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INVESTIGATION OF LASER FREQUENCY STABILIZATION

by Vincent J. Corcoran, Richard E. Cupp, William T. Smith, and James J. Gallagher

Prepared by
MARTIN MARIETTA CORPORATION
Orlando, Fla.
for Electronics Research Center

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LIST OF SYMBOLS

$\dot{\theta}$	-	rate of change of IF output signal phase angle
K_o	-	controller proportionality constant
I_2	-	input controller current
ϕ_v (t)	-	random frequency drift of the laser
F (s)	-	transfer function of the network following the phase detector
V_d (s)	-	output voltage of the phase detector
K_m	-	phase detector proportionality constant
v_i (t)	-	reference voltage
v_o (t)	-	IF output signal voltage
n (t)	-	IF output noise voltage
n_c (t), n_s (t)	-	amplitudes of orthogonal IF output noise voltage components
ω_o	-	angular frequency of IF signal
ω_i	-	angular frequency of reference voltage
θ_i	-	reference voltage phase angle
V_i	-	amplitude of reference voltage
V_o	-	amplitude of IF output signal voltage
θ_o	-	IF output signal phase angle
K_d	=	$\frac{K_m V_s V_o}{2}$
$\dot{\theta}_e$	-	rate of change of phase error

Θ_i	=	$\omega_i t + \theta_i$
Θ_o	=	$\omega_o t + \int \dot{\theta}_o \, dt$
θ_e	-	phase error
τ_2, τ_1	-	time constants of lag-lead network
C_T	-	piezoelectric translator capacitance
$\Delta\omega_P$	-	angular frequency limit of pull-in
ζ	-	damping factor of second order loop
K_V	-	dc loop gain
ω_n	-	angular natural frequency of second order loop
$\Delta\omega_L$	-	angular frequency limit of lock-in
T_P	-	time required to lock
$\Delta\omega$	-	angular frequency less than $\Delta\omega_P$ and greater than $\Delta\omega_L$
B_L	-	angular frequency loop bandwidth
G	-	open loop gain
K	=	$K_o \, K_d$ for phase locking through power supply
	=	$K_o \, K_d \, C_T$ for phase locking through piezoelectric translator
ΔL	-	change in cavity length
L	-	cavity length
S_T	-	translator sensitivity
v_2	-	translator voltage

INVESTIGATION OF LASER FREQUENCY STABILIZATION

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SUMMARY

Investigations have been performed on the stabilization of a far infrared laser. Both phase stabilization and frequency stabilization have been considered. Theoretical treatment of the phase-locking process has been made and experimental studies have been performed on the phase-locking of the laser to a harmonic of a frequency standard. Stability characteristics of the laser systems have been studied, and two of the HCN lasers, operating on the 890 GHz line, have been heterodyned to yield linewidths on the order of 10 kHz. An AFC loop has been employed to lock the HCN laser to the frequency standard. A stability on the order of 1 part in 10^8 has been achieved.

I. INTRODUCTION

During the past five years laser activity has been extended to the far infrared wavelength region. As a result, the output wavelength of gas lasers has been steadily increased to the point where the longest achievable wavelength is overlapped by the shortest wavelength that is generated harmonically from microwave oscillators. The availability now makes possible several investigations which were not considered previously possible.

Because of the overlap of laser transitions with the signals obtained by harmonic generation from conventional oscillators, it has been possible to mix the output of lasers with the outputs of klystrons, and thereby measure very accurately the laser output frequency. This has been achieved with the

HCN laser transitions at 890 GHz and at 960 GHz by mixing with the 12^{th} and 13^{th} harmonics of a 70 GHz klystron (Reference 1). More recently, it has been possible to observe the DCN line at 190 microns (Reference 2), and the H_2O line at 118 microns (Reference 3) by beating against a harmonically generated signal.

Several applications of the far infrared lasers require greater stability of these sources than is available when operated in a free running mode. Thus, the establishing of standard frequency signals, velocity of light measurements, the extension of existing frequency standard techniques to the optical region and the eventual use of precise tunable signals depend upon the availability of far infrared signals with stabilities on the order of parts in 10^8 or better. Previous work, performed in the Electromagnetics Department of Martin Marietta with the support of the United States Army Electronics Command, has provided the preliminary basis for the extension of frequency control to the far infrared (Reference 4).

The objective of the investigations performed under this contract has been to develop the means of obtaining from the HCN and/or H_2O lasers now in operation in the Martin Marietta laboratories an IF signal of sufficient spectral purity so as to permit eventual phase-locking of the laser to a frequency standard. It has initially been desired to obtain stabilities on the order of a part in 10^8 by either phase-locking to the multiplied frequency standard signal or by locking with an AFC circuit to the frequency standard signal. With the AFC loop, the stability of one part in 10^8 has been achieved.

During the course of this contract, a complementary program, sponsored by ECOM, has been performed. This investigation, "Extension of Frequency

Control to the Infrared Region," was sponsored by the Frequency Control and Solid State Division, United States Army Electronics Command, Fort Monmouth, New Jersey, under Contract DAAB07-68-C-0206; Dr. Helmut Hellwig was the technical monitor. While both programs have been concerned with the same subject, no repetition of work was performed, but instead a more extensive investigation of the many effects involved has been carried out. Thus, a theoretical treatment of phase-locking of the laser and various experimental studies of the phase-locking have been performed on the ECOM contract, while the NASA effort has concentrated on the stability characteristics of the laser, the beating of two HCN lasers and the eventual AFC of the laser by the harmonically generated frequency standard signal. The work has been concerned mainly with the HCN laser since it is more accessible by harmonic generation, but all techniques are applicable to the H_2O laser. For the purpose of completeness, the investigations performed on both contracts are discussed in this report.

II. LASER STABILITY MEASUREMENTS

In order to determine the stability and factors affecting the stability of an HCN laser, a series of experiments were performed in which two free-running lasers were mixed in open-structure, point contact mixer. The two lasers are shown in Figure 1. The laser on the right is mounted on a cement beam for stability purposes. The laser uses the box configurations for the mounting of the mirrors and is approximately 12 feet long. The gas inlet is in the near box and the pump outlet is in the far box. The laser on the left is mounted on a granite slab and essentially has the same configuration as the other laser, but is only 10 feet long. In Figure 1, both lasers are mounted on six-inch inner tubes. The tube shown perpendicular to the lasers was being used for gain measurements of HCN at 890 GHz.

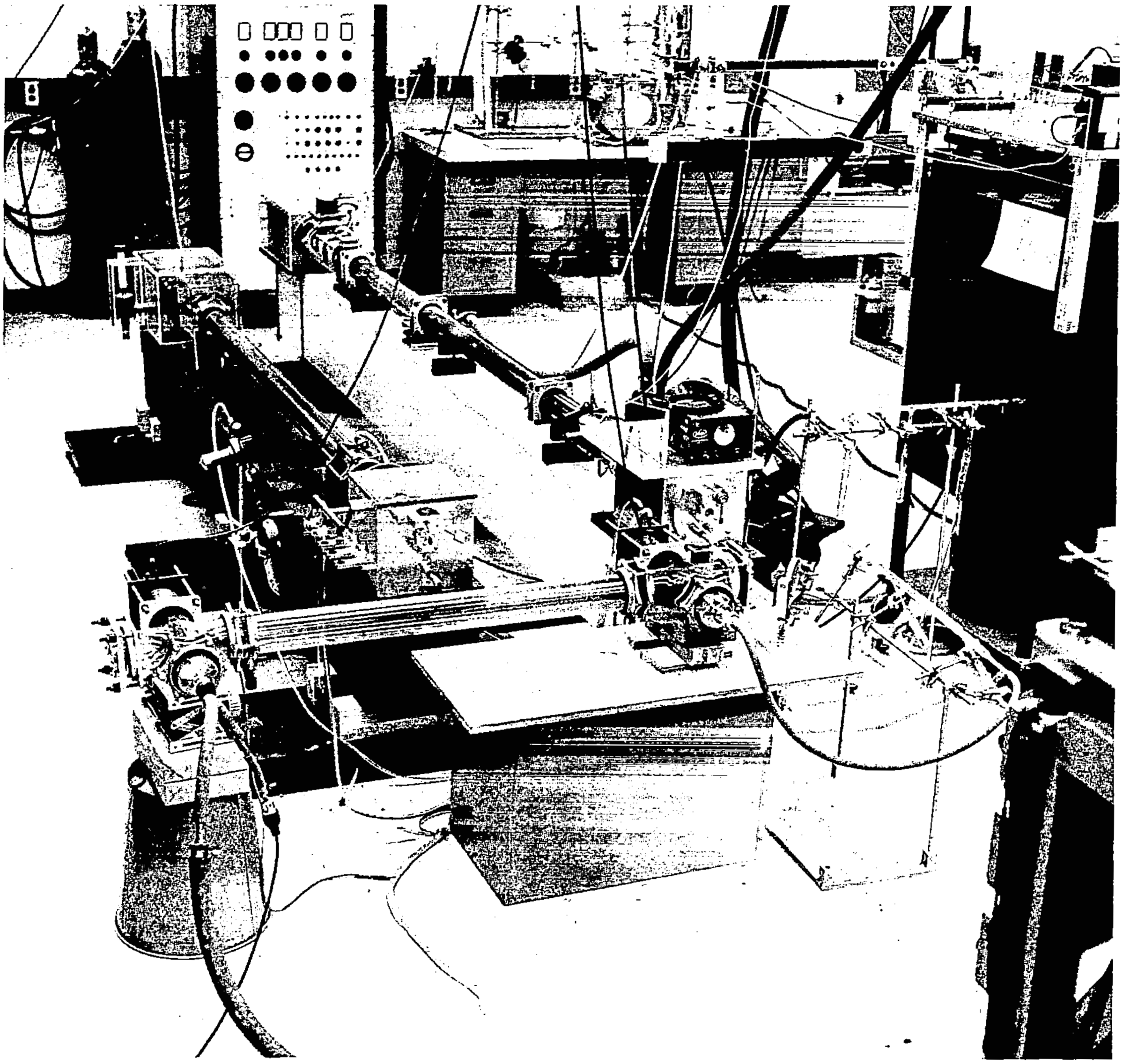


Figure 1. Photograph of Two Lasers Used to Make Laser Stability Studies

The open-structure point contact diode, shown in Figure 2, is constructed on the same principles as the conventional waveguide mixers, except that the laser signals are coupled to the diode through two 1/2 inch holes. Small mirrors, mounted on gimbal supports, reflect the signals back to the diode structure. It was found, during these investigations, that the optimum part of the diode for the laser signals to strike is the hook in the tungsten whisker rather than the junction of the whisker and crystal.

A block diagram of the mixing experiment is shown in Figure 3. The output of the mixer is amplified in a video amplifier. The amplified signal is displayed on an oscilloscope and mixed with a local oscillator. The side band that is generated is displayed in the frequency domain on a spectrum analyzer. The results of the first experiment are shown in Figure 4. Widths in excess of 50 kHz were obtained in all observations.

The first modification to the above experiment was to isolate each laser from the ground by setting it on six inner tubes, which can be seen in Figure 1. Only slight improvement in the stability occurred.

The next modification was to stabilize the discharges in the laser tubes by using an ethyl ether and ammonia mixture instead of natural gas and nitrogen. The effect on the beat is shown in Figure 5. The line in Figure 5a has narrowed considerably, in most cases being less than 20 kHz. In the time domain representation, Figure 5b, the drift was found to be at a 120 Hz rate, thus indicating that the ripple on the power supply could be a major source of instability. By the use of filtering and a feedback network, a constant current supply can be generated; with the reduced ripple and drift of the current from the power supply, each laser should be more stable with a resultant reduction in the linewidth of the beat. With such a circuit,

