FINAL REPORT
for
"STABILIZED GAS LASER OSCILLATORS"

(24 June 1964 - 21 June 1966)

Contract No. NAS 5-3927

Prepared by

Electronics Research Laboratory
Syracuse University Research Corporation
Post Office Box 26, University Station
Syracuse, New York

for

Goddard Space Flight Center
Greenbelt, Maryland

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ABSTRACT

This is the final report on Contract No. NAS 5-3927, "Stabilized Gas Laser Oscillators". This contract involved the design, development, fabrication, evaluation, and delivery of two phase-locked, frequency-stabilized gas lasers.

The contract was awarded by the National Aeronautics and Space Administration, Goddard Space Flight Center, to the Electronics Research Laboratory, Syracuse University Research Corporation, Syracuse, New York.

The phase-locking scheme employed utilized the comparison of the frequency of a signal derived from a crystal oscillator to the frequency of the self-beat signal of the laser in order to generate an error signal which would minimize the difference frequency. The first system was delivered on 2 April 1965, the second system on 21 June 1966.

It is concluded that these two laboratory prototypes have proven the feasibility and practicality of the phase-locking scheme employed.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

INTRODUCTION AND HISTORY

This is the final report on Contract No. NAS 5-3927, "Stabilized Gas Laser Oscillators", which was awarded on 24 June 1964 to the Electronics Research Laboratory (ERL), Syracuse University Research Corporation (SURC), by the National Aeronautics and Space Administration (NASA), Goddard Space Flight Center (GSFC). This contract involved the design, development, fabrication, evaluation and delivery of two phase-locked, frequency-stabilized gas lasers.

Preliminary work included the examination of several commercial gas lasers as a familiarization and noise-evaluation study. Detector evaluation and studies of possible locking techniques followed. Within two months construction was begun on the first system, but design and development problems caused a three-month slippage in delivery schedules. The first system was delivered to NASA/GSFC on 2 April 1965.

The second system was beleaguered by vendor supply problems from the beginning. Two modifications were written into the contract to provide funds for additional experimentation, and after several months of design alterations and experimentation, a major detrimental factor was traced to a vendor error wherein we were supplied with a component, one of the laser end mirrors, other than the one ordered. Within five weeks of correction of this error, the second system was working satisfactorily. It was delivered to the sponsor on 21 June 1966. The last five months of effort were funded by SURC, however, since contractural funding had expired.

The two systems are similar in design, with the second system being more refined than the first, as was planned. The design concept incorporated into these two systems involves the extraction of the beat-signal between two longitudinal laser modes and the comparison of this signal with a crystal controlled reference oscillator to generate an error signal. This error signal is then applied to one piezoelectric-mounted laser mirror.

Since the frequency separation between two adjacent uniphase modes is given by

$$\Delta\nu = \frac{c}{2L}$$

(plus other minor frequency-pulling terms), it is apparent that if $\Delta\nu$ is held constant, so too will L be held constant. In this equation, c is the speed of light in the lasing medium and L is the geometrical cavity length, i.e., the mirror separation.

When locked, the short-term intra-cavity frequency drift was measured (at one-second intervals) to be only one or two cycles, which is really just a reflection of the stability of the phase reference crystal oscillator.

PHASE-LOCKING SCHEME

The phase-locking scheme employed in the performance of this contract resulted from the following considerations:

Consider the optical resonant cavity formed by the two mirrors of a conventional gas laser. In order that this cavity shall be resonant at a wavelength λ, the mirror separation and alignment must satisfy the conditions that (1) a coherent wavefront passing a fixed point in a given direction must travel some closed path until it passes through the same point in the same direction, and (2) the net phase shift, β, which this wave has accumulated must be an integral number of 2π radians:

$$\beta = N2\pi \tag{1}$$

In a laser with mirror separation L, the total closed path distance traveled would be 2L. The number of wavefronts contained in this closed path would be

$$n = 2L/\lambda$$

and the corresponding net phase shift over the closed path is

$$\beta = n2\pi = 4\pi L/\lambda \tag{2}$$

From Equations (1) and (2), it follows that for optical resonance the mirror separation L must be an integral number of half-wavelengths:

$$L = N\frac{\lambda}{2}$$

and that $n = N$

Since L is usually on the order of centimeters, or even meters, while λ is measured in microns (10^{-6} meters), it is obvious that the number of wavefronts, N, is very large.

