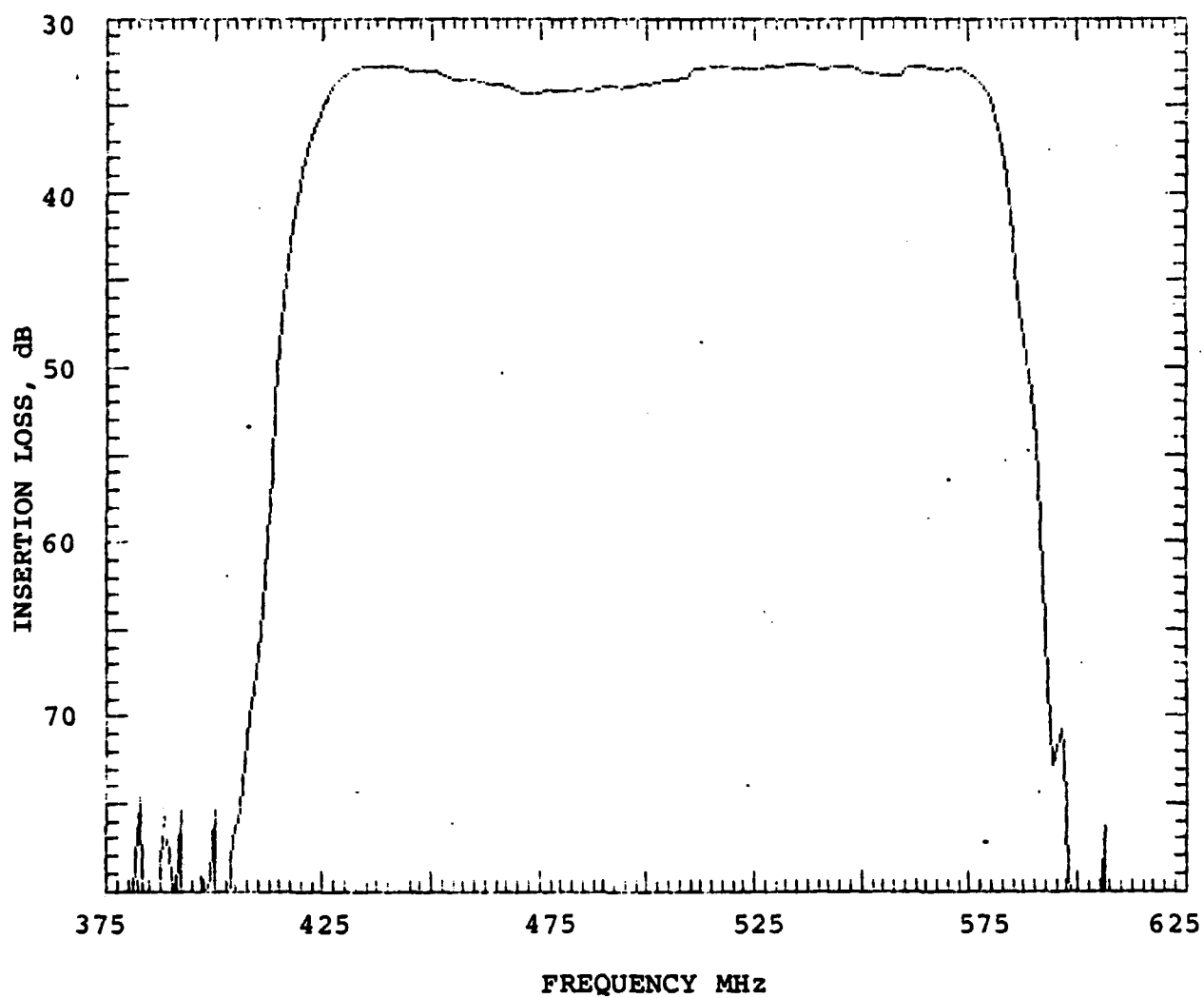


Figure 7. Frequency response of Hughes RAC.