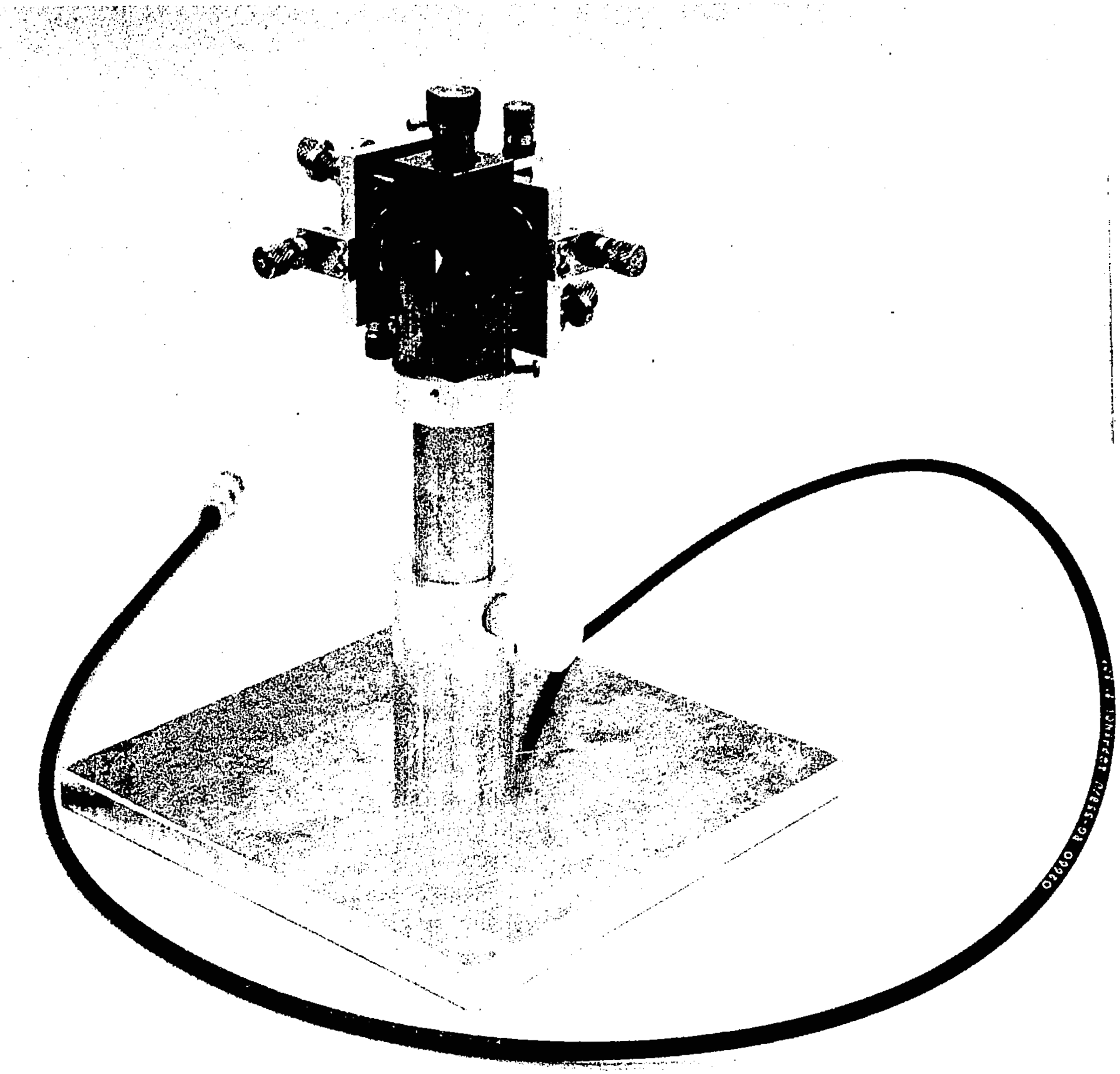


Figure 2. Photograph of Open-Structure, Point-Contact Mixer

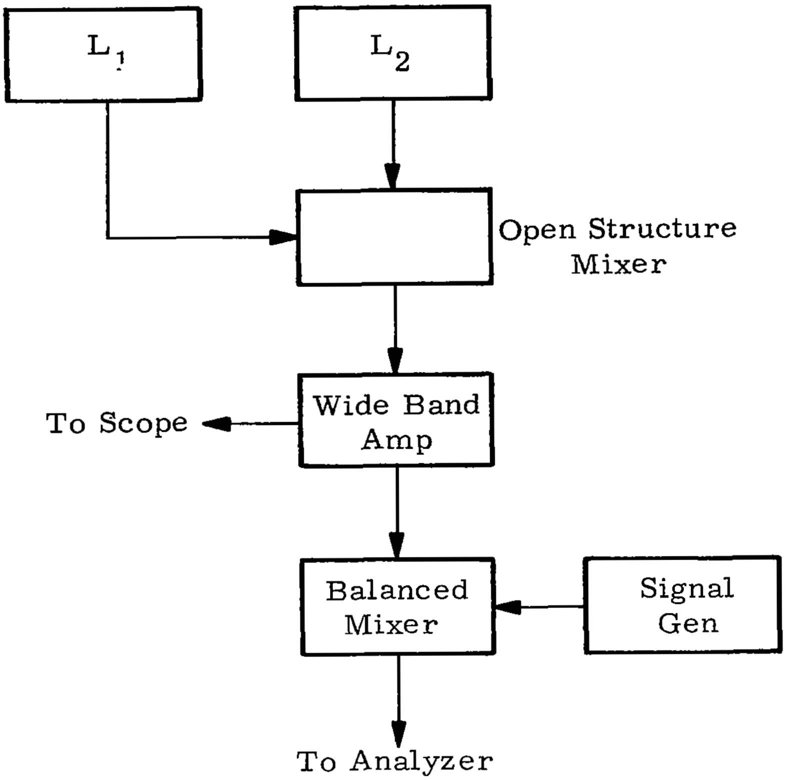


Figure 3. Block Diagram of Experiment to Study Factors Affecting Laser Stability

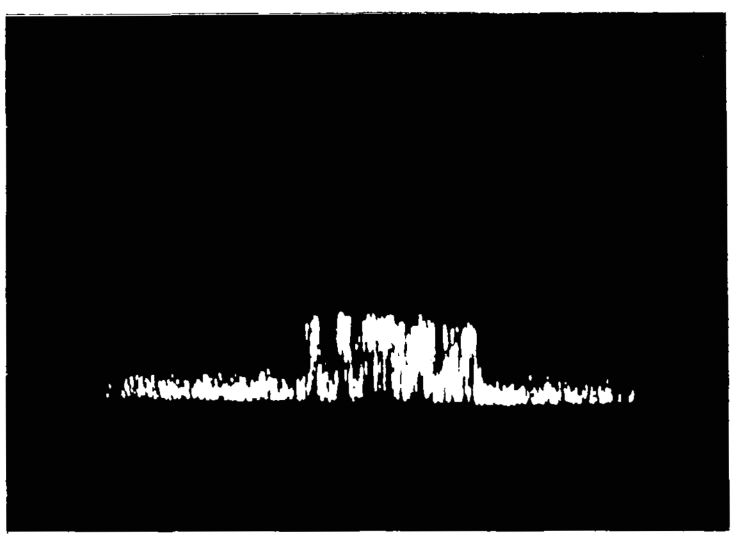


Figure 4. Frequency Domain Representation of Beat Between Two Lasers from HP Spectrum Analyzer 851B/8551B Bandwidth 30 kHz, Scan Width 50 kHz/cm, Sweep Time 10 ns

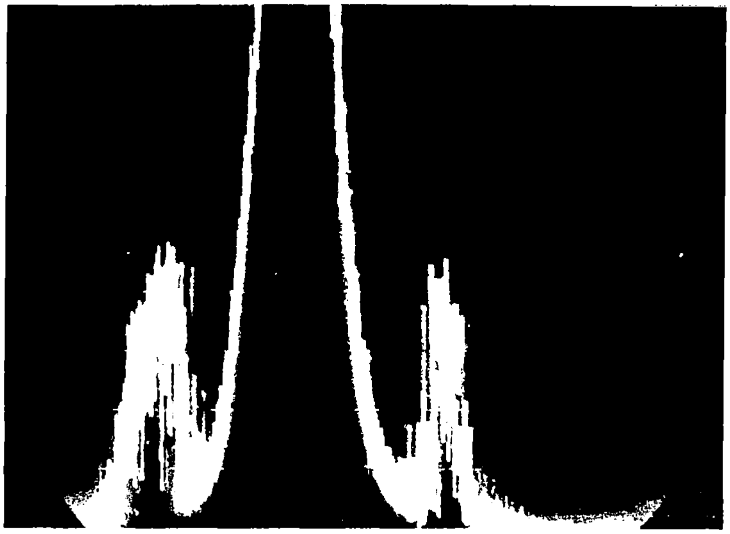


Figure 5a. Frequency Domain Representation of Beat Between Two Lasers from Polarad Spectrum Analyzer. Sweep Width, 25 kHz/cm. Center Line is RF Local Oscillator.

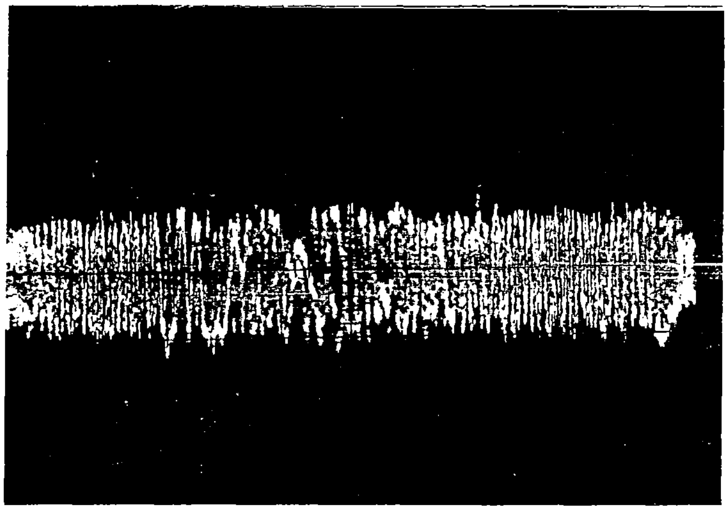


Figure 5b. Time Domain Representation of Above Signal. Drift from High Frequency to Zero Beat to High Frequency Occurred at 120 Hz Rate.

the laser employed in the phase-lock experiments has not shown a significant narrowing of the beat.

While further reduction of the beat width should occur, the linewidth 10-20 kHz is more narrow than the beat between the laser and klystron harmonic has been until recently. This indicates a need for improvement in the spectral purity of the multiplying chain, which will be discussed in a later section.

III. PHASE LOCKED LASER

The problem of generating a standard frequency in the submillimeter wave region and phase locking a submillimeter wave laser to the standard frequency has been investigated analytically and experimentally. The experimental portion of the program had been started in earlier investigations (Reference 4); however, the analysis of the phase lock problem began during the period of this contract.

A. Theory

In order to obtain design guidelines for phase locking the laser to the submillimeter frequency standard, a detailed analysis of the phase lock system was needed. The results of the analysis, which are given in Appendix A, indicate the complexity of the problem. The analysis of the system results in a nonlinear differential equation with random driving functions.

Two approaches to obtain solutions were taken. The first was to put the problem on a computer to obtain solutions. The second was to fit the problem to previous analyses so the previous results could be used.

The computer program for the approximation of phase locking through the power supply without filtering was run to check the program and to determine whether running more complicated programs on the computer would be fruitful. The results, given in Appendix Section V, clearly show the phase locking and the effect of the loop gain on the time to lock. Work toward obtaining solutions for the more complicated problems has been continued.

Due to limited time and resources, the present problem was analyzed in terms of existing programs. These results, given in Appendix Section IV, provide design equations to determine the capability of the system to lock and to ascertain the most desirable design for lock.

A glance at the equations themselves would not uncover any particular problems. However, practical problems that prevent the achievement of the desired parameters do exist. For example, the sensitivity and capacitance of a piezoelectric translator are limited by its design and these parameters affect other parts of the system; the low sensitivity makes high voltages necessary, causing breakdown problems, the capacitance causes amplifier design problems, etc.

The design of a phase lock loop using a piezoelectric translator will now be considered for a few conditions to illustrate the approach. The drift range of the laser is assumed to be 10 kHz and the piezoelectric translator is assumed to be a Lansing Research Model 21.233 which has a sensitivity S_T of 0.79 μ/1000V and a capacitance C_T of 0.045 μf.

From Appendix A the value of K_o C_T is given by

$$K_o \ C_T = \frac{\omega_o \ S_T}{L}$$

For an 890 gHz frequency and a 3 meter cavity,

$$K_o \ C_T = \frac{2\pi \times 890 \times 10^9 \times 0.79 \times 10^{-9}}{3}$$

$$= 1470$$

The variables that are available are K_d, τ_1 and τ_2. Since $\Delta\omega_L$, $\Delta\omega_P$ and T_P are interdependent, an iteration technique to arrive at the desired design is used. Assume that

$K = 10^6,\ \tau_2 = 10^{-6},\ \tau_1 = 10^{-4}$. Then

$$K_d = 680/\text{volt}$$

$$B_L = \omega_n = \left(\frac{K}{\tau_1}\right)^{1/2} = 10^5 \text{ rad/s}$$

$$\Delta\omega_P = \left[2K\left(\frac{1 + K\tau_2}{\tau_1}\right)\right]^{1/2} = 2 \times 10^5 \text{ rad/s}$$

$$\Delta\omega_L = \frac{1 + K\tau_2}{\tau_1} = 2 \times 10^4 \text{ rad/s}$$

$$T_P = \frac{(\Delta\omega)^2}{\frac{K}{\tau_1}\left(1 + \frac{K\tau_2}{\tau_1}\right)} = 5 \times 10^{-5} \text{ s for } \Delta\omega = 10^5$$

$$\left(S/N_L\right) = \left(S/N_i\right)\frac{B_i}{2B_L} = 180 \text{ for } \left(S/N_i\right) = 36$$

$$\tau_1 = R\ (C_T + C) \approx R\ C_T$$

$$R = \frac{\tau_1}{C_T} = 2 \times 10^3\ \Omega$$

$$C = \frac{\tau_2}{R} = \frac{10^{-6}}{2 \times 10^3} = 500 \text{ pf}$$

This design, therefore, would pull in the laser if it were off by 30 kHz but would not lock in; i.e., it would skip cycles and the time for lock would be 50 μs. The system bandwidth is 16 kHz and the maximum voltage out of the phase detector and amplifier must be 680 volts. At dc, all 680 volts is across the piezoelectric translator. At 16 kHz, the impedance of the piezoelectric device is 210 ohms and the network has an impedance of approximately 2000 ohms so the device draws approximately 0.3 amp. The amplifier therefore, draws considerable power.

It would be desirable to reduce the amplifier requirements. The bandwidth could be reduced by increasing τ_1. Let $K = 10^6$, $\tau_2 = 10^{-6}$, $\tau_1 = 10^{-3}$. Then

$$K = 680/\text{volt}$$

$$B_L = \omega_n = 3.2 \times 10^4 \text{ rad/s}$$

$$\Delta\omega_P = 6.3 \times 10^4 \text{ rad/s}$$

$$\Delta\omega_L = 2 \times 10^3 \text{ rad/s}$$

$$T_P = 5 \times 10^{-5} \qquad \text{for } \Delta\omega = 10^4$$

$$\left(S/N_L\right) = 560$$

$$R = \frac{\tau_1}{C_T} = 20\text{K ohms}$$

$$C = \frac{\tau_2}{R} = 50 \text{ pf}$$

This design will pull in a 10 kHz offset frequency and will lock in approximately the same time as before. The system bandwidth is now 5 kHz. The voltage at DC is the same and at 5 kHz the impedance of the piezoelectric translator is 700 ohms. Therefore, the device in this case draws only 30 ma.

A further variation in K or τ_2 would probably result in continued improvement. Eventually the most desirable set of values would be established governed both by the theory and the practical limitations.

B. Techniques

The earlier attempts at phase-locking the laser to the harmonic of the frequency standard have been previously described (Reference 4). The techniques employed were similar to those described below. However, a number of modifications were made in these experiments; some changes were suggested by the phase lock analysis and the laser stability studies.

A block diagram of the equipment used to attempt phase locking the HCN laser signal to the submillimeter frequency standard is shown in Figure 6. A Varian VC705 reflex klystron is phase-locked to the ninth harmonic of an X-band reflex klystron, which itself is phase locked to the sum of an harmonic of a rubidium frequency standard signal and an interpolation oscillator signal. The eleventh harmonic of the Varian VC705 is generated and mixed with an HCN laser signal at 890,758 GHz in a point contact multiplier. This beat frequency signal is amplified in an LEL 30 MHz IF amplifier and sent to the Model 2650 A Dymec Transfer Oscillator Synchronizer. The phase error signal from the synchronizer before filtering is amplified, filtered, and fed to the piezoelectric translator on which one of the laser mirrors is mounted.

The amplifier and filter were designed to provide sufficient loop gain and loop bandwidth to capture the beat frequency signal. A schematic diagram of the amplifier and filter is shown in Figure 7.

The signal generated by beating the eleventh harmonic of the Varian VC705 with the laser output is shown in Figure 8 after amplification by the 30 MHz IF amplifier. Figure 8a is the time domain representation of the beat frequency signal reproduced from a type 647 Tektronix oscilloscope. The frequency spectrum of the beat is shown in Figure 8b. The figure was obtained from a Polarad spectrum analyzer with an STU-1A RF tuning unit. The short term drift range or the bandwidth integrated over the short term drift is approximately 50 MHz.