In view of this last statement, consider a second mode of operation in which another wavelength, λ', meets the resonance conditions such that

$$N' = N + 1$$

Then there will be one more wavefront in the closed path associated with λ' than there is with λ:

$$2L/\lambda' = 2L/\lambda + 1$$

Converting to frequency by the use of the relation $c = \nu\lambda$ gives

$$2L\frac{\nu' - \nu}{c} = 1$$

or $$\Delta\nu = \frac{c}{2L} \tag{3}$$

Equation (3) is an expression for the frequency separation between two adjacent modes of laser oscillation. There exist minor correction terms to this expression which, however, do not invalidate the above development[1]. This expression reveals that a laser with mirror separation of L = 60 cm has the potential to oscillate in several longitudinal modes which are separated from one another by a frequency of about 250 MHz. Since the Doppler-broadened line width of the neon atom transition is much larger than this, the output of the He-Ne laser can consist of several of these discrete modes simultaneously.

When the laser is operated such that more than one longitudinal mode is excited and the beam is directed onto the sensitive surface of a suitable square-law detector, a 250 MHz signal will be present at the detector output since this detector acts also as a mixer and can extract the difference beat-frequency between the modes.

Referring to the block diagram shown in Figure 1, a crystal-oscillator derived 220 MHz signal is input to a converter along with the 250 MHz signal from the laser detector. The output signal from the converter is the 30 MHz difference frequency due to the two inputs. This signal is then fed into a phase detector along with another 30 MHz signal derived from the same crystal oscillator.

If the 30 MHz signal due to the laser-detector tends to vary, the phase detector output will consist of an error signal proportional to the amount of variance. When the system is "locked", this error signal is a dc voltage (CAUTION: HIGH VOLTAGE, approximately 150 volts dc) and its amplitude is proportional to the phase difference of the two input signals. Thus, if the laser varies, the output of the phase detector will increase or decrease depending on the direction of the frequency drift in the laser.

This error signal is input to a stack of piezoelectric ceramic discs upon which is mounted one of the laser mirrors. If the laser cavity length should tend to change, due to thermal drift, mechanical shock, etc., the 250 MHz laser beat signal tends to change also (Equation (3)), causing the converter output signal to vary from 30 MHz. The phase detector then generates an error signal causing the piezoelectric discs to change their dimensions such that the cavity length is maintained constant.

Referring back to Equation (3), and using the relation $c = \nu\lambda$, we get

$$\Delta\nu = \frac{\nu\lambda}{2L}$$

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1. Bennett, W. R., Jr., "Gaseous Optical Masers", Applied Optics, Supplement 1: Optical Masers, 1962.