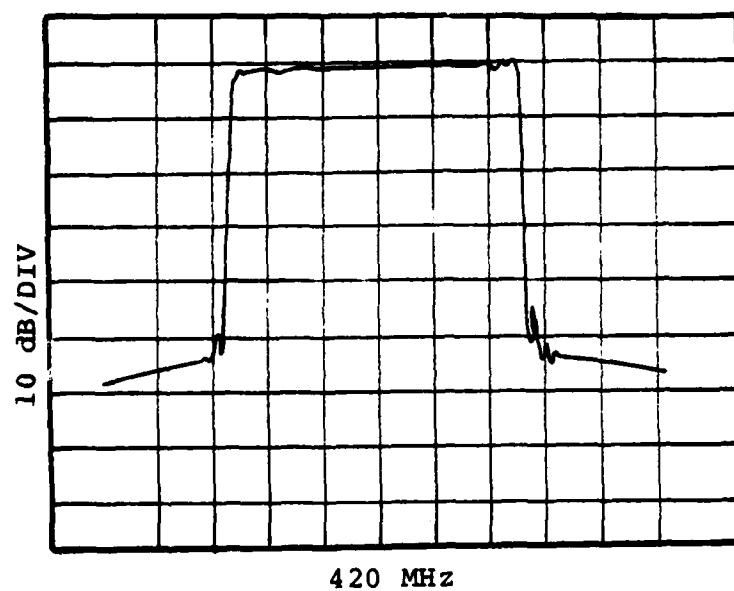


Figure 8. Frequency response of MIT RAC.

Experimental Measurements

Demonstration at IF

We have shown in a previous section that in order to obtain a true Fourier transformation of a signal, it is necessary to first pre-multiply it by a chirp of opposite slope as the RAC, pass this product through the RAC, and then post-multiply the output by another chirp of opposite slope as the RAC (Figure 4). We further showed that if the input pulse width fell within certain limits, that passing the signal through the RAC alone produced a good approximation to a Fourier transform, without the need for pre- and post-multiplying chirps.

It is useful to ask questions about the limitations of this technique. How critical are the pulse width limits? If a pre-multiply chirp must be used, what happens if its chirp slope does not exactly match that of the RAC? What happens if its frequency vs. time characteristic is slightly nonlinear?

We have preformed some experiments aimed at answering these questions at 60 MHz using the Raytheon 6 MHz bandwidth, 20 micro-second dispersion RAC.

Figure 9a) and b) show experimental set-ups used. In Figure 9a). a CW signal is gated with two cascaded double-balanced mixers (for good on-off ratio) and the resulting narrow pulse is amplified and passed through the RAC. This simulated a Fresnel transform, which should approximate a Fourier transform

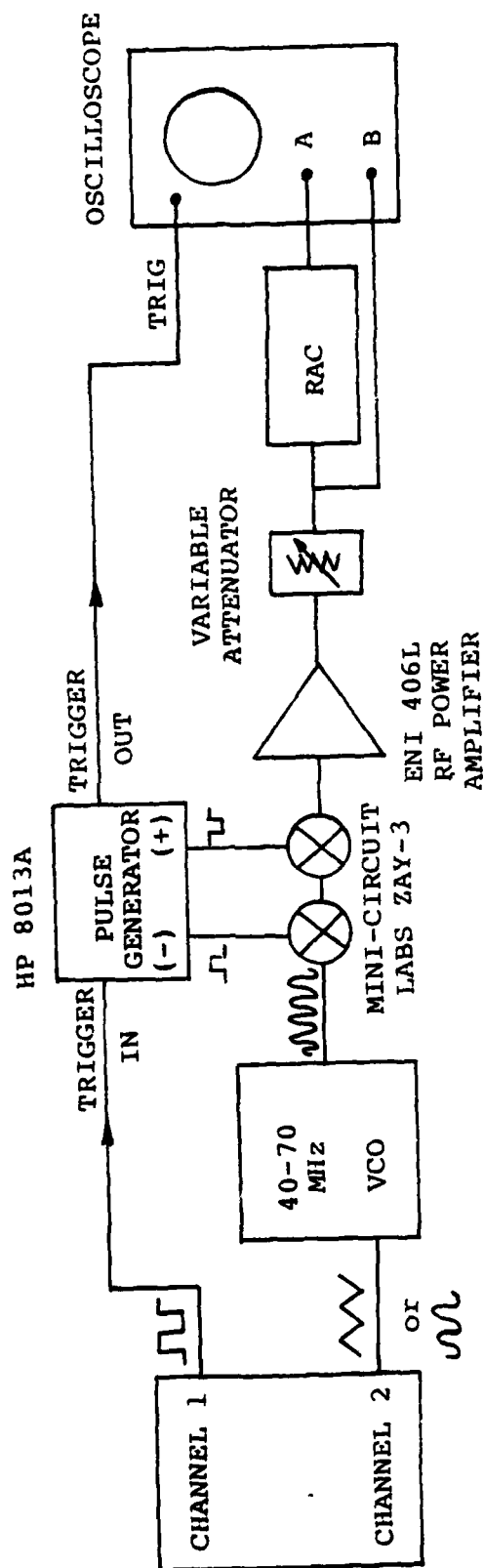


Figure 9b. Experimental setup to measure Chirp Fourier transform with SAW RAC.

if the pulse width lies within $0.67 \mu\text{sec} \leq \tau_{\text{pulse}} \leq 1.22 \mu\text{sec}$ for this particular RAC.