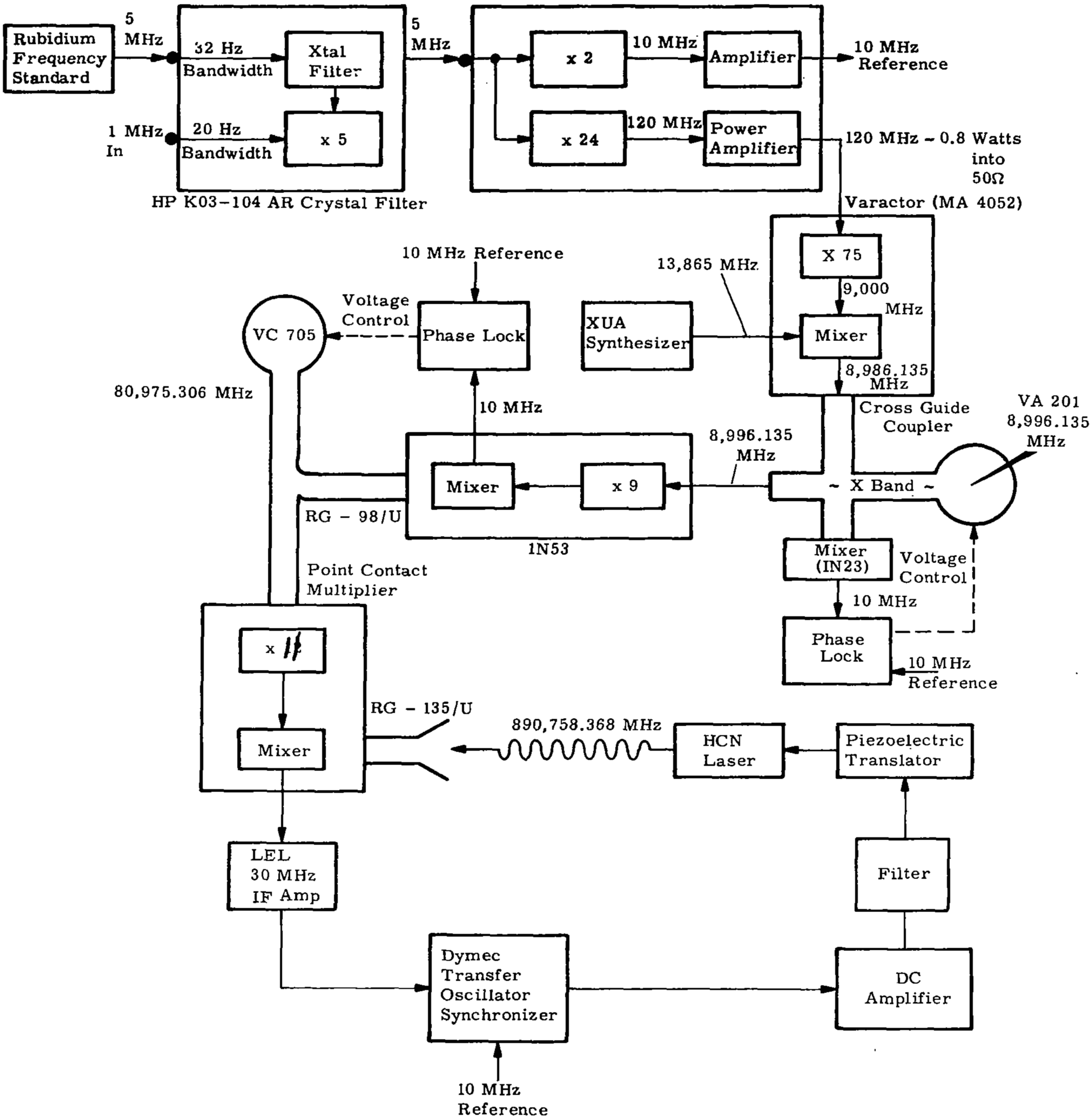


Figure 6. Block Diagram of Equipment Used for Attempt to Phase-Lock an HCN Laser

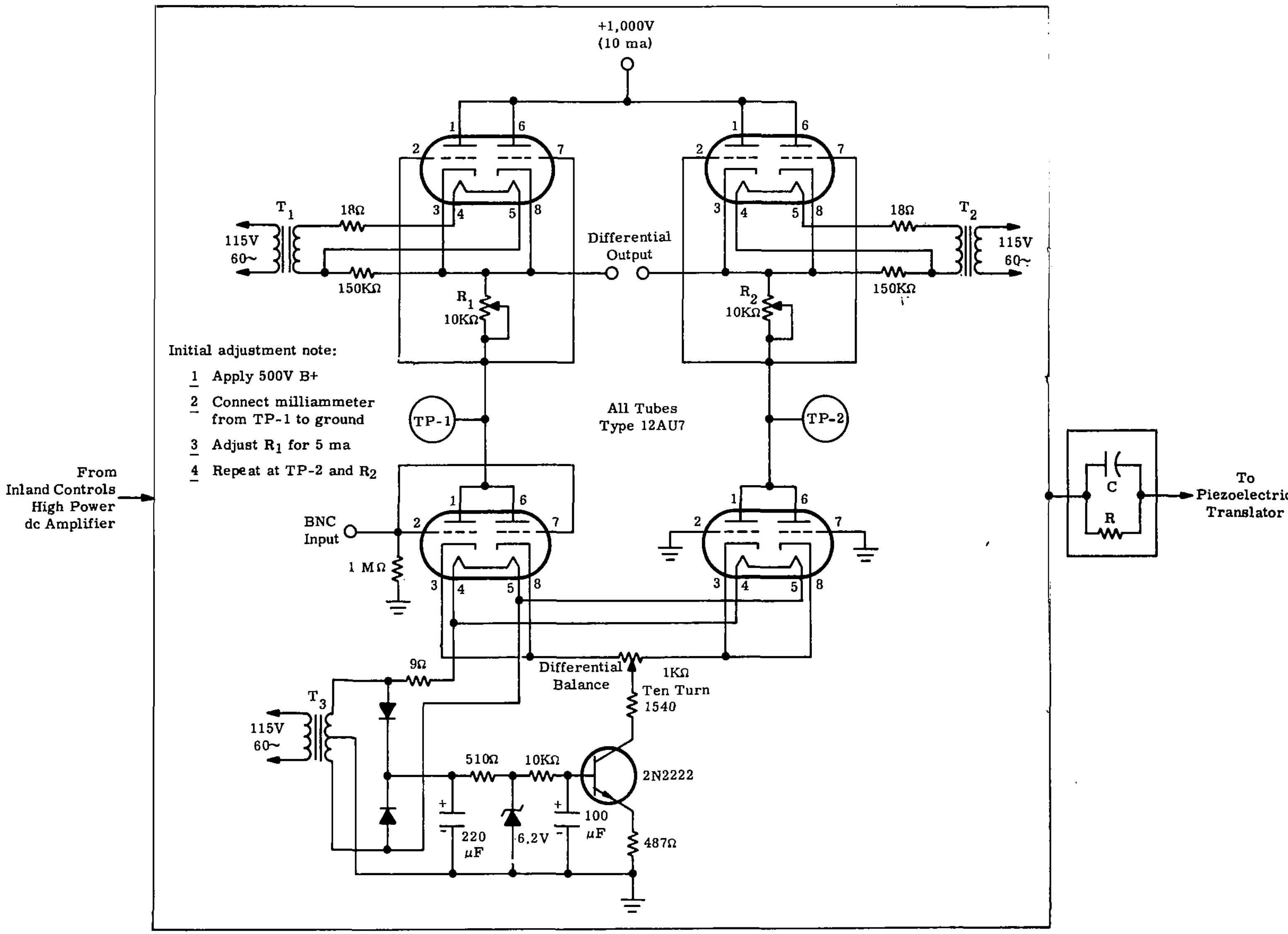


Figure 7. Schematic Diagram of Amplifier and Filter Used in HCN Laser Phase Lock Loop

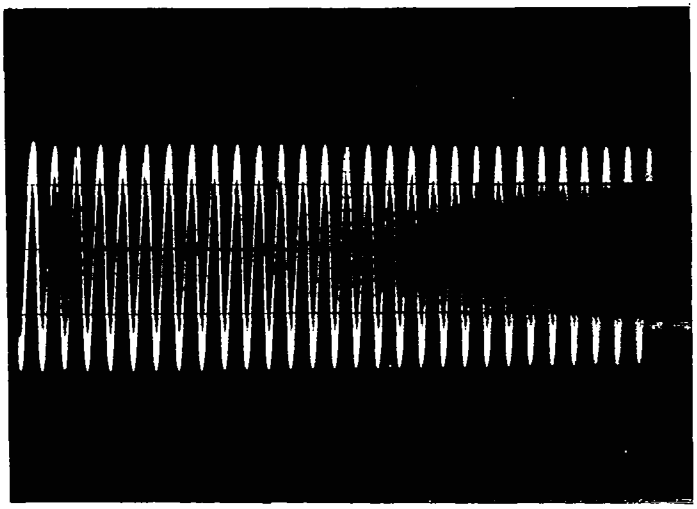


Figure 8a. 30 MHz Beat Between Laser
and Multiplied Frequency Standard
(Time Domain Representation)

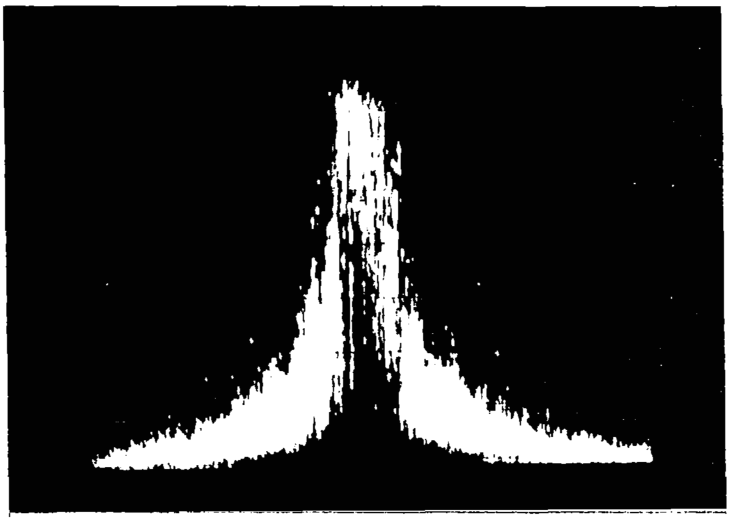


Figure 8b. 30 MHz Beat Between Laser and Multiplied Frequency
Standard (Frequency Domain Representation) Scan Width)
50 kc/cm; BW, 30 kc; Scan Time 10 ms/cm

<u>Signal to Noise Improvement</u>. - A number of variations of the equipment diagrammed in Figure 6 were tried. With the HCN laser operating at 890,758 MHz the following signals were used:

Tube	Harmonic
Varian VC714	6
OKI 70V10	10
OKI 70V11	12
Varian VC715	9

Also the seventh harmonic of a Varian VC715 tube was mixed with the 960 GHz line from an HCN laser. All of these changes were made with the intention of improving the signal-to-noise ratio out of the IF amplifier. It was found, however, that the primary limitation on the signal-to-noise ratio was due to saturation in the IF amplifier. When that problem was eliminated, then the signal-to-noise ratio was satisfactory, as indicated in Figure 8a.

Mechanical Isolation. - In an attempt to narrow the width of the beat between the laser and the submillimeter frequency standard, modifications were made to isolate the laser from mechanical vibrations. The laser was isolated from the floor with six inner tubes as shown in Figure 9. Any coupling of vibrations through hose connections was also eliminated by turning off the sources of vibration and by isolating them. The use of geophones showed that the vibrations were reduced as seen in Figure 10; however, no change occurred in the beat frequency signal.

Discharge Stability. - Another suspected source of the beat frequency drift was the instability of the discharge and the current. The change from a mixture of natural gas and nitrogen to a mixture of ethyl ether and ammonia resulted in a significant change in the discharge stability as shown in Figure 11. In Figure 11a the instability of the discharge causes it to appear uniform. The appearance of the striations in Figure 11b indicates the temporal stability of the discharge with the ethyl ether-ammonia mixture.

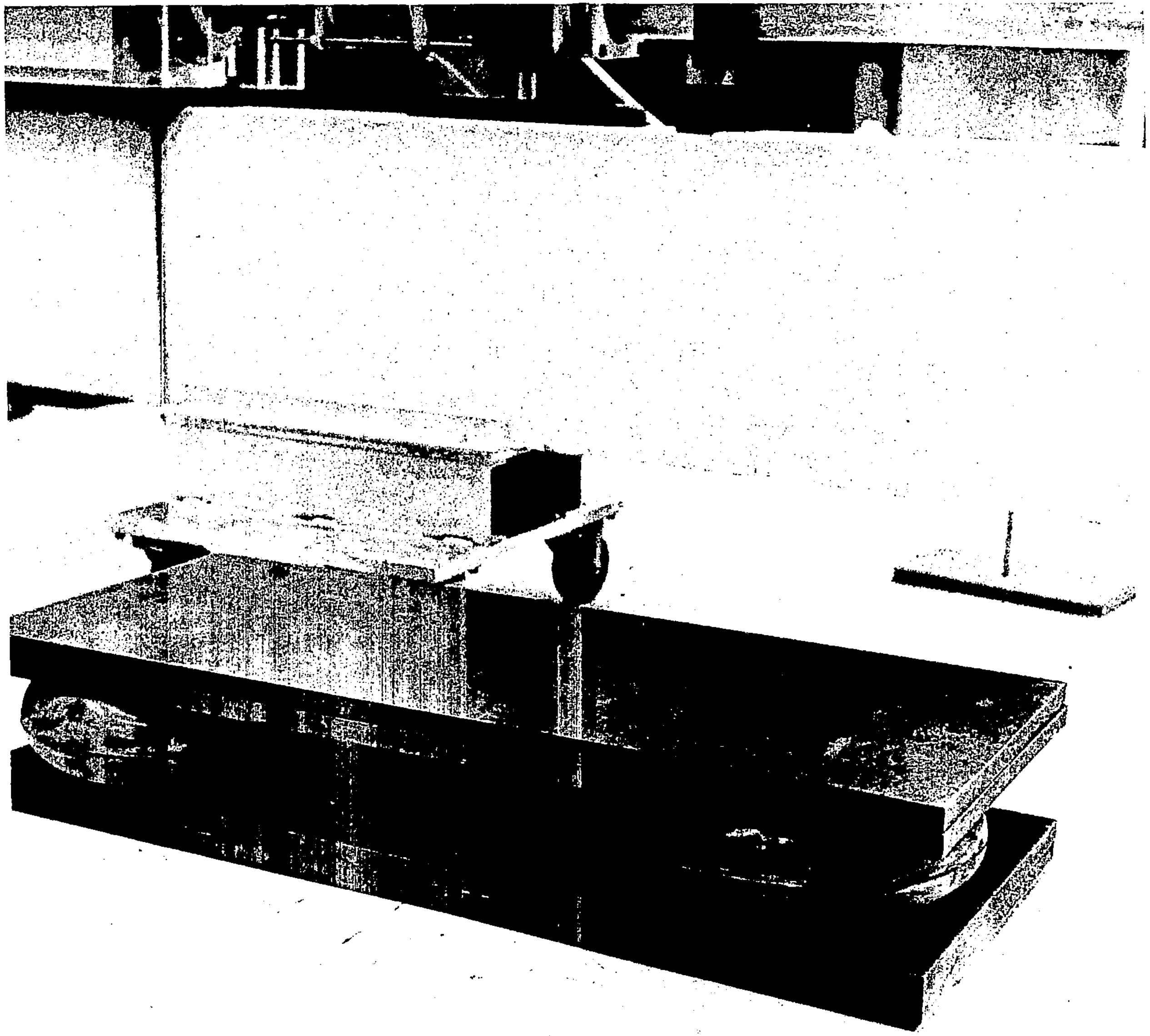


Figure 9. Arrangement of Inner Tubes for Isolation of Laser from Vibrations

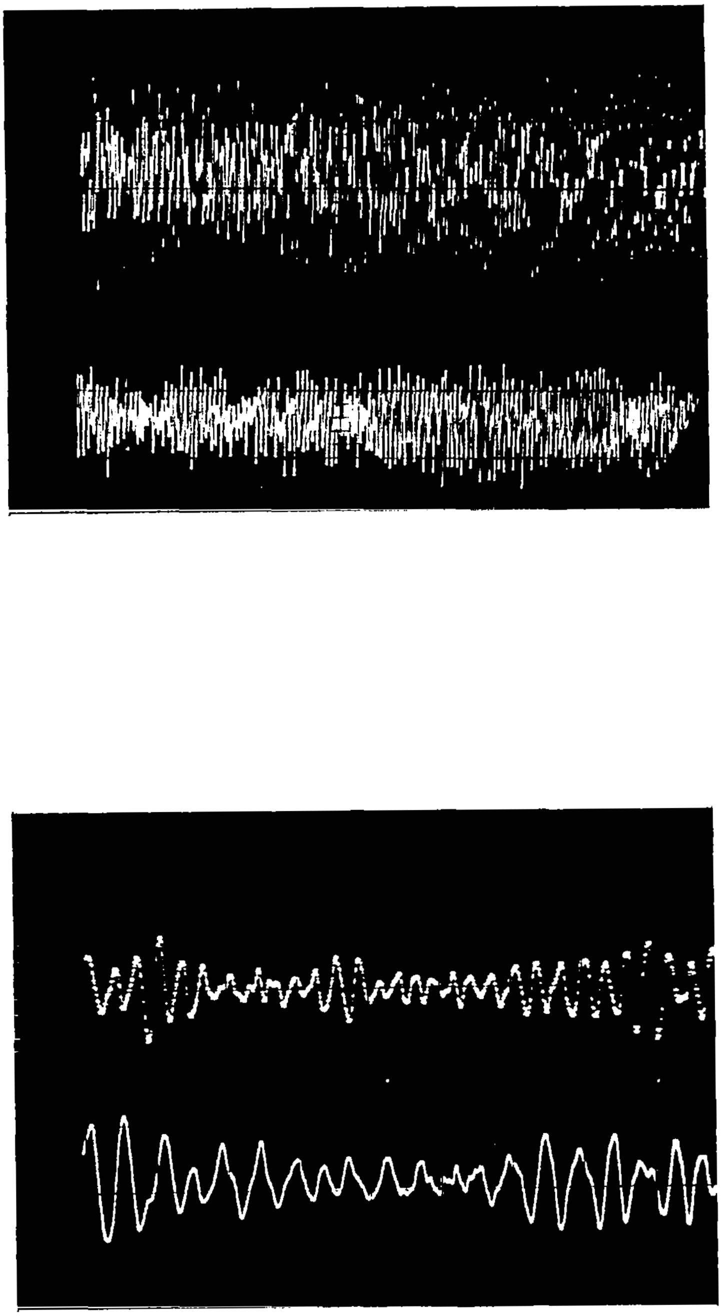


Figure 10. Geophone Recording of Laser Vibrations Without Isolation and With Isolation from Floor With Inner Tubes and Pump and Fan Off