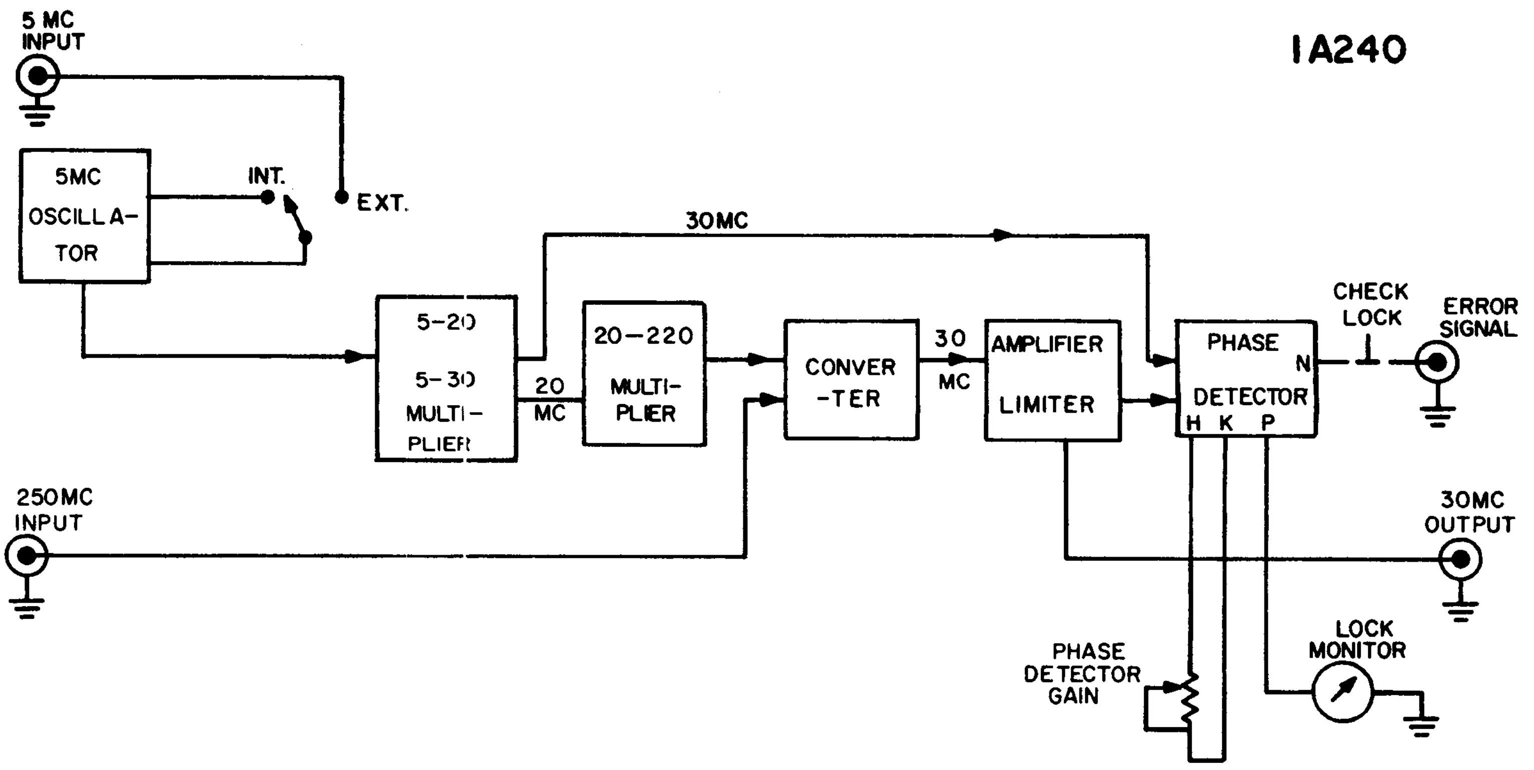


Figure I. BLOCK DIAGRAM OF STABILIZING SCHEME

But $\lambda/2L$ is just the reciprocal of the number of wavefronts contained in the closed path, which remains constant. Hence, the intra-cavity beat frequency is related to the optical frequency, ν, of the laser output beam through the constant N:

$$\Delta\nu = \frac{\nu}{N} \tag{4}$$

where, for the He-Ne laser, $\nu = 5 \times 10^{14}$ Hertz, approximately.

A TYPICAL APPLICATION

In an optical communications link utilizing homodyne detection, it is necessary that the carrier frequency, ν, not vary during the transit time of the signal by more than the information bandwidth. Consider, for example, a 60 cm He-Ne laser having an information bandwidth of 10 MHz being reflected from an artificial satellite at an altitude of about 10^6 meters. N would have a value of about 2×10^6 for this length laser and the round-trip transit time of the information-carrying signal would be about 7 msec.