Figure 9b) shows a simulation of a true Chirp Fourier transform. A sawtooth wave driving a voltage controlled oscillator provides the necessary pre-multiply chirp; no post-multiply chirp is needed, since we are only interested in the envelope of the signal. The signal to be pre-multiplied by the chirp is the rectangular pulse generated by the pulse generator. The envelope of the output of the RAC is expected to be the Fourier transform of the rectangular pulse, which is a $\sin(x)/x$.

To be more quantitative, the input pulse of amplitude A and width τ_i has a Fourier transform

$$V(f) = A\tau_i \frac{\sin(\pi f \tau_i)}{(\pi f \tau_i)} \quad (13)$$

which has a main lobe width $\Delta f = \frac{2}{\tau_i}$ MHz between first zeroes. The chirp slope μ of the device is

$$\mu = \pi \frac{\Delta F}{\Delta T} = \pi \cdot \frac{6\text{MHz}}{20\mu\text{sec}} \quad (14)$$

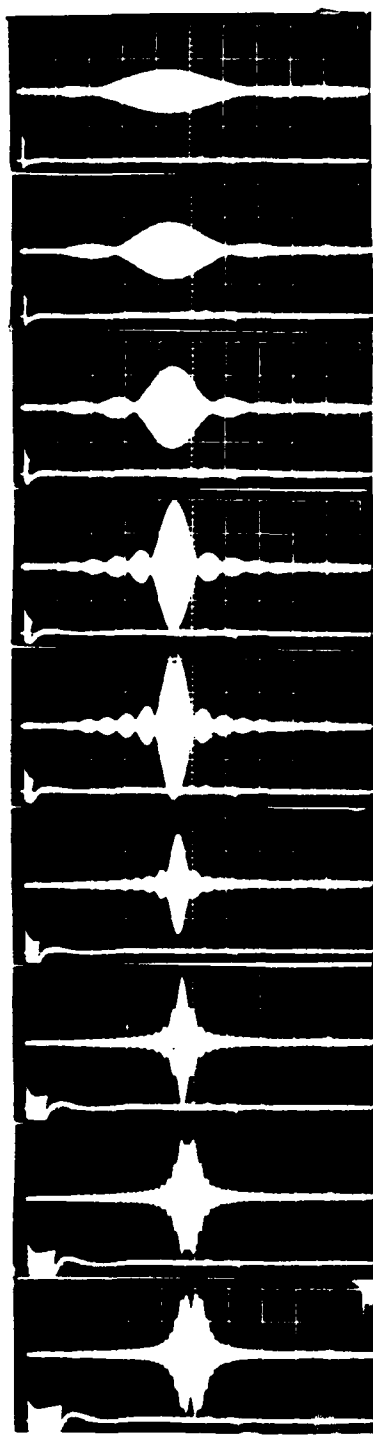
The relationship between output pulse width and frequency is

$$\begin{aligned} \Delta\omega &= 2\mu\tau_{\text{out}} \\ \text{or} \\ \Delta f &= \frac{\mu}{\pi} \tau_{\text{out}} \end{aligned} \quad (15)$$

From Equation (13) above, the output pulse width should vary inversely with input pulse width, while the output amplitude should be directly proportional to input pulse width.

Figure 10a) and b) shows a side-by-side comparison of these two modes of operation, the Fresnel mode, Figure 10a), (left side) and the chirp Fourier transform (Figure 10b), (right side) as the width of the input pulse is varied. Within the pulse width limits mentioned above, the two results are as identical as experimental determination will allow. Numerical data taken from these photographs, in the recommended pulse width range, shows the output to indeed be a true Fourier transform for either mode of operation. The output pulse width varies inversely with input pulse width, and the peak amplitude varies directly with input pulse width as expected from the Fourier transform relationship described above.