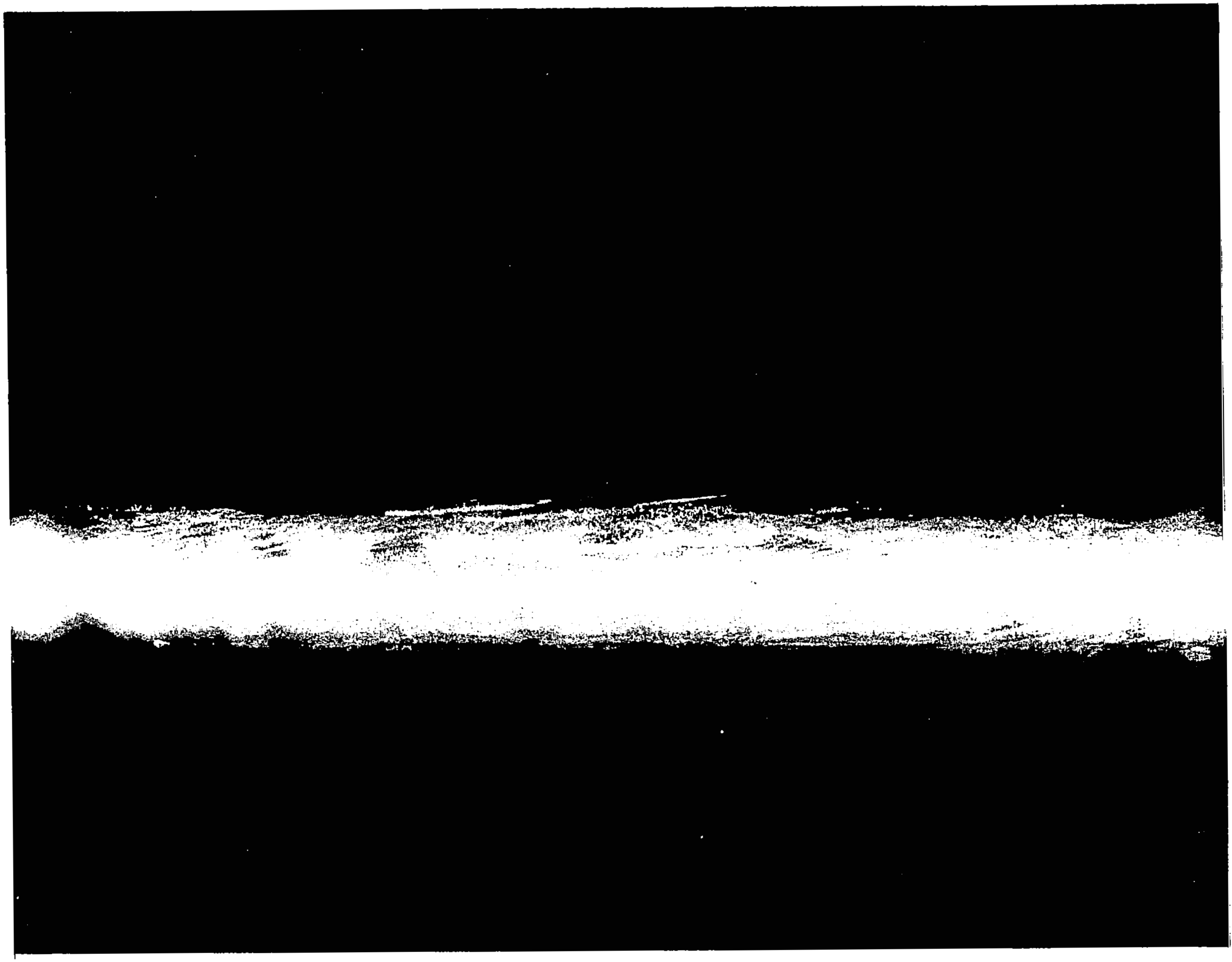


Figure 11a. Discharge Stability Condition: Unstable Discharge

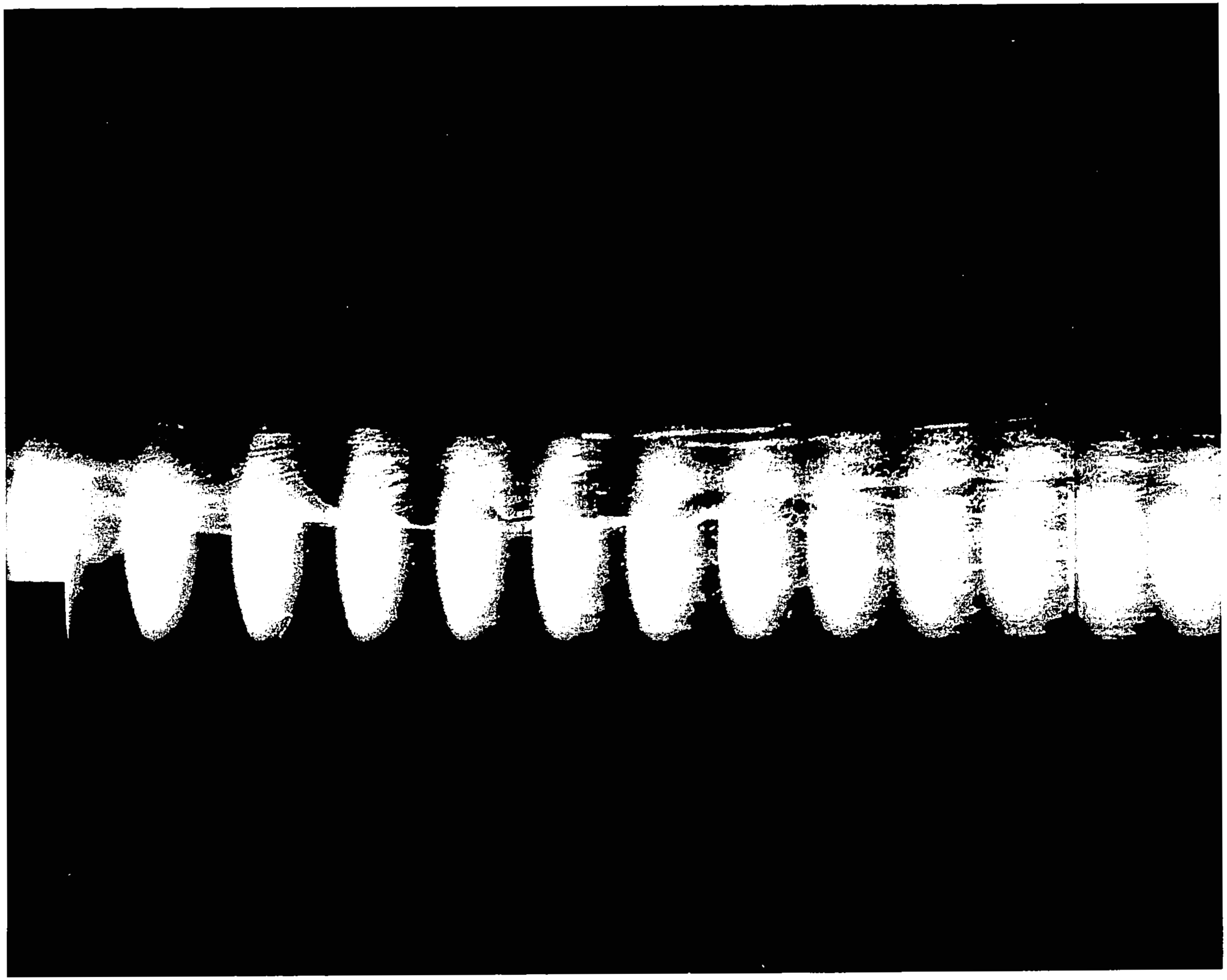


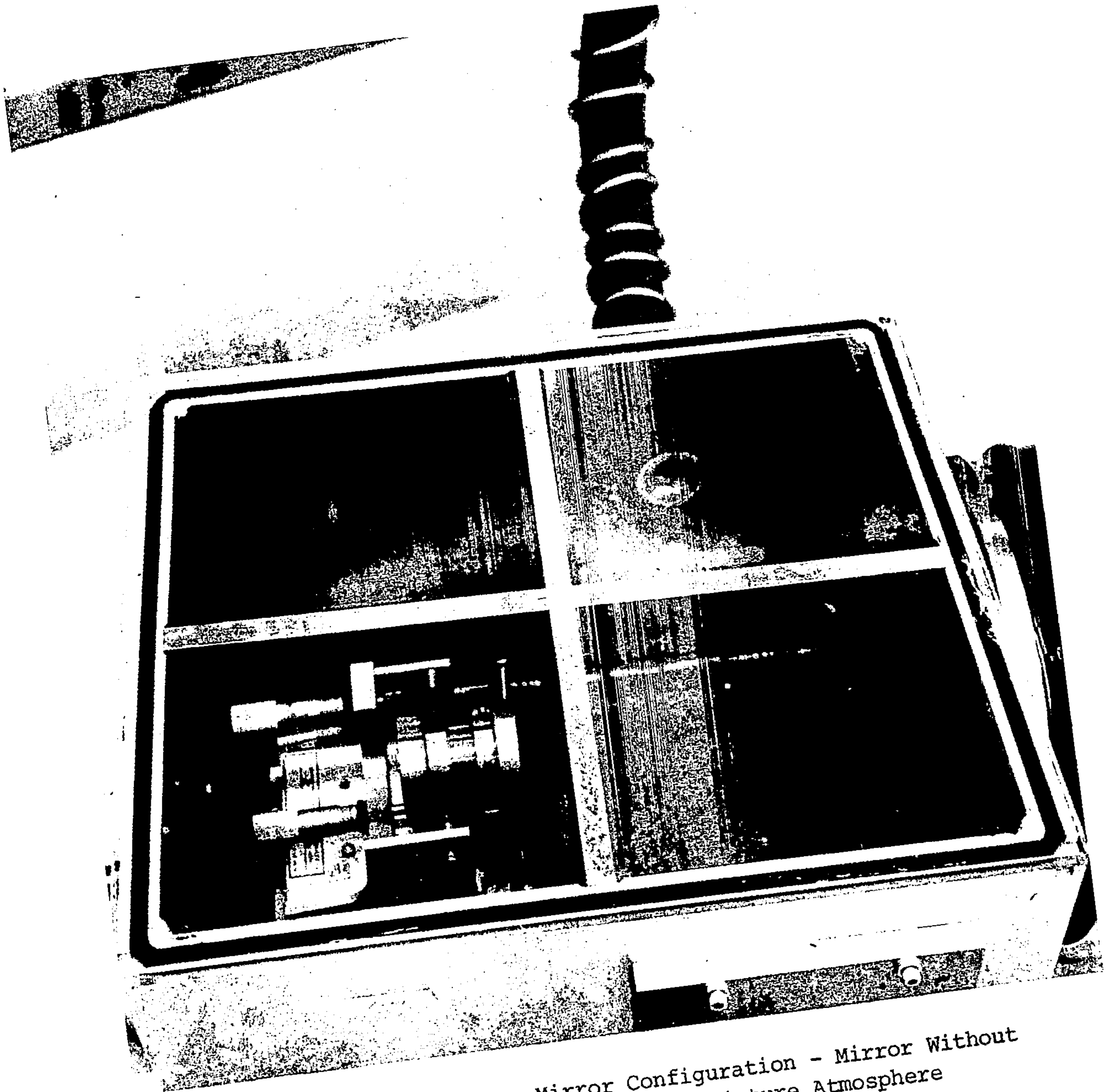
Figure 11b. Discharge Stability Condition: Stable Discharge with Standing Striations

In addition to the visual stability of the discharge, the stability of the current was examined. Neither improvement in the current nor the discharge resulted in a change in the beat frequency signal.

Breakdown. - The laser used in these experiments had been operated with the mirrors in the gas mixture atmosphere as shown in Figure 12. Whenever a voltage above approximately 200V was applied to the piezoelectric translator, on which the output mirror was mounted, breakdown would occur. That problem was circumvented by making a Brewster window from polypropylene and operating the output mirror in the atmosphere (see Figure 12b). With the Brewster window system the beat frequency signal-to-noise ratio was reduced by a factor of two and the breakdown voltage was greater than 1500V.

Multiplier Chain Instability. - At the same time that experiments were being performed on the phase lock equipment, the laser stability studies were being made by mixing two free running HCN laser signals and observing the beat frequency as discussed in Section II. One result of the laser stability studies was that the laser linewidth appeared to be less than 20 kHz. The beat between a laser and a multiplied microwave signal, however, was 50 kHz. This result immediatedly made the microwave signal the suspected source of the instability, and it simultaneously explained the discrepancy between improvements in the laser characteristics and lack of improvement in the beat between the laser and the multiplied microwave signal.

In the first experiment, which verified the fact that the microwave signal was the source of the instability, the multiplier chain from 5 to 120 MHz was eliminated and a 120 MHz crystal oscillator was used as the standard. The block diagram of the equipment is shown in Figure 13. The beat generated in this experiment is reproduced from a Marconi spectrum analyzer in Figure 14.



12a. HCN Laser Mirror Configuration - Mirror Without Window in Gas Mixture Atmosphere

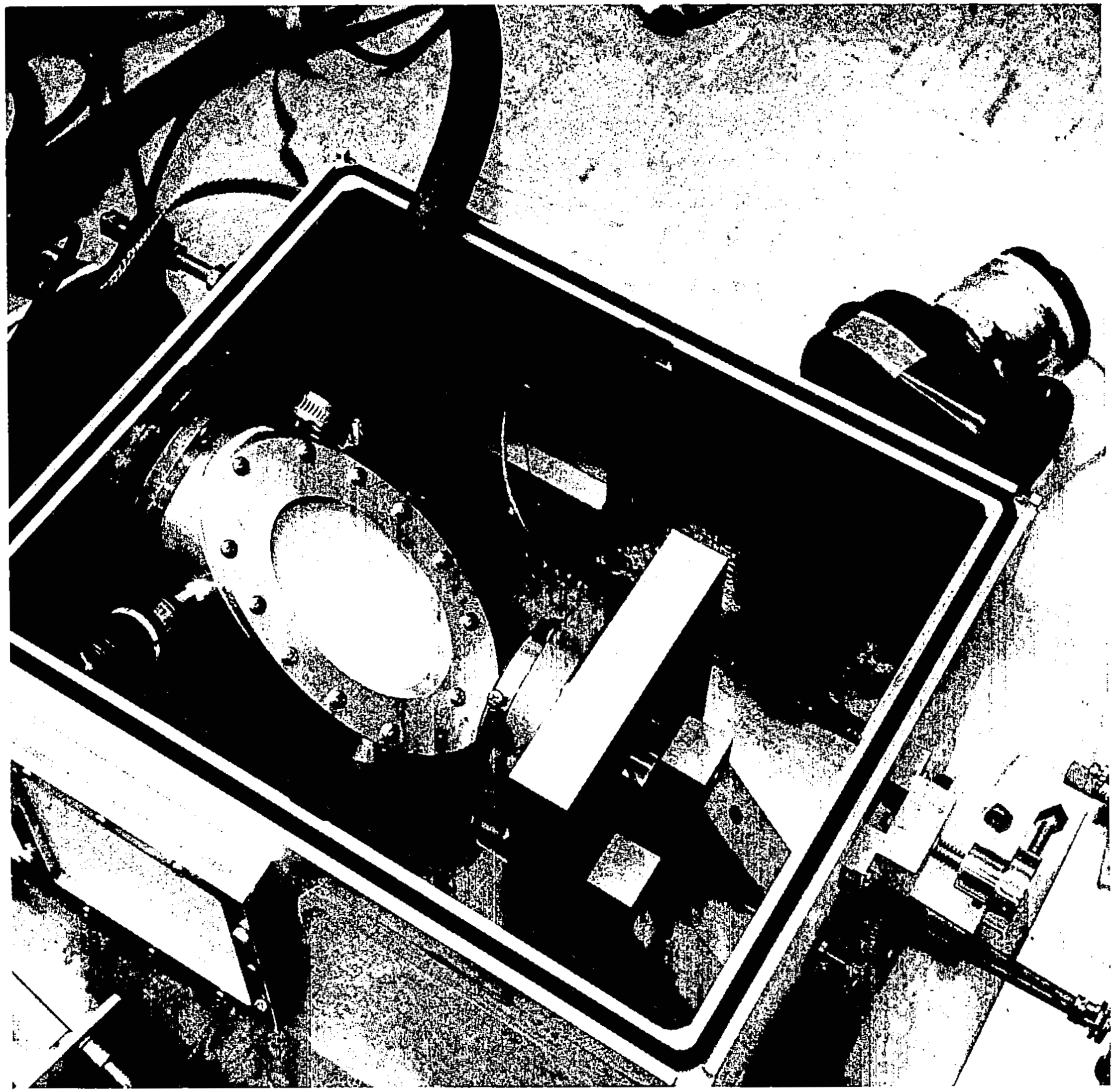


Figure 12b. HCN Laser Mirror Configuration - Mirror with Brewster Angle Window at Atmospheric Pressure