From Equation (4) then, in order that ν not vary by more than 10 MHz during the 7 msec interval, it is necessary that $\Delta\nu$ not vary more than about 5 Hz during this time.

A free-running unstabilized laser can vary in beat frequency by several hundred cps, while the results of our experiments indicate that our laboratory prototype phase-locked lasers do not vary in beat-frequency by more than one or two Hz. Thus, a stabilized laser is required for this type of optical communication and the stabilization scheme employed by SURC under this contract is a practical method of achieving the necessary short-term stability.

CONSTRUCTION OF THE SURC LASER SYSTEM

THE LASER

One should bear in mind that these systems were laboratory models only, with the metal parts, such as the adjustable mirror mounts, being manufactured in our machine shop with conventional tooling. Much higher precision could be attained by purchasing high quality micrometer drives, etc. for the laser adjustments. The gas filled plasma tubes were purchased from Spectra-Physics, Incorporated, Mountain View, California; the optical cavity mirrors from Perkin-Elmer Corporation, Norwalk, Connecticut; the piezoelectric ceramic discs from Clevite Corporation, Bedford, Ohio; and the structural quartz cylinders were made to our specifications by the CKC Quartz Company, Plainfield, New Jersey. An RCA 7102 multiplier phototube and a Philco L4501 solid-state device were both used successfully as detectors. All of the electronics were designed and built at SURC, except that a 280 volt dc power supply manufactured by Technipower, Incorporated, of Norwalk, Connecticut, was incorporated into the phase-lock loop of the second system.

Figure 2 is a photograph of the entire system, which is seen to consist of the RF laser exciter, the laser itself, the detector and the "lock-box". Peripheral equipment (not shown) includes the power supply for the detector, oscilloscope, etc.

The supporting structure for the laser is a stress relieved quartz cylinder, chosen because of the low thermal coefficient of expansion of this material, and for its inherent mechanical stability. The metal mirror mounts are fabricated from stainless steel stock, with RTV gaskets poured in place between the mirror mounts and the ends of the quartz cylinders. The laser design is conventional with the plasma tube retained by teflon collars mounted near the ends of three longitudinal stainless steel rods. The piezoelectric-mounted plane mirror is manually adjustable along the laser axis, and the spherical mirror can be tilted in two planes in addition to a small amount of axial adjustment. Both lasers can be adjusted to have a 60 cm cavity length, and both lasers used the hemispherical cavity configuration. The radius of curvature of the spherical mirror in the first system is 61.9 cm; that used in the second system is 60.5 cm. The mirror material is fused silica. Each laser emits its energy from both ends, the first with a 50-50 distribution in output energy, the second with a 25-75 distribution with 75% passed by the wavefront correcting spherical mirror.

THE RF EXCITER

Figure 3 is a schematic for the power source which drives the laser. This RF exciter provides approximately 40 watts of crystal controlled 24 MHz energy to excite the laser gas tube into fluorescence. The exciter contains an electron coupled crystal oscillator, a class C power amplifier, and a voltage regulated power supply.