As the pulse width limits are exceeded, however the Fresnel mode output pulse begins to deviate from a simple $\sin x/x$ shape, becoming a more complicated shape reminiscent of optical diffraction patterns. (In fact, the progression of pulse shapes is exactly like the progression of amplitude profiles one would obtain in an optical diffraction experiment, at various distances from a rectangular slit). Beyond the pulse width limits established above, widening the input pulse increases the output pulse width, and the approximation to a Fourier transform

FRESNEL
TRANSFORM MODE

a) FRESNEL TRANSFORM

INPUT PULSE WIDTH

0.3 μsec

0.4 μsec

LOWER LIMIT

0.6 μsec

1.0 μsec

1.2 μsec

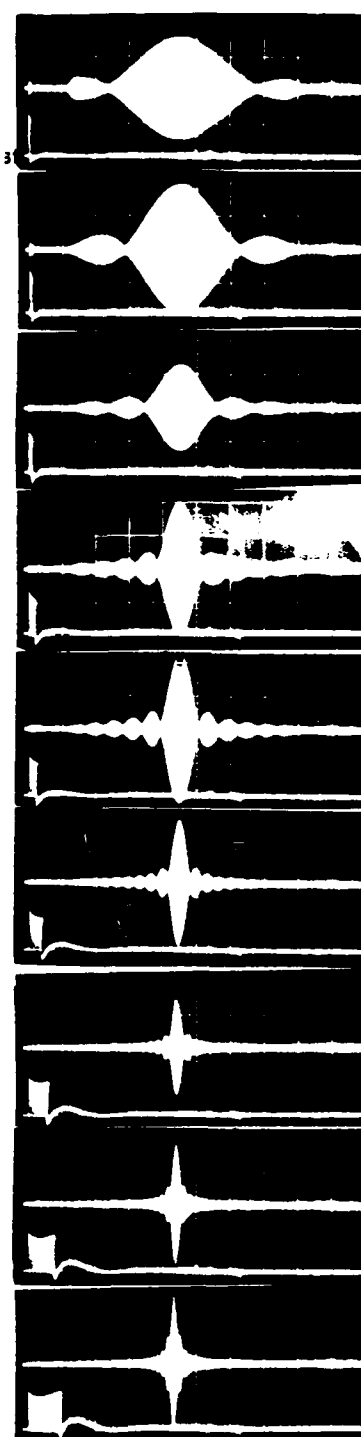
UPPER LIMIT

2.0 μsec

3.0 μsec

4.0 μsec

5.0 μsec

CHIRP FOURIER
TRANSFORM MODE

b) CHIRP FOURIER TRANSFORM

Figure 10. Comparison of Fresnel vs. Chirp Fourier transform performance for various pulse widths.

relationship breaks down. Still, the output pulse shape looks fairly close to a $\sin x/x$ out to about twice the upper pulse width limit, so these pulse width limits given earlier are not critical.

The photographs clearly show that for short pulse widths, there is no advantage to doing the extra pre-multiplication by a chirp, since the Fresnel transform is not discernably different from the Fourier transform. For larger pulse widths, however, that is no longer true, and one is forced to either pre-multiply or simply gate the signal on for a short time, and look at only a piece of the signal at a time. (There are advantages to this latter approach, which will be described in the next section).

If it is necessary to pre-multiply, then the allowable mismatch $\Delta\mu$ between pre-multiply chirp slope and device chirp slope $[(\mu_2 - \mu_1)$ in Equation (10)] can be found by an argument similar to the one used to find the upper pulse width limit. We insist that

$$\Delta\mu t_p^2 \leq \pi/2$$

where t_p = input signal duration. If we express t_p as a fraction of the dispersion time T :

$$t_p = \alpha T$$

then the allowable chirp slope tolerance may be expressed as

$$\frac{\Delta\mu}{\mu} \leq \frac{1}{\alpha^2 (T\Delta f)}$$

i.e., inversely proportional to the device time-bandwidth product, and to the square of the pulse duration. Figure 11 supports this. The three traces a) - c) are a result of varying the chirp slope by $\pm 43\%$ about the nominal value used in the center trace b). The pulse shapes are essentially identical, because the input pulse width were only 1 μsec ($\alpha=0.05$, so our allowed tolerance is $\Delta\mu/\mu \leq 167\%$). Traces d) to f) show the opposite extreme: the effective input pulse width is now equal to the entire dispersion time of the device ($\alpha=1$, so the allowable $\Delta\mu/\mu \leq 0.4\%$); a chirp slope variation of $\pm 5.5\%$ distorts the spectrum beyond all recognition.