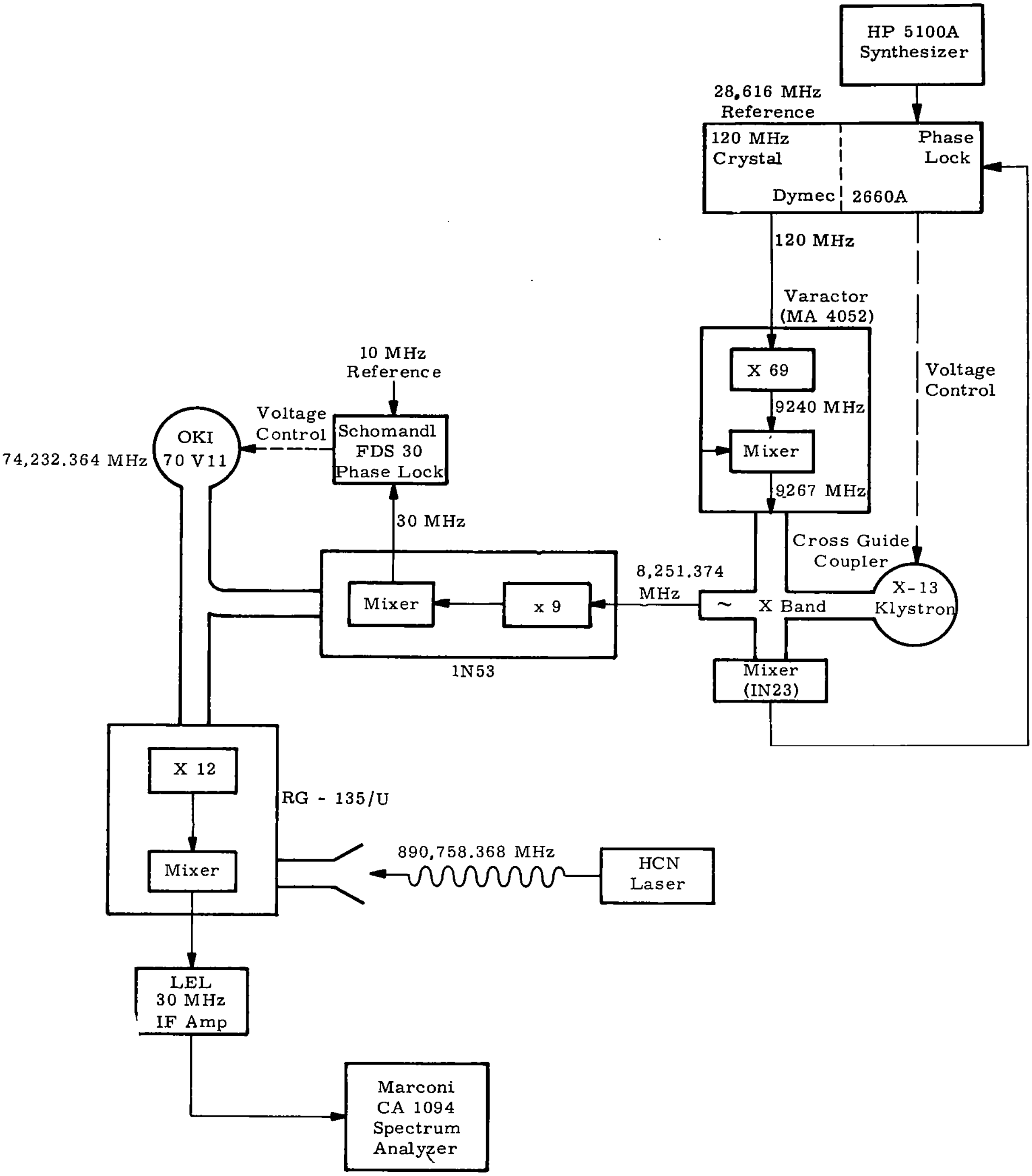


Figure 13. Block Diagram of Equipment Used to Determine Source of Instability in Laser-Microwave Beat

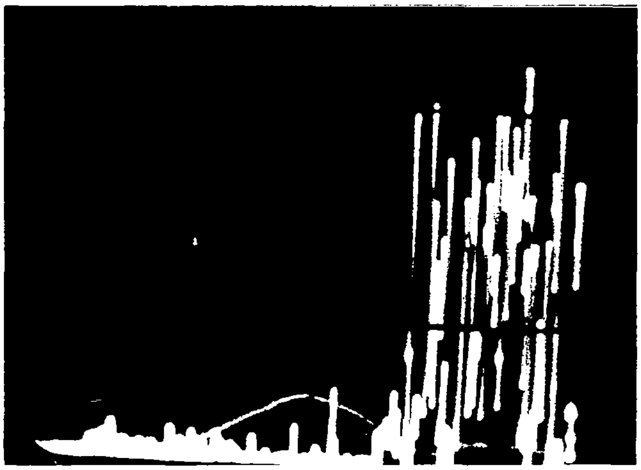


Figure 14. Beat Generated by Experiment Diagrammed in Figure 12. Total Spectrum Width 30 kHz, Sweep Time 1 Second, Bandwidth 150 kHz.

The drift range has been reduced from 50 kHz in Figure 8b to 10 kHz in Figure 14. This experiment, therefore, showed that a major source of instability had been in the microwave signal rather than in the laser signal. It also showed that the results of the experiments in which no improvement in signal stability had resulted from changes made on the laser should be reexamined after the microwave sources of instability have been reduced.

IV. AUTOMATIC FREQUENCY CONTROL OF THE HYDROGEN CYANIDE LASER

In order to achieve an improvement of the stability of a far infrared laser, it is also possible to consider automatic frequency control of these devices. With such techniques, stabilities on the order of a few parts in 10^8 can be readily attained. The phase-locking of the laser to the harmonic of the microwave source requires further work; however, with equipment similar to that described in the previous section, the laser has been locked by AFC methods to the generated millimeter signal.

The AFC of the HCN laser has been performed on the 890 GHz line by beating the laser with the 12th harmonic of an OKI 70 V10 to produce a 60 MHz IF signal. The 60 MHz signal was amplified, and a discriminator response was produced in a Micro-Now Model 201. The output signal is amplified in a DC amplifier and applied to the piezoelectric element controlling the position of one of the laser mirrors. Under AFC, a significant change in the characteristics of the 60 MHz beat is observed on the spectrum analyzer. Vibrational effects, which are evident in the unlocked free-running operation, are no longer present in the AFC mode. By tuning the microwave harmonic, it is possible to tune the laser frequency. A variation of the harmonic of the frequency standard by as much as 600 kHz shows no variation in the frequency of the IF, indicating that the laser is following the microwave signal when AFC is employed. No significant change in the linewidth is observed as it remains on the order of 10 kHz; however, the signal remains well within the 10 kHz for periods of several hours. This corresponds to a stability on the order of a part in 10^8 for this period.

Further improvement of this figure is evident from recent investigations. In order to provide an improvement in linewidth during the unlocked operation, a laser, 9 feet in length, with 4-inch glass tubing has been assembled. Invar rods are employed to maintain the separation of the laser mirrors. The laser mirrors have 3.875 inch diameters, a 24-foot radius and 0.090 inch holes for coupling out the energy. With this laser, linewidths of approximately 5 kHz have been observed on the Marconi spectrum analyzer. With this laser, it should be possible to realize stabilities on the order of 5 parts in 10^9 by AFC techniques.

Several difficulties still remain in the overall system, which have delayed the phase-locking of the laser and make the AFC technique difficult. Improvement in the piezoelectric elements is necesary. Improved sensitivity and lack of resonances is required. With the original mirrors, made of 2.875 inch diameter, 0.500 inch thick quartz, a 500 volt signal from the DC amplifier resulted in a 150 kHz swing up to 700 Hz (frequency input) but produced a resonance at 450 Hz with a 300 kHz swing. In order to move the resonance to a higher frequency, a 0.250 inch thick, 2.938 inch diameter flat aluminum plate was fabricated. This lighter plate moved the resonance to 680 Hz. Modulation was possible to 1500 Hz. It would be desirable to have the resonance at a higher frequency ($\approx$ 2 kHz or higher) so that a flat frequency response up to this frequency is available.

Investigations are now being performed to provide an accurate quantitative figure for the stability. Counting techniques and discriminator calibration are being considered as methods for providing this figure. When phase-locking is eventually achieved, the desirable technique will be the beating of two lasers locked to a microwave source.

V. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

The problem of phase locking a laser signal to a submillimeter frequency standard has been investigated analytically and experimentally. In addition, laser stability studies to augment the laser-microwave phase locking experiment were performed. Improvements in signal-to-noise ratio and laser and microwave stability have been made. Although phase locking has not been achieved, it appears to be analytically feasible, and no experimental information has indicated an impasse. It is expected, therefore, that continued work in this area would result in the phase locking of a laser signal to a submillimeter frequency standard.

The HCN laser has been locked to a harmonic of a frequency standard with a longterm stability on the order of a part in 10^8. With linewidths on the order of 5 kHz now being achieved in a new laser, it should be possible to improve this stability by approximately an order of magnitude.

This program was originally intended as the first phase of a 3-phase study to achieve stabilities on the order of a part in 10^8, to establish interferometric techniques for wavelength measurements and to employ these techniques for a measurement of the velocity of light. The goal of phase I has been achieved, and it is now possible to proceed with the following phases.

On the basis of the work performed during this contract and the prospects for locking a far infrared laser, work should be continued on the frequency control of infrared lasers. The following investigations warrant further consideration in future programs:

1 Continued improvement of the spectral purity of the microwave oscillator from which the millimeter wave signal is generated. With the linewidth of the beat signal now reduced to 5 kHz, it is possible that further reduction of this width can result from an improved spectrum of the originating source. Two new multiplying chains are scheduled for delivery to the Electromagnetics Laboratory in March, and the spectral purity of the signals from these devices will be ascertained in the beating experiments.

2 Improvement of the laser power supplies. Instability and noise can be originating from the power supplies. A current regulator, assembled

to provide further improvement in the discharge stability, has shown no change in the spectral characteristics.

3 With the improved linewidth, a reassessment of the effects of vibrations should be performed. The new system, with invar rods to minimize the effect of physical motion of the two laser mirrors, will provide a means for investigating these effects.

4 Investigations should be continued to improve the discharge configuration by improving the electrode geometry.

5 Improved mirror holders are needed and will contribute to the stability of the system.

6 An improved means of feeding the control signal to the laser is needed. Thus far, the use of the piezoelectric elements has not been successful, but work will continue on improving this technique. Present plans call for feeding an AFC signal through the power supply while the phase-locking signal is applied to the piezoelectric element on the laser mirror.

7 Methods for enhancing the signal-to-noise ratio of the heterodyne signal between the laser and the microwave source should be studied. The possibility of using a higher frequency millimeter wave source can be investigated. Both a 127 GHz Varian klystron and a 300 GHz carcinotron are available for these studies. Phase locking of the carcinotron will be necessary. Improvement of the mixer structures could result in an enhanced S/N. The initial use of open structures has proven relatively successful for heterodyning two lasers, and with the appropriate focusing mechanism, should be applicable to the mixing of the laser and microwave signal. A new open-structure mixer will accept two laser signals and a microwave signal.

8 The actual phase locking of the laser to the multiplied signal should be achieved in the near future. Work should continue on this aspect and should eventually be extended to higher frequency laser systems. The locking of the H_2O laser at 118 microns is the next most likely system to be continued.

9 The development of mixing techniques for use with the CO_2 laser at 10.6 microns is required for the application of frequency control techniques for the near infrared wavelength region, and consideration of these techniques will be made in future investigations.

10 In future work in this laboratory spectroscopic investigations will be performed with the HCN laser. Free radicals and other molecules which have energy levels tunable with magnetic fields will be studied. In addition, a continued effort toward obtaining better detectors, non-linear devices and components will be made. An absorption cell, inserted into the laser interferometer, is being constructed for magnetic resonance of paramagnetic molecules. Experimentation is being performed in preparation for the heterodyning of the SO_2 laser with a harmonic of the carcinotron.

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2. Hocker, L. O. and Javan, A., Physics Letters 26A, 255 (1968).

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4. J. J. Gallagher, R. E. Cupp and R. A. Kempf, "Millimeter and Submillimeter Device Research," Final Report, Contract DA-28-043-AMC-02484(E), January, 1968, OR 9111; J.J. Gallagher, V. J. Corcoran and R. E. Cupp, "Extension of Frequency Control to the Infrared Region," Contract DAAB07-68-C-o206, Semiannual Report, August, 1968, OR 9625.

APPENDIX A

I. PHASE LOCKING LASERS

Introduction. - The technique of phase locking has been used to improve the stability and bandwidth of oscillators up to the millimeter wavelength region. A discussion of phase lock techniques applied to lasers, especially the HCN laser is given below. For phase locking to be successful a number of questions must be answered satisfactorily by the analysis and experiment. The first question is whether acquisition can be successful. This requires the consideration of the nonlinear differential equation governing the operation of the loop. When acquisition is successful, the characteristics of the locked laser can be determined from the linearized equation.

Two techniques, phase locking through the power supply and phase locking with a piezoelectric translator as part of the cavity control, are considered. With each technique the inputs affecting phase locking are the noise output from the IF amplifier and the random drift of the laser; the reference is assumed to be essentially a sine wave. The random drift shows up directly as a noise source in the laser signal phase. The amplified mixer noise, which is assumed to be additive, affects the result when it is multiplied by the reference.

II. PHASE LOCKING THROUGH POWER SUPPLY

For a laser that has the control current (voltage) applied to the power supply, the phase lock loop is shown in Figure A-1. The laser is

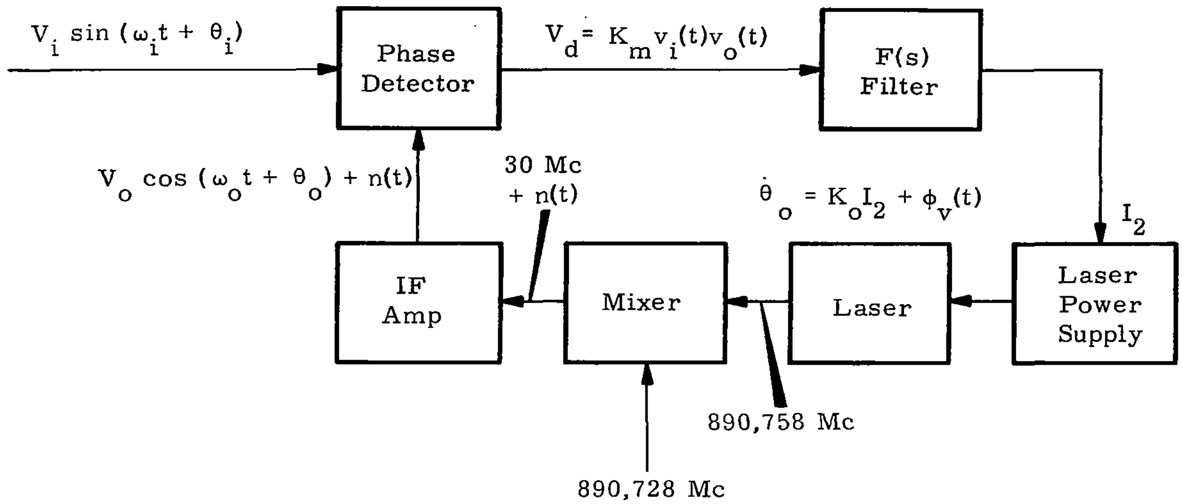


Figure A-1. Block Diagram of Laser Phase Lock Loop When Locking Through Power Supply

considered to be an HCN laser operating at 890,758 GHz, and the IF is assumed to be 30 hz. If the power supply is assumed to have a resistive internal impedance and the laser is assumed to be resistive, then it can be assumed that $\dot{\theta}_o = K_o I_2$ is valid, that is, the frequency is proportional to the current.

From Figure A-1,

$$\begin{aligned}\dot{\theta}_o &= K_o I_2 + \phi_V(t) \\ &= K_o F(s) V_d + \phi_V(t) \\ &= K_o F(s)[K_m v_i(t)] + \phi_V(t)\end{aligned}$$

where $\phi_V(t)$ is the representation of the random drift of the laser. A mixed notation is used in the above equations which is corrected at the end when the differential equation is written.

The noise out of the IF amplifier is given by

$$n(t) = n_c(t) \cos \omega_o t + n_s(t) \sin \omega_o t$$

where $n_c(t)$ and $n_s(t)$ are Gaussian and have power spectra that are modified by the IF amplifier response.

Substitution of the noise expression into

$$V_d = K_m v_i(t) v_o(t)$$
$$= K_m V_s \sin(\omega_i t + \theta_i)[V_o \cos(\omega_o t + \theta_o) + n(t)]$$

gives

$$v_d = K_d \sin[(\omega_i - \omega_o)t + (\theta_i - \theta_o)]$$
$$+ \frac{K_d}{V_o} n_c(t) \sin[(\omega_i - \omega_o)t + \theta_i]$$
$$- \frac{K_d}{V_o} n_s(t) \cos[(\omega_i - \omega_o)t + \theta_i]$$

where $K_d = K_m \frac{V_s V_o}{2}$. The last expression for v_d is the result of the expansion of the product of sines and cosines and retaining the difference terms only.