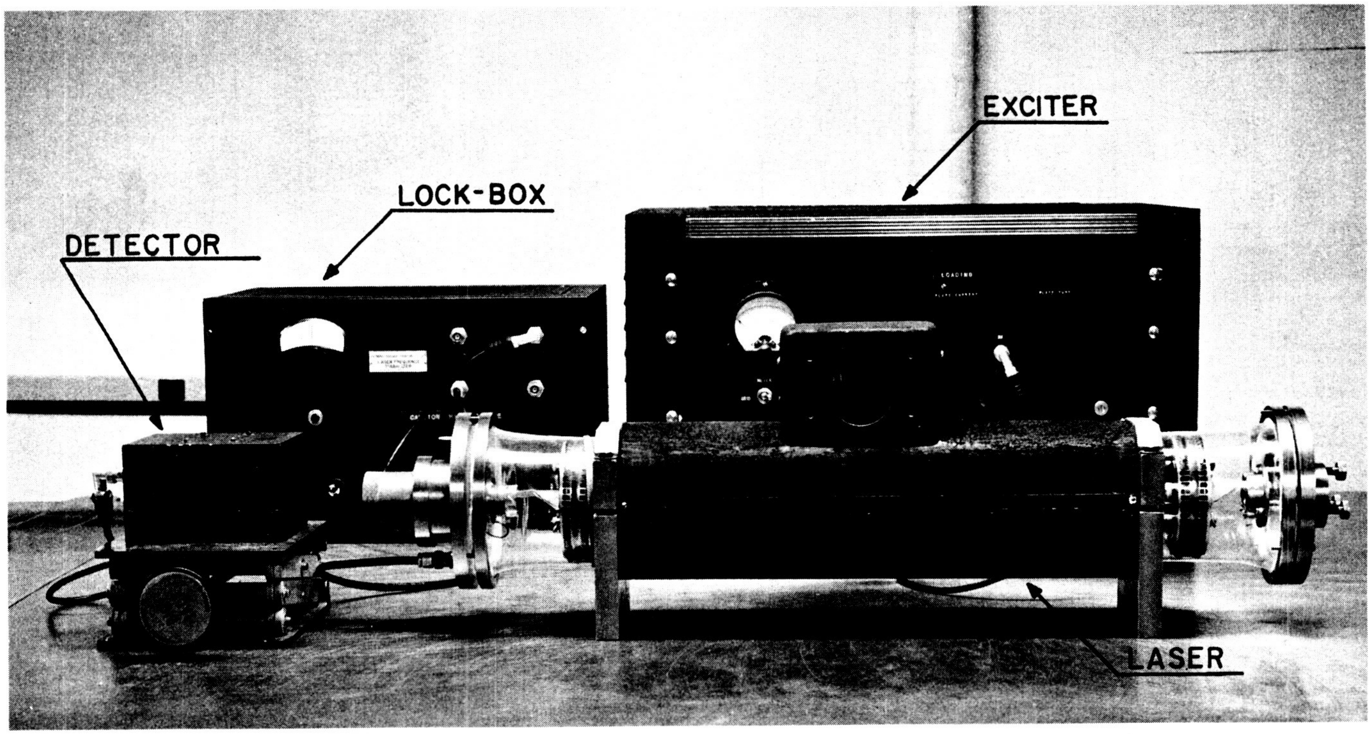
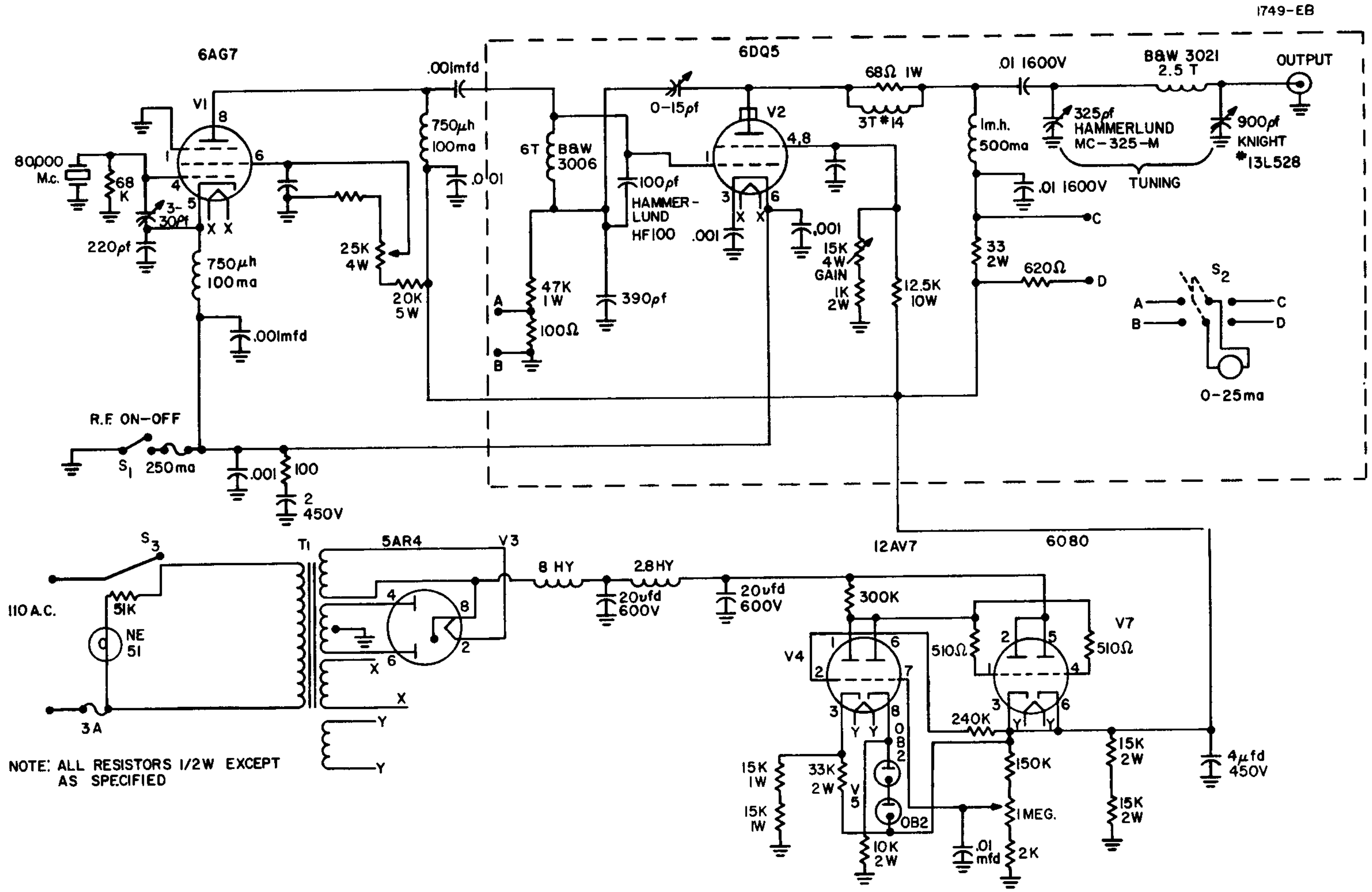