Finally, the effects of a non-linear chirp slope in the pre-multiplying chirp are shown in Figure 12. The same experimental set-up as Figure 9b) was used, but the VCO was driven with a sine wave instead of a triangle wave. By adjusting the amplitude and frequency of the sine wave, as well as the triggering of the pulse generator, it was possible to generate a chirp whose average slope was equal and opposite to that of the RAC, but whose frequency vs. time characteristics had varying degrees of nonlinearity. In Figure 12a) - c), the amplitude and frequency of the sine wave driving the VCO was adjusted so that

PHOTOS a) - c) HAVE 1 μ sec
PULSE ($\alpha = 0.05$) INTO
RAYTHEON 60 MHz RAC

UPPER TRACES: RAC OUTPUT
1.5 MHz DIVISION

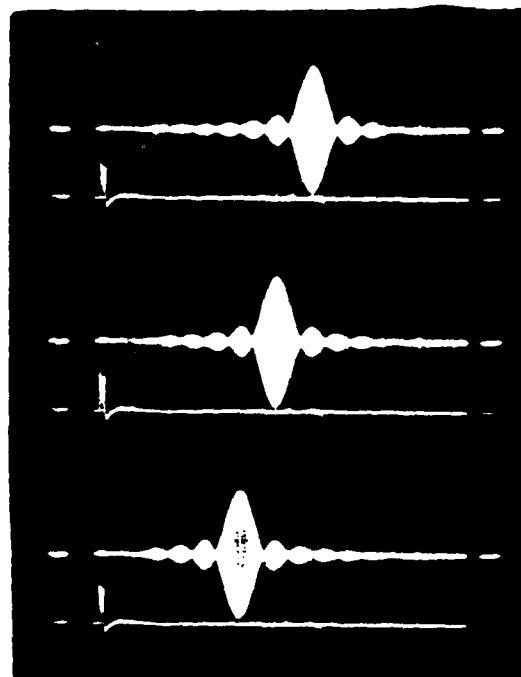
LOWER TRACES: RAC OUTPUT
5 μ sec DIVISION

- a) PRE-MULTIPLY CHIRP SLOPE
MISMATCHED - 43%
- b) PRE-MULTIPLY CHIRP SLOPE
MATCHED TO RAC
- c) PRE-MULTIPLY CHIRP SLOPE
MISMATCHED + 43%

a)

b)

c)



PHOTOS d) - e)
20 μ sec PULSE INTO RAC
($\alpha = 1.0$)

- d) PRE-MULTIPLY CHIRP SLOPE
MISMATCHED - 5.5%
- e) PRE-MULTIPLY CHIRP SLOPE
MATCHED TO RAC DEVICE
- f) PRE-MULTIPLY CHIRP SLOPE
MISMATCHED + 5.5%

d)

e)

f)

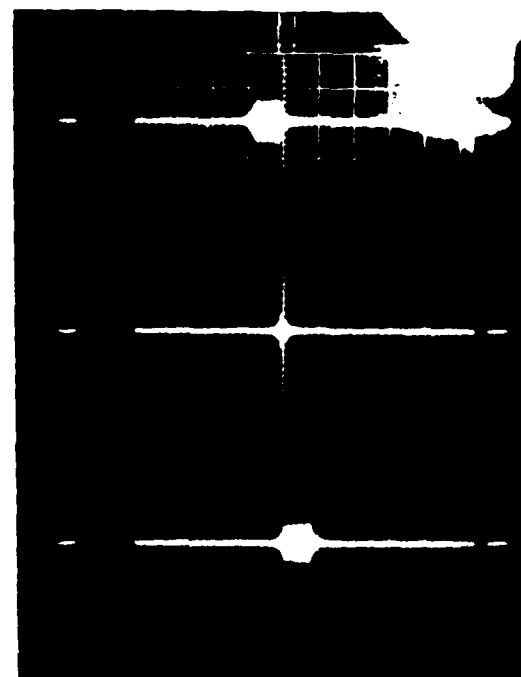


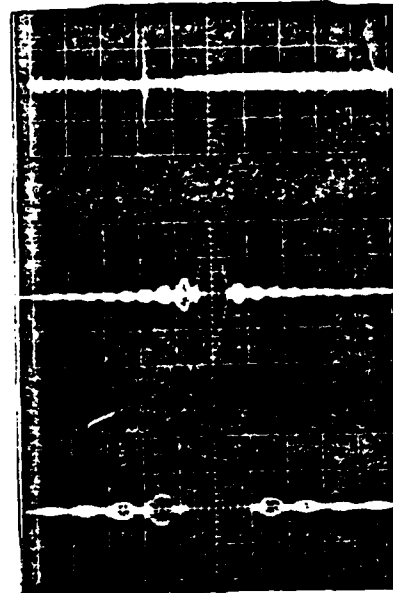
Figure 11. Effects of chirp slope mismatch between pre-multiply chirp and RAC device.