The phase error is given by

$$\dot{\theta}_e = (\Theta_i - \Theta_o) = \omega_i t + \theta_i - \omega_o t - \int \dot{\theta}_o \, dt$$

so that

$$\dot{\theta}_e = (\omega_i - \omega_o) - \dot{\theta}_o$$

When $\omega_i = \omega_o$, which is a reasonable assumption since $\phi_V(t)$ can account for any difference in frequency,

$$\dot{\theta}_e = -\dot{\theta}_o$$

If the expression for v_d is substituted into the expression for $\dot{\theta}$ and the arbitrary phase θ_i is set equal to zero, then

$$\dot{\theta}_o + K_o F(s) K_d \sin \theta_e = K_o F(s) \frac{K_d}{V_o} n_s(t) - \phi_V(t)$$

This is the general equation for phase locking a laser through a resistive load.

Two special cases are of interest:

1) When F(s) = 1,

$$\dot{\theta}_e + K_o K_d \sin \theta_e = K_o \frac{K_d}{V_o} n_s(t) - \phi_V(t)$$

which is a first order differential equation that is quite amenable to solution when θ_e is small.

2) When $F(s) = \frac{1 + \tau_2 s}{1 + \tau_1 s}$, (see Figure A-2 for the case of infinite load impedance)

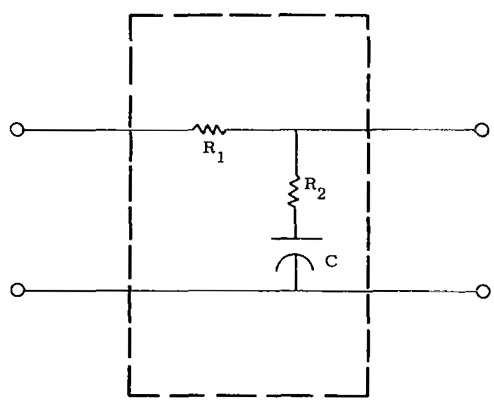
$$s\theta_e + K_o \frac{1 + \tau_2 s}{1 + \tau_1 s} K_d \sin\theta_e$$

$$= K_o \frac{1 + \tau_2 s}{1 + \tau_1 s} \frac{K_d}{V_o} n_s(t) - \phi_V(t)$$

or in the time domain

$$\tau_1 \ddot{\theta}_e + (1 + K_o K_d \tau_2 \cos \theta_e) \dot{\theta}_e + K_o K_d \sin \theta_e$$

$$= \frac{K_o K_d}{V_o} [\tau_2 \dot{n}_s(t) + n_s(t)] - [\tau_1 \dot{\phi}_V(t) + \phi_V(t)]$$



$\tau_2 = R_2 C$
$\tau_1 = (R_1 + R_2) C$

Figure A-2. Lag-Lead Network in Laser Phase Lock Loop which is the same equation as would be obtained for locking a microwave source using a lag-lead network. This equation has been thoroughly analyzed under a number of special conditions, but not for acquisition with random inputs.

III. PHASE LOCKING THROUGH CAVITY

When the laser is to be phase locked by controlling the cavity length with a linear piezoelectric translator, then the block diagram of the system is as shown in Figure A-3. The equation for this loop when $\omega_i = \omega_i$ and $\theta_i = 0$ is

$$\dot{\theta}_e = \dot{\theta}_o$$

$$\dot{\theta}_e = -K_o K_d \frac{F(s)}{s} \sin \theta_e + K_o K_d \frac{F(s)}{s} \frac{n_s(t)}{V_o} - \phi_V(t)$$

where the 1/s is due to the fact that the piezoelectric translator can be represented electronically as a capacitor.

For the case F(s) = 1, the equation becomes

$$\dot{\theta}_e + \frac{K_o K_d}{s} \sin \theta_e = \frac{K_o K_d}{s} \frac{n_s(t)}{V_o} - \phi_V(t)$$

or

$$\ddot{\theta}_e + K_o K_d \sin \theta_e = K_o K_d \frac{n_s(t)}{V_o} - \dot{\phi}_V(t)$$

An undesirable characteristic of this equation can be seen by letting $\sin \theta_e \to \theta_e$. The homogeneous solution of the equation is oscillatory so the system would be unstable. A filter must be used to stabilize this system. When the filter is a series resistor, then damping is introduced into the system.

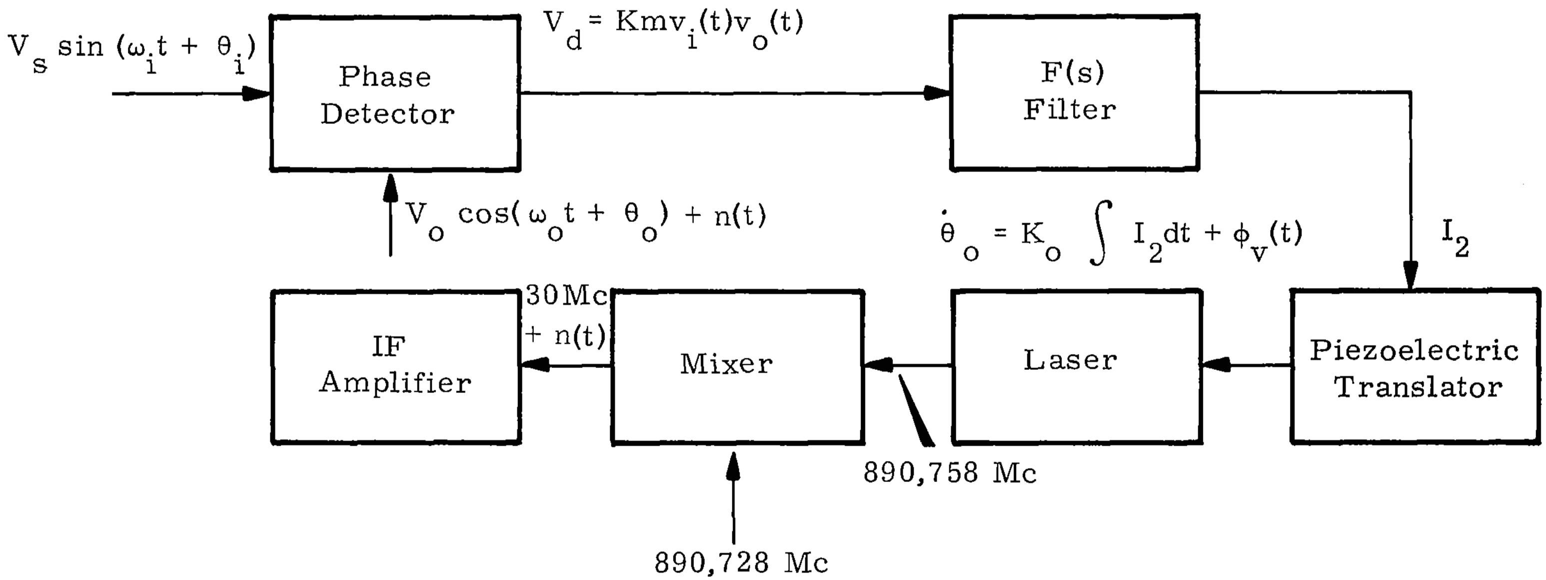


Figure A-3. Block Diagram of Laser Phase Lock Loop When Locking With Piezoelectric Translator

If the circuit of the filter is as shown in Figure A-4, then

$$F(s) = C_T \frac{1 + \tau_2 s}{1 + \tau_1 s}$$

The differential equation is then

$$\dot{\theta}_e + K_o K_d C_T \frac{1 + s\tau_2}{1 + s\tau_1} \sin \theta_e$$
$$= K_o K_d C_T \frac{1 + s\tau_2}{1 + s\tau_1} \frac{n_s(t)}{V_o} - \phi_V(t)$$

This equation is identical to the second order equation for phase locking through the power supply or to phase locking a microwave source. The advantage of having a standard equation is that results of previous analyses of the equation can be used as guides. The next section is concerned with arriving at design equations for the phase locking of the laser.

IV. DESIGN EQUATIONS

The analysis of second order loops for phase locking has been considered by a number of authors and the work has been summarized by Gardner (Reference A-1). For acquisition, the signal to be phase locked is usually assumed to be offset in frequency at the start of acquisition. Qualitatively this seems to be an easier signal to lock than a randomly drifting signal because the phase is not accelerating initially; however, since the frequency at some time is moving toward the reference it may, in some cases, be easier to lock the laser. The only way to check the assumption that the available equations are valid would be to run a computer program on the laser phase lock equations. This is currently being completed.

Pull-in occurs when the VCO slowly changes direction and, if not interrupted, will eventually lock up. If $\Delta\omega_P = \left| \omega_i - \omega_o \right|$ then

$$\Delta\omega_P = 2\sqrt{\zeta \ \omega_n K_\sigma}$$

where ω_n is the natural frequency of the second order loop

ζ is the damping factor and K_v is the dc loop gain or $K_o K_d F(0)$

Lock-in occurs when there is no skipping of cycles so that the signal pulls in immediately. The equation for lock-in is

$$\Delta\omega_L = 2 \ \zeta \ \omega_n$$

The time required to go from some angular frequency offset somewhat less than $\Delta\omega_P$ to $\Delta\omega_L$, at which time the loop quickly locks, is given by

$$T_P \approx \frac{(\Delta\omega)^2}{2\zeta \ \omega_n{}^3}$$

Also, by considering the half power points of the closed loop gain, the bandwidth is found to be

$$B_L \approx \omega_n$$

To proceed further it is necessary to evaluate the above expressions in terms of the physical parameters of the system. The second order equation is obtained by considering the demoninator of θ_e in the s plane when $\sin\theta_e = \theta_e$ and $\frac{n_s}{V_o}$ and $\phi_V = 1$.

For the locking through the power supply

$$\frac{G}{1+G} = \frac{S \ K_o K_d F(S)}{S + K_o K_d F(S)}$$

so

$$\tau_1(1+G) = S^2 \quad \frac{1 + K_o K_d \tau_2}{\tau_1} \quad S + \frac{K_o K_d}{\tau_1}$$

$$= S^2 + 2 \ \zeta \ \omega_n + \omega_n{}^2$$

It is evident, therefore, that

$$\omega_n = \left(\frac{K_o K_d}{\tau_1}\right)^{1/2}$$

$$\zeta = 1/2 \left(\frac{K_o K_d}{\tau_1}\right)^{1/2} \left(\tau_2 + \frac{1}{K_o K_d}\right)$$

When locking is to be achieved through the piezoelectric translator, then $K_o K_d$ is replaced by $K_o K_d C_T$.

The equations for pull-in and lock-in terms of the system parameters are given by

$$\Delta\omega_P = \left[2K \left(\frac{1+K\tau_2}{\tau_1}\right)\right]^{1/2}$$

$$\Delta\omega_L = \frac{1+K\tau_2}{\tau_1}$$

$$T_P = \frac{(\Delta\omega)^2}{\frac{K}{\tau_1}\left(\frac{1+K\tau_2}{\tau_1}\right)} \qquad \Delta\omega_P > \Delta\omega > \Delta\omega_L$$

$$B_L = \left(\frac{K}{\tau_1}\right)^{1/2}$$

where $K = K_o K_d$ for phase locking through the power supply and $K=K_o K_d C_T$ for phase locking through the piezoelectric translator.

The evaluation can be carried a step further by considering the physcal parameters in terms of the components of the system. In each case K_d, the maximum voltage out of the phase detector in volts^{-1}. K_o is the sensitivity of the transducer in Hz/volt. For the regulation through the power supply the sensitivity can be measured. The time constants for power supply control are given in Figure A-2.

For control through the piezoelectric translator the value of $K_o C_T$ can be found from the translator. The piezoelectric translator moves the laser mirror so that the frequency of the laser is changed by

$$\dot{\theta} = \omega = \omega_o \frac{\Delta L}{L}$$

and the change in the length of the cavity is related to the voltage across the translator by

$$\Delta L = S_T v_2$$

Since the translator is electrically a capacitor, the voltage is related to the current by

$$v_2 = \frac{1}{C_T} \int i_2 \, dt$$

The value of K_o, therefore, is given by

$$K_o = \frac{\dot{\theta}_o}{\int i_2 \, dt} = \frac{\omega_o}{L} \frac{S_T}{C_T}$$

and $K_o C_T$ is given by

$$K_o C_T = \frac{\omega_o}{L} S_T$$

The time constants are given in Figure A-4.

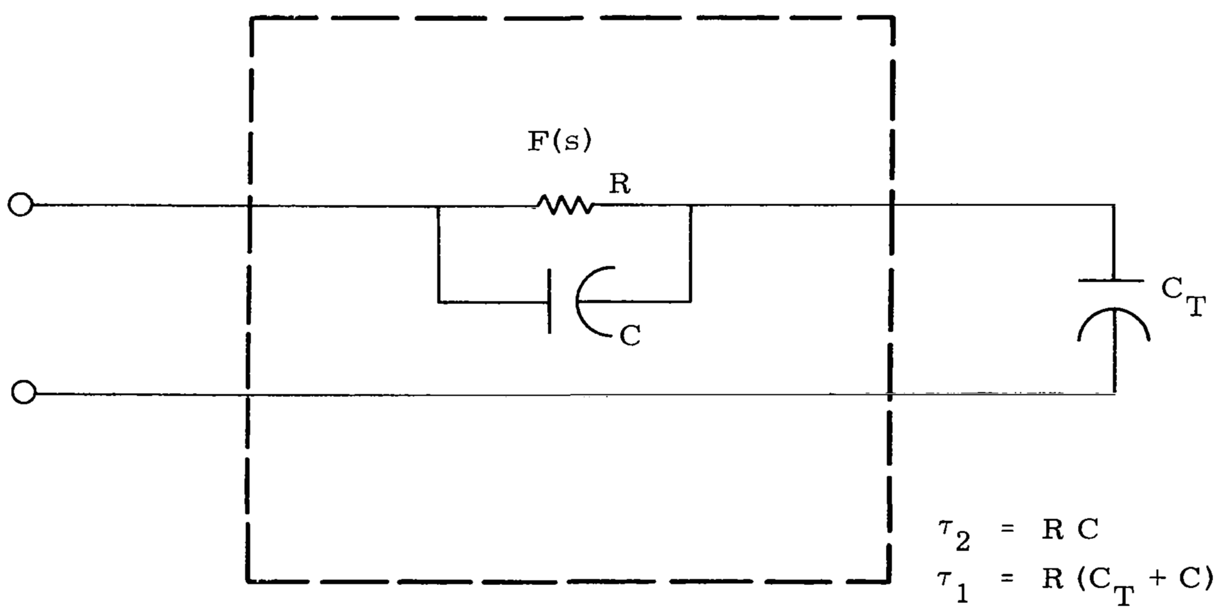


Figure A-4. Filter Network for Second Order Loop When Load is a Piezoelectric Translator (Represented by C_T)

V. COMPUTER ANALYSIS

A computer program for the phase lock loop using current control of the power supply and without filtering was run. These conditions result in a first order nonlinear differential equation with the only system control being the loop gain. The inputs are the mixer noise and the laser drift. The results of a few runs are shown in Figures A-5 to A-10. Since the mixer noise and drift noise are affected in the same way for a first order system, only the drift noise is used. Also, the S/N in the actual system has been well above the 6 dB level required for lock.

In the figures the effects of varying the rms value of the noise fluctuations, σ, and the loop gain, K_oK_d, are evident. As σ decreases for a given K_oK_d the fluctuations in the phase decrease and lock occurs for longer periods. For a given σ the time to lock is inversely proportional to the loop gain and the fluctuations in phase after lock decrease as the loop gain increases.

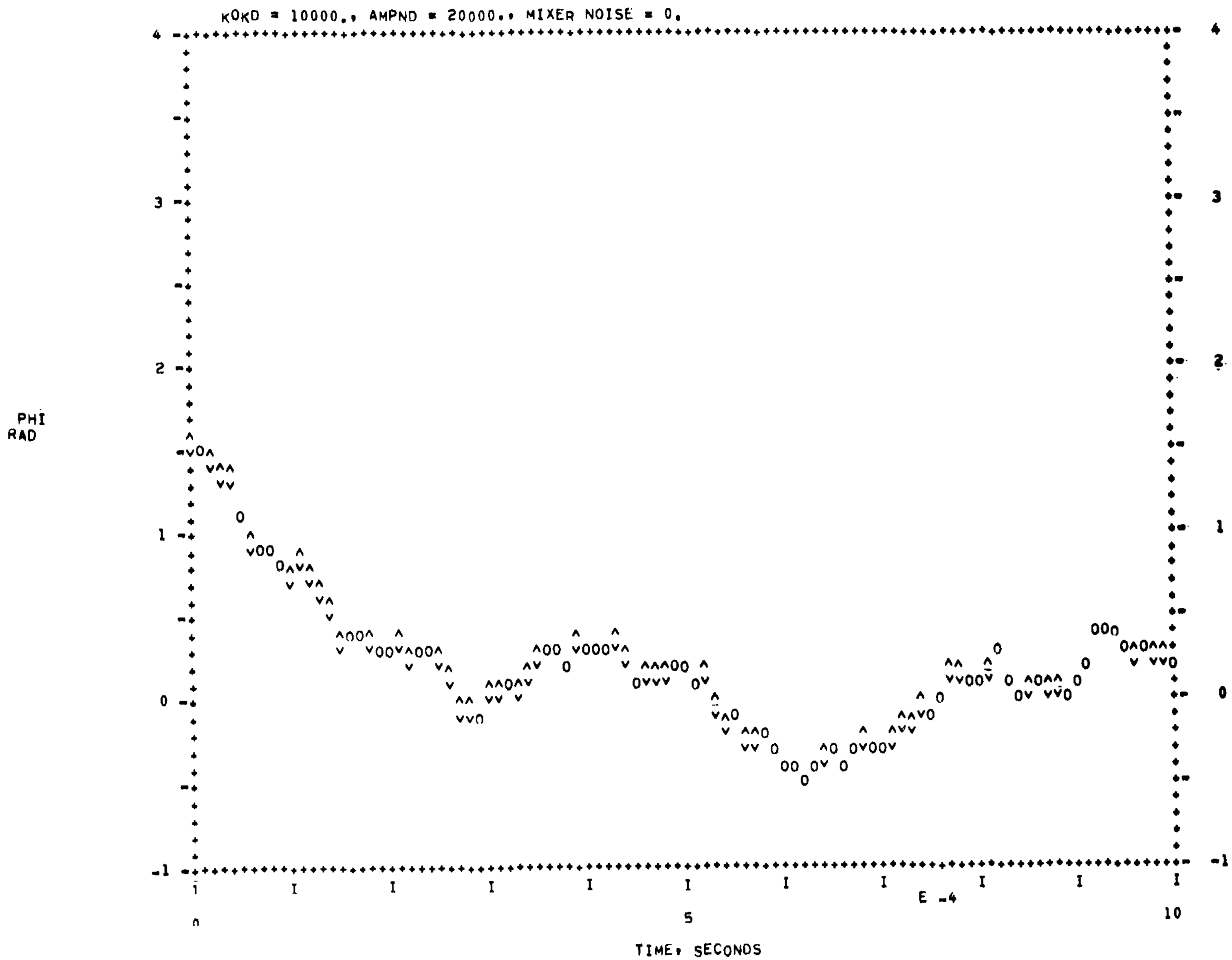


Figure A-5. Loop Gain = 10^4; RMS Noise = 10^4

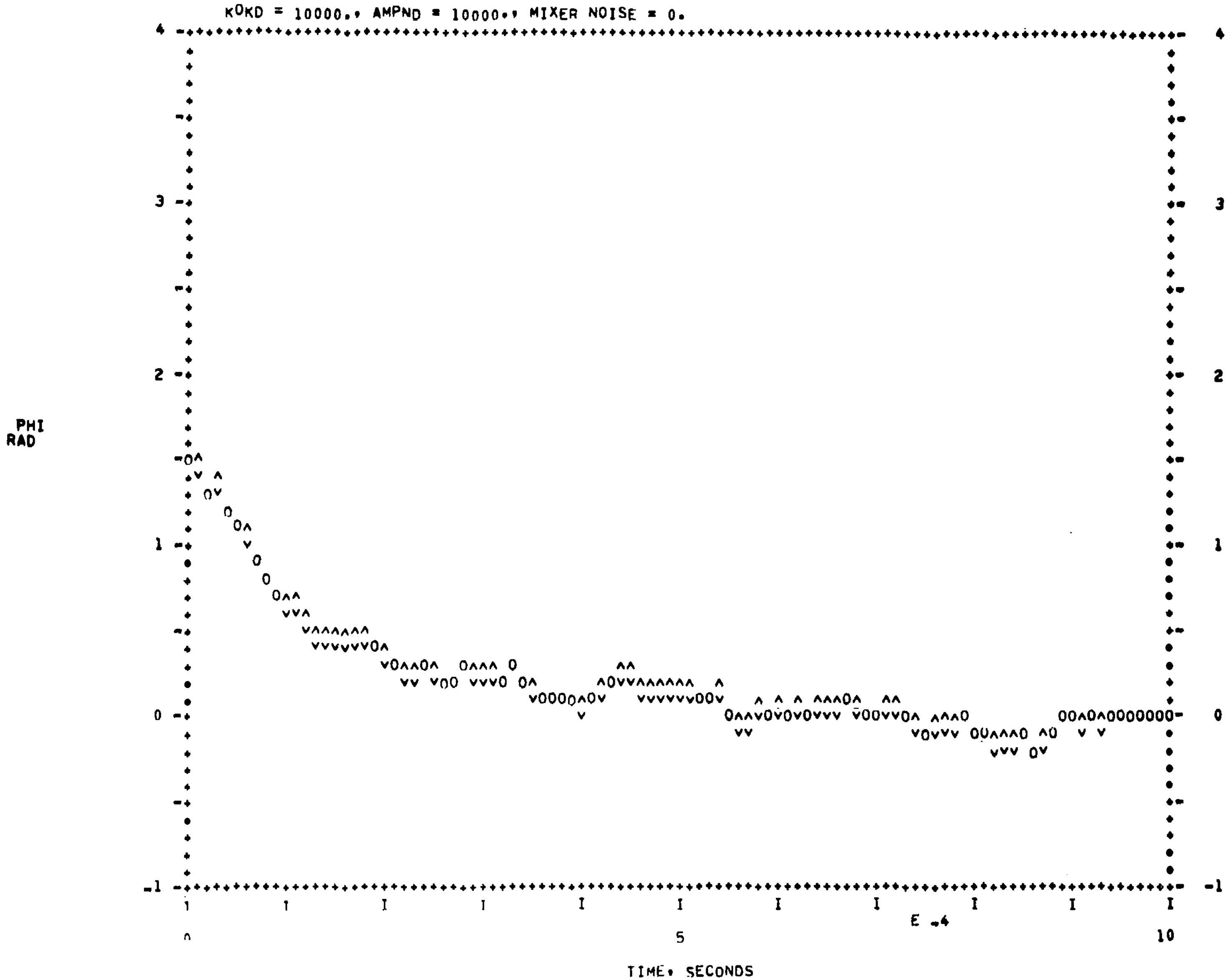


Figure A-6. Loop Gain = 10^4; RMS Noise = 10^4

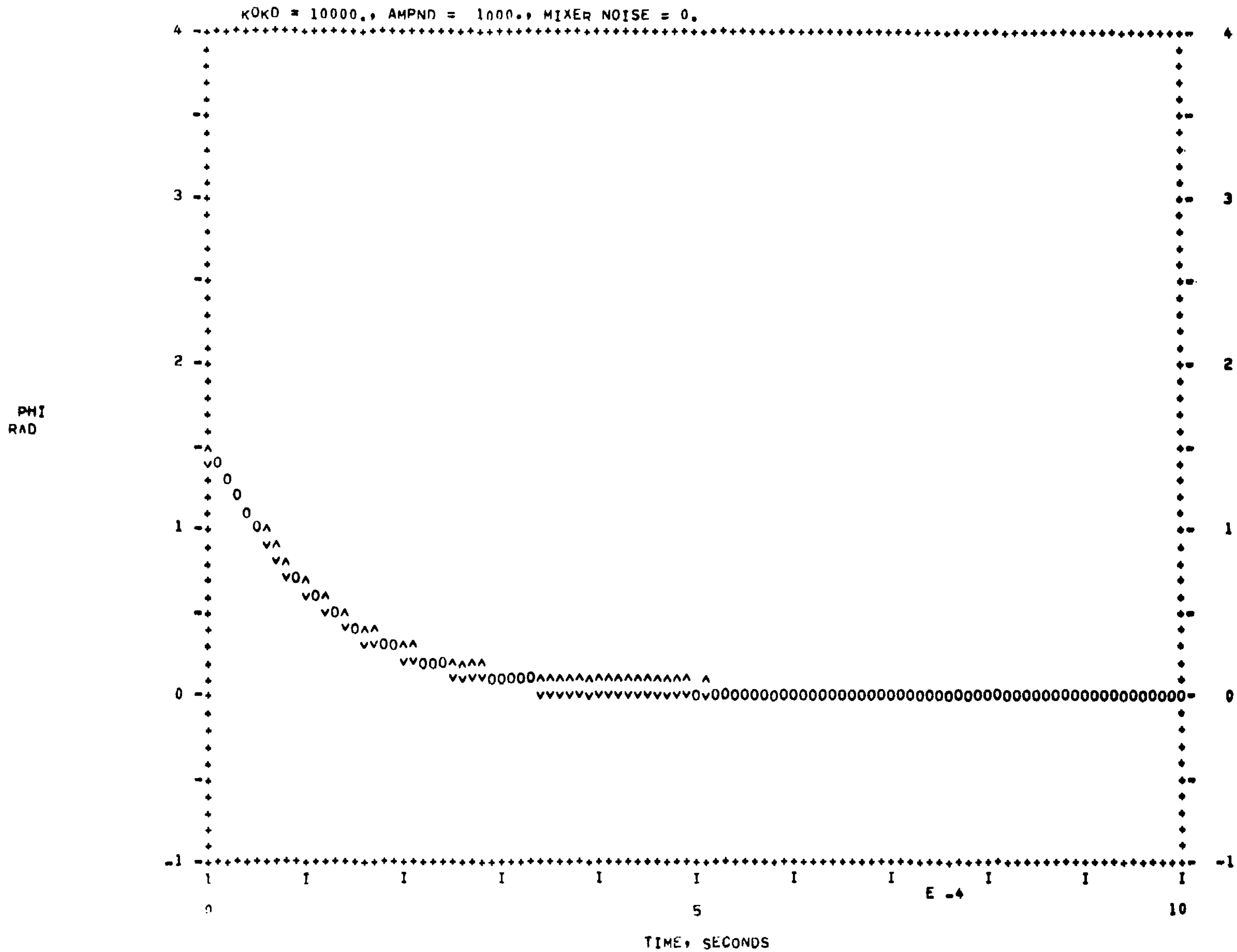


Figure A-7. Loop Gain = 10^4; RMS Noise = 10^3

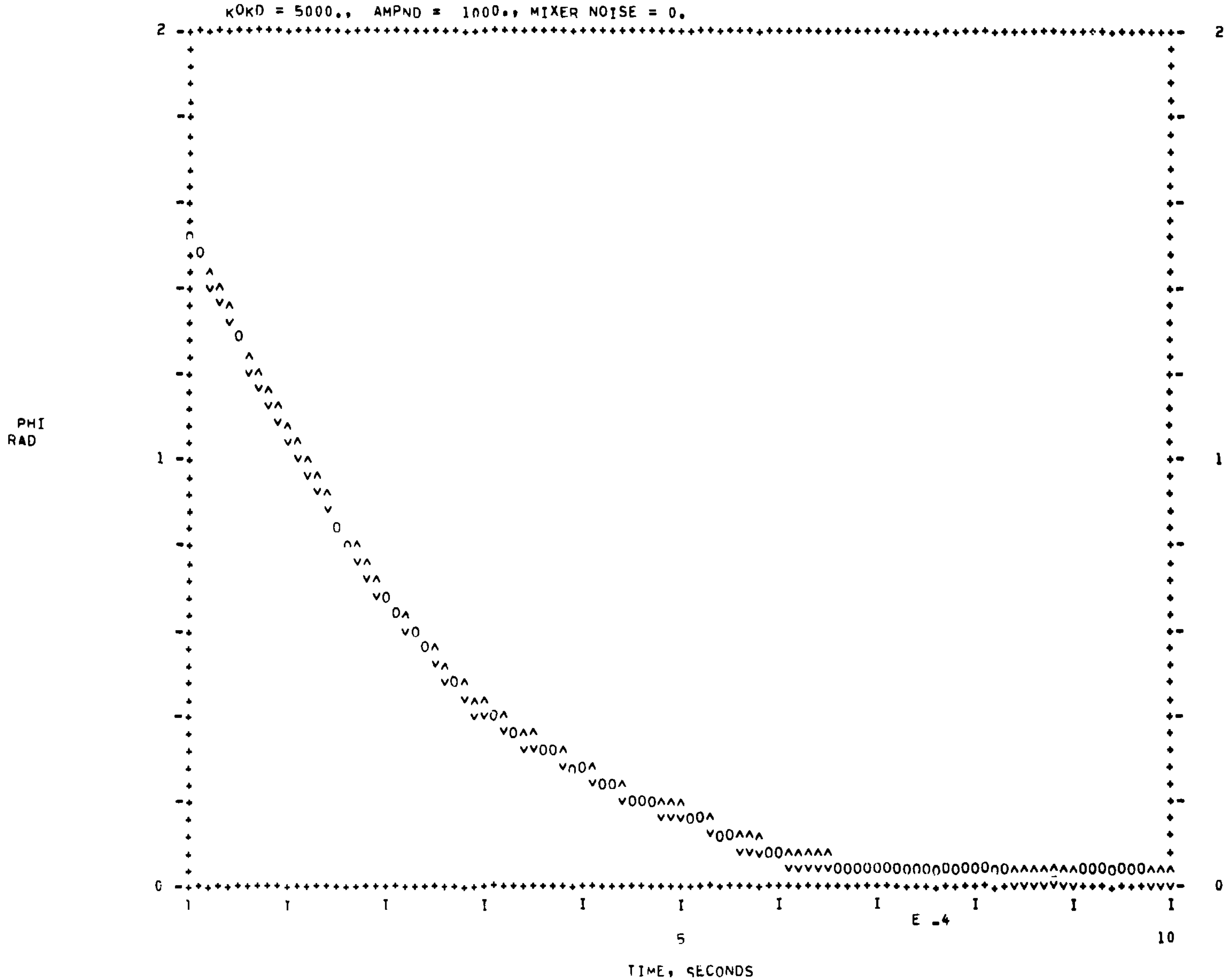


Figure A-8. Loop Gain = 5 X 10^3; RMS Noise = 10^3

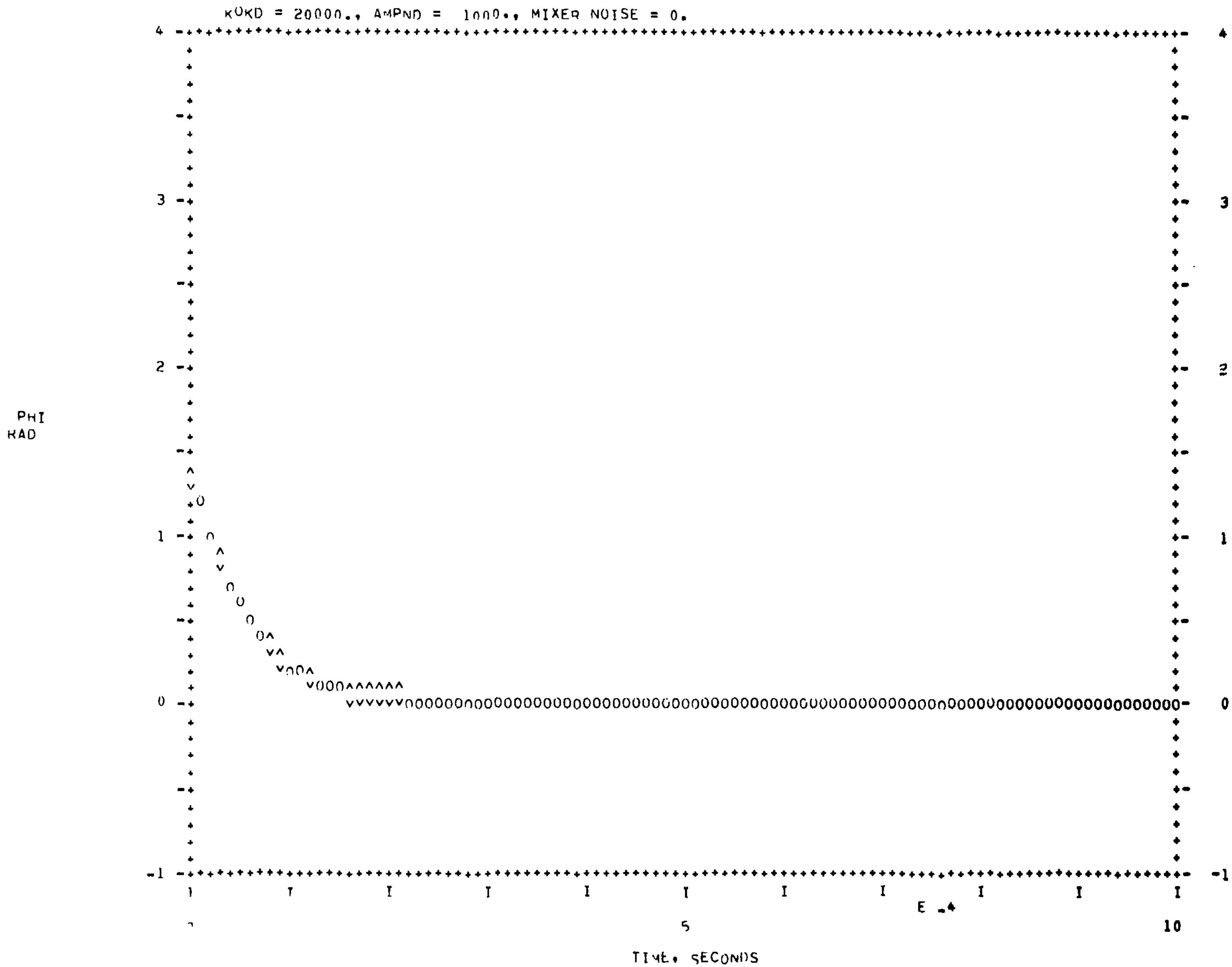


Figure A-9. Loop Gain = 2 X 10^4; RMS Noise = 10^3

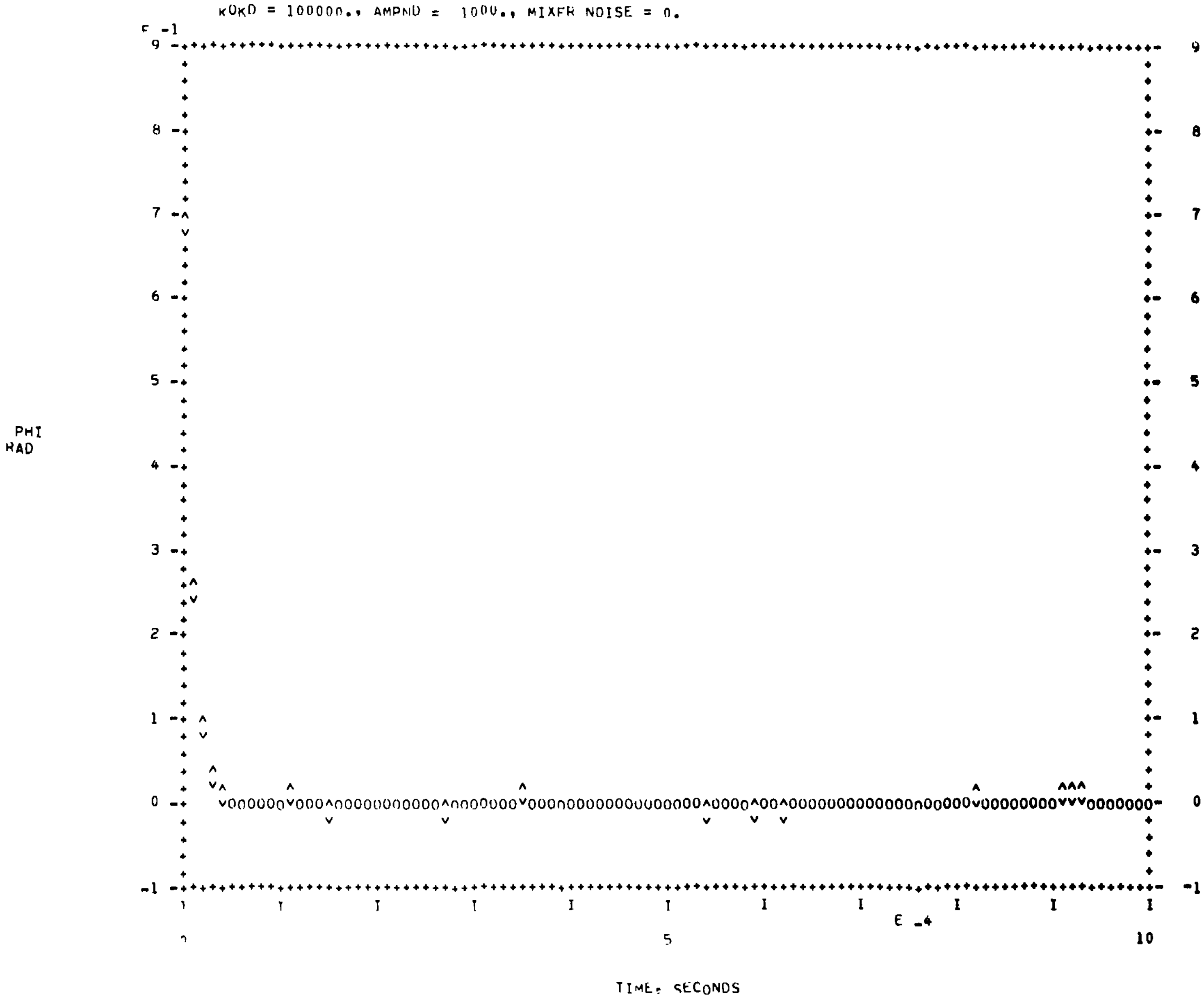


Figure A-10. Loop Gain = 10^5; RMS Noise = 10^3

REFERENCE

APPENDIX A

F. M. Gardner, Phaselock Techniques, John Wiley & Sons, Inc., New York, 1966

APPENDIX B

CW GAIN CHARACTERISTICS OF THE 890 GHz HCN LASER LINE

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ABSTRACT

Abstract -- Continuous wave unsaturated gain characteristics of the 890 GHz HCN laser line have been measured versus current for various flowing mixtures of CH_3CN and H_2O.

The HCN laser, which has been operated pulsed[1] and continuously[2], is of interest because it is one of the few submillimeter lasers that has been operated continuously[2,3]. Studies have explained the transitions involved[4,5], and the frequency of the laser lines have been measured[6]. The gain of the laser transitions is an important parameter for improving the performance of these long wavelength lasers[7] which are potentially useful for spectroscopy and the accurate measurement of the velocity of light. The gain of a water vapor laser in the pulse mode has previously been measured[8]. Gain measurements of the 890 GHz HCN line during continuous excitation as a function of current and pressure are reported here for various mixtures.

A schematic of the apparatus used to measure the gain in a continuous mode is shown in Figure B-1. Radiation at 890 GHz emitted from the HCN laser is collimated with a front surface reflector. The collimated beam fills the entrance window of the amplifier cell. After passing through the cell, the radiation is chopped, collected with a conical light pipe, and detected with a Golay cell. The output of the Golay cell goes to a lock-in amplifier which is synchronized to the chopper, then to a recorder.