- a) X-Y TRACE; HORIZONTAL AXIS IS SINE WAVE WHICH SWEEPS VCO (AMPLITUDE 10 DIVISIONS) VERTICAL AXIS IS RAC OUTPUT. CHIRP SLOPE MATCH OCCURS ON LINEAR PORTION OF ARM CURVE, 1.8 DIVISIONS FROM ZERO CROSSING.
- b) CLOSEUP OF CORRELATION PEAK ON NORMAL TIME SWEEP ($0.2 \mu\text{sec}/\text{DIV}$). SHOWS SYMMETRICAL SHAPE.
- c) FURTHER CLOSEUP OF CORRELATION PEAK: $0.1 \mu\text{sec}/\text{DIV}$.

a)

b)

c)



- d) X-Y TRACE AS IN a) ABOVE: CHIRP SLOPE MATCH MADE TO OCCUR CLOSE TO PEAK OF SINE CURVE, INTRODUCING MORE NON-LINEARITY IN PRE-MULTIPLY CHIRP.
- e) CLOSEUP OF CORRELATION PEAK ON NORMAL TIME SWEEP ($0.5 \mu\text{sec}/\text{CM}$). DISTORTION OF CORRELATION PEAK DUE TO NONLINEAR PRE-MULTIPLY CHIRP IS EVIDENT.
- f) COMPARISON OF SINE WAVE VCO INPUT (UPPER TRACE) TO RAC OUTPUT (LOWER TRACE) SHOWS POSITION OF CHIRP SLOPE MATCH ALONG SINE CURVE.

d)

e)

f)

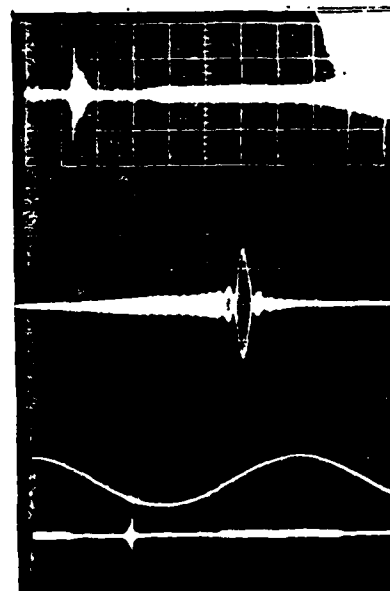


Figure 12. Effected chirp slope nonlinearity in pre-multiply chirp. VCO in Fig. 9b) driven by sine wave, whose amplitude and frequency are adjusted to match average slope of chirp to that of RAC at different positions on sine curve.

sine wave had the proper slope close to its zero crossing, where the sine wave is most linear. The pulse generator was made to trigger when the sine wave was in that vicinity; the signal which passed through the mixers was thus a brief chirp whose frequency slope was fairly linear. The output of the RAC, shown in Figure 12a) - c), is very much like a $\sin(x)/x$. In Figure 12d) - f), the sine wave driving the VCO was adjusted to have the proper average slope closer to its negative peak, where the sine curve is more nonlinear. When the resulting chirp is passed through the RAC, the output pulse is highly asymmetrical and distorted.

Experiments at 35 GHz

Our original intention was to develop an optical heterodyne system to test a $1220\text{ }\mu\text{m}$ $^{13}\text{CH}_3\text{F}$ laser (245 GHz). For the local oscillator, the seventh harmonic of a 35 GHz stabilized klystron was to be used. Time did not permit us to complete the 245 GHz system, but were able to simulate the features of such a system by pulsing a 35 GHz klystron on and off, mixing its output pulse with the output of a frequency-stabilized klystron local oscillator, and spectrum-analyzing the resultant IF pulses.

The local oscillator was stabilized by a frequency-lock loop arrangement incorporating a Pounds discriminator⁹ and an electronics package graciously loaned to us by Micro-Now, Inc. of Chicago. The arrangement is shown in Figure 13.

Several points should be stressed about these experiments. Firstly, although the L.O. klystron was stabilized, the pulsed klystron was not. In addition to being pulsed on and off, the original klystron was also subject to whatever random frequency fluctuations might occur in an unstabilized oscillator. One source of instability became evident immediately: a very small amount of remanent 60 Hz ripple was found on the klystron repeller supply voltage: 0.4V peak to peak out of a DC value of 2000V, or 0.02%. This small voltage was enough to cause several MHz of FM on the signal klystron, which was clearly visible with the high-resolution 60 MHz Raytheon RAC, as will be shown.

This posed no major problems for a SAW chirp transform spectrum analyzer, though, since the 60 Hz ripple just caused the output spectra of the klystron pulses to jitter a few MHz. The single shot ability of this transform technique enabled clear spectra to be obtained merely by photographing single oscilloscope traces. Other spectral analysis techniques based on averaging many pulses together would have had trouble here.

Another point to be mentioned here is that for most of this series of photographs, an envelope detector was used. This tends to produce cleaner looking traces, but the non-linearity of the detector diode makes the spectrum sidelobes appear smaller than they really are.

A third point is that for most of these photos, the signal klystron was pulsed on for about 10 μ sec, very much longer than the Fresnel mode pulse width limits for this device. We could have looked at the spectrum of the entire pulse by pre-multiplying the IF with a chirp of the proper slope. In fact, we could obtain the effect of that multiplication essentially for free, merely by sweeping the L.O. klystron at the correct rate.

However, by simply passing the long IF pulse through a gating mixer before the RAC, it becomes very easy to look at the spectrum of a small piece of the signal pulse. By moving the gating window around in the IF pulse, one can see how stable the frequency is as the pulse evolves in time: whether it chirps during the turn-on and turn-off transients, whether there may be several distinct stages of the original pulse, that might be evident only by looking at its frequency evolution.

That is what was done in this experiment. The klystron was pulsed on for 10 μ sec, and the IF pulse from the microwave mixer was further gated with a 2 μ sec window which could be moved anywhere in the pulse.

When the grating window was placed in the center of the 10 μ sec klystron pulse, and the oscilloscope was triggered repetitively so that the pulse-to-pulse jitter could be seen, traces like those shown in Figure 14 were obtained. The lower trace shows the input pulse to the RAC while the upper trace shows

the RAC output after envelope detection. Horizontal time scale is 5 μsec /division, or 1.5 MHz per division in the spectral display. The pulse frequencies seem to be varying within a range of ± 1.5 MHz, due to the aforementioned 60 Hz ripple on the klystron repeller. Changing the oscilloscope triggering, so that only one trace is photographed, results in the clean-looking spectra shown in Figure 15. The $\sin(x)/x$ character evident in these traces is what we would expect for the spectrum of a 2 μsec rectangular piece gated out of the center of the 10 μsec klystron pulse.

If we move the gating window around in the pulse, we find that the spectra obtained are of the same form everywhere but at the very leading edge. Spectra of the first 2 μsec of the klystron pulse are shown in Figure 16; now the spectrum is highly unsymmetrical, due to chirping of the klystron during this time interval. The upper traces of the figure shows 10x expansion of the input pulse to the RAC. The envelope of this section of the pulse is closer to rectangular in shape than its spectrum would suggest, indicating that an appreciable amount of FM-ing must be occurring within the pulse as well.

Figure 17 shows portions of the spectra obtained when the klystron is only pulsed on for 1 μsec . The full spectrum of this pulse is wider than the 6 MHz bandwidth of the particular RAC, so not all of it is seen in one trace. The upper trace shows some of the lower sidelobes and the majority of the main

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Figure 14.

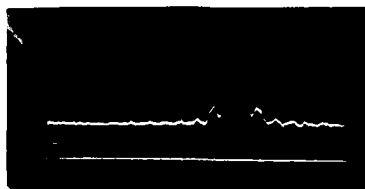
LOWER TRACE: 2 μ sec CENTER
SEGMENT GATED OUT OF A LONG
KLYSTRON PULSE. HORIZONTAL
SCALE 5 μ sec/DIV.

UPPER TRACE: MULTIPLE EXPOSURE
OF SPECTRA OF PULSE SEGMENTS.
HORIZONTAL SCALE 1.5 MHz/DIV.



Figure 15.

SINGLE EXPOSURE OF FIGURE 13
DATA.



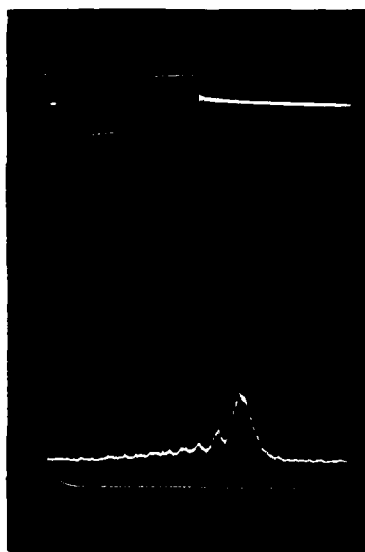
a)

Figure 16.

a) 10x EXPANDED TRACE OF FIRST
2 μ sec SEGMENT OF LONG
KLYSTRON PULSE.