The amplifier cell is constructed of 3 inch Kimax tempered glass pipe. The cell is 145 cm with an active region of 116 cm. Windows of quartz or mylar are used at the entrance to and exit from the cell. A modified mercury arc power supply is used to excite the gas discharge. The stainless steel electrodes to which the power supply is connected are water cooled. The gasses are pumped from the manifold through the cell by a Welsh 1397 forepump.

The aperture of the conical light pipe is 19 mm, so the light pipe collects only the central portion of the radiation exiting from the amplifier cell which has a 78 mm ID and a 55 mm window.

Measurements were made on flowing mixtures of CH_3CN and H_2O. First, the radiation was measured with an evacuated cell, and then with an unexcited gas. No absorption by the unexcited gas was observed. When the gas mixture in the cell was excited, a discernable change in the detection radiation was observed. The amplitude of the input radiation was varied to insure that saturation did not occur during the measurements.

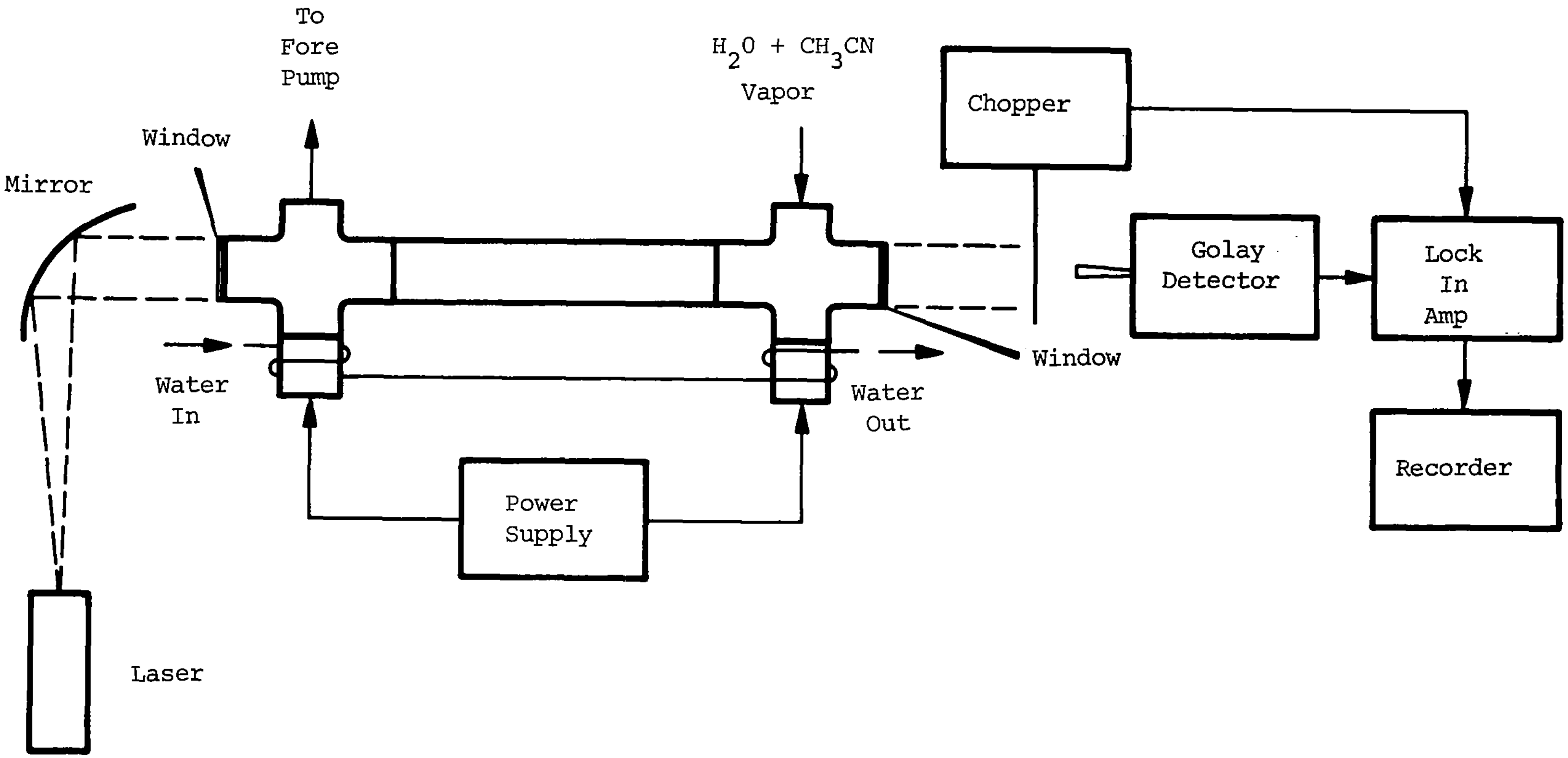

Figure B-1. Schematic of Experiment to Measure Unsaturated CW Gain of 890 GHz HCN Laser Line

Curves of gain per meter versus current for various mixtures of CH_3CN and H_2O are shown in Figure B-2. The data indicate that the gain is dependent upon the partial pressures of the gasses and the current. These data should be useful both for designing HCN lasers with CH_3CN and H_2O mixtures and as a basis of comparison for other chemical mixtures that produce HCN laser action.

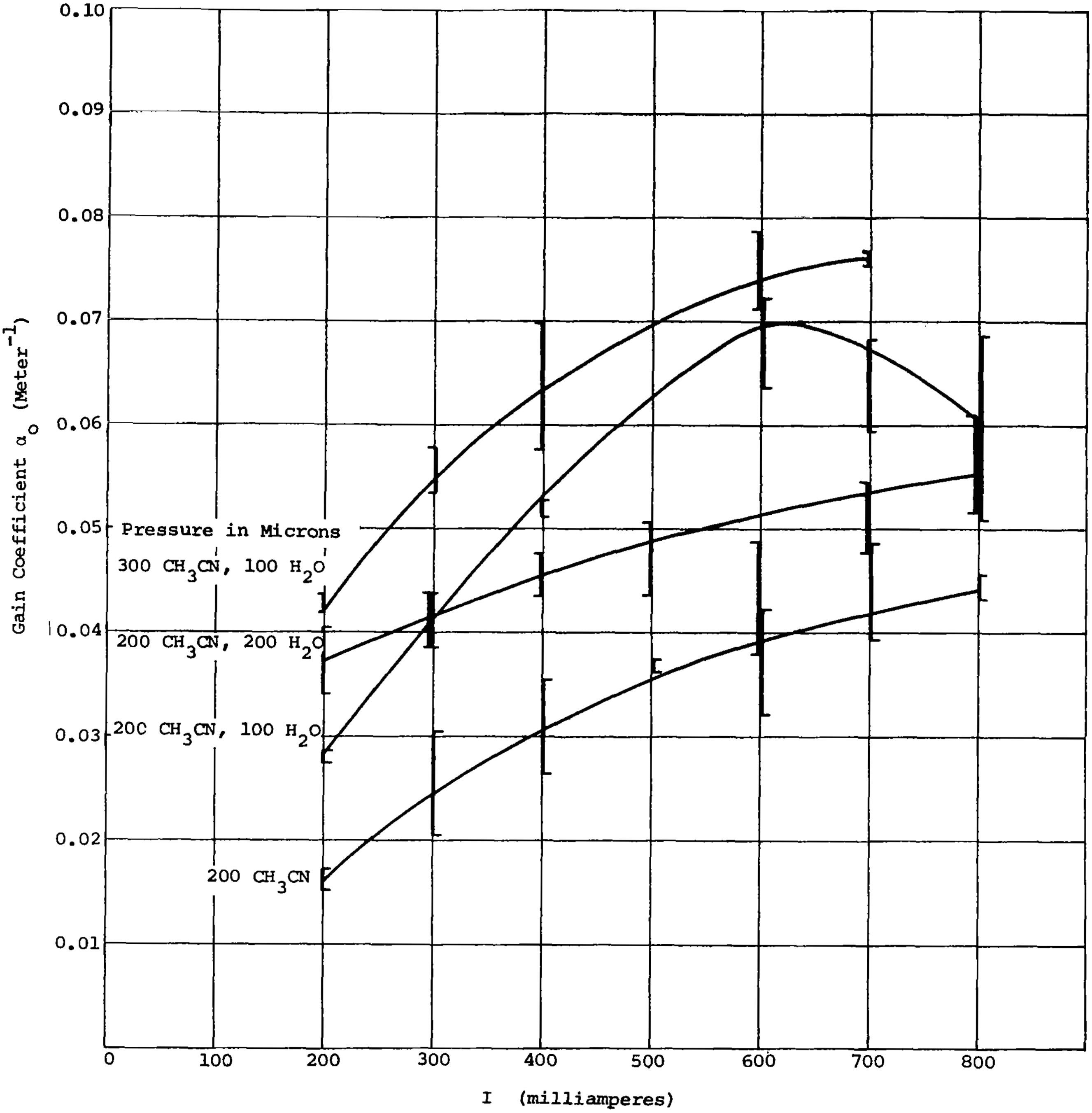

Figure B-2. Curves of Gain per Meter versus Discharge Current for Various Mixtures of CH_3CN and H_2O

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APPENDIX B

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APPENDIX C

NEW TECHNOLOGY

After a diligent review of the work performed under this contract, no new innovation, discovery, or invention was made.

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