b) SPECTRUM OF a).

b)



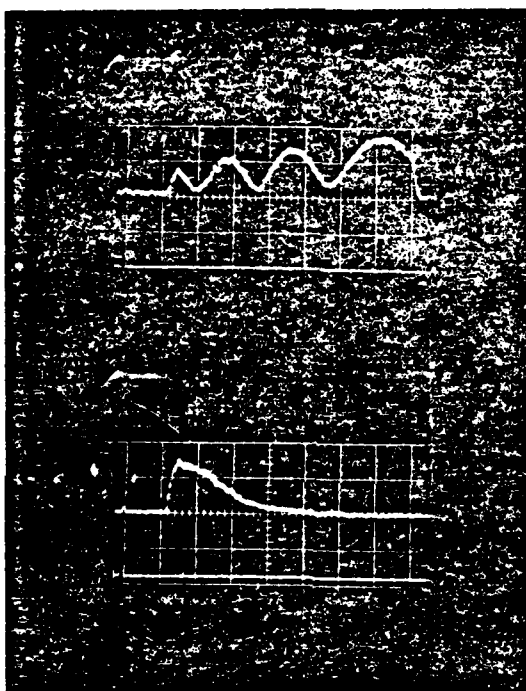


Figure 17. Different segments of the spectra of a 1.0 μ sec klystron pulse. Rightmost lobe of upper trace is main lobe of spectrum. Lower trace shows upper half of main lobe; note absence of upper sidelobes of spectrum, similarity of shape to trace in Figure 15b).

lobe of the spectrum. The lower trace shows half of the main lobe, and the fact that there are no upper sidelobes. The shape of this spectrum is therefore very similar to that of the first two microseconds of the longer klystron pulse. This short klystron pulse is essentially all transient.

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VII. PERSONNEL ASSOCIATED WITH GRANT AFOSR 76-2988

	<u>Percent of Time</u>	
Paul D. Coleman, Professor Principle Investigator	10%	1 February 1976 - 15 January 1980
E. J. Danielewicz Research Assistant	50%	1 February 1976 - 20 August 1976
E. G. Malk Research Assistant	50%	1 February 1976 - 5 January 1980
R. Ziolkowski Research Assistant	50%	1 February 1976 - 20 July 1976
D. Parsons Visiting Ass't Professor	50%	1 June 1977 - 30 July 1977
William Lee Research Assistant	50%	21 May 1976 - 5 January 1980
Joseph Niesen Research Assistant	50%	23 August 1976 - 20 September 1977
	17%	21 August 1977 - 20 May 1978
John Leap Research Assistant	50%	1 October 1977 - 20 April 1978
Raymond Chu Research Assistant	50%	21 March 1977 - 20 July 1977
Robert Miller Research Assistant	25%	6 January 1979 - 20 May 1979
	50%	21 August 1979 - 5 January 1980
David Kim Research Assistant	50%	21 April 1978 - 30 December 1979
Jimmie Smith Secretary	25%	1 February 1976 - 15 January 1980
Donald S. Fulton Electronics Technician	25%	1 February 1976 - 20 May 1979

VIII. MANUSCRIPTS

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IX. TECHNICAL MEETING PAPERS

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2. "Assignments of the High Power Optically Pumped CW Laser Lines of CH_3OH ", Paper M-3-7, Second International Conference of Submillimeter Waves and Their Applications, San Juan, Puerto Rico, December 6-11, 1976.
3. "Present and Future Problems in the Far IR", Invited Paper M-I, Second International Conference on Submillimeter Waves and Their Applications, San Juan, Puerto Rico, December 6-11, 1976.
4. "Far IR Laser Technology", 6th ARPA Tri-Service Millimeter Wave Meeting, Harry Diamond Laboratories, Adelphi, Maryland, November 1977.
5. "Laser Emission in the 83-223 μm Region from PH_3 with Laser Line Assignments", Third International Conference on Submillimeter Waves, University of Surrey, Guildford, England, March 1978.
6. "Far Infrared/Submillimeter Wave Technology and Applications", SPIE Technical Symposium, Reston, Virginia, April 1977.
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X. THESIS

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2. "A Phosphine Far Infrared Laser Optically Pumped by a CO₂ TEA Laser", J. W. Niesen, 1978.

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2. "Stimulated Raman and Hyper-Raman Scattering in the FIR Region", K. J. Kim, 1979.
3. "Optically Pumped Frequency Stable Tunable Maser and Infrared-Microwave Double-Resonance Experiments in Ammonia", E. G. Malk, 1980.