FIGURE 2. THE OPERATIONAL SYSTEM



NOTE: ALL RESISTORS 1/2W EXCEPT AS SPECIFIED

Figure 3. SCHEMATIC OF THE LASER EXCITER

The oscillator stage V_1 operates at 8 MHz between the V_1 screen and cathode circuits with the frequency being controlled by an 8 MHz crystal in the feedback circuitry. The plate is tuned to 24 MHz, causing V_1 to perform also as a multiplier with sufficient power output to drive the class C amplifier stage V_2. The drive to stage V_2 is controlled by the 25K ohm potentiometer in the V_1 screen circuit.

The class C stage V_2 amplifies the 24 MHz to a sufficient level (50 watts) to drive the laser. A pi network tuned circuit in the plate of V_2, adjustable through the loading and tuning controls, provides an output impedance of 50 ohms to the laser. The power output is adjustable by the 15K ohm gain control in the screen circuit. Neutralization of the power amplifier is provided by the 1 - 15 picofarad variable capacitor between the plate of V_2 and the bottom end of the grid circuit. This neutralization capacitor is adjusted for minimum 24 MHz output in the plate circuit with the high voltage disconnected from the V_2 screen and plate. This is a critical adjustment and need be performed only if tube V_2 is replaced.

The power supply, consisting of tubes V_3 through V_7, provides approximately 420 volts dc to the exciter. The dc output is well filtered and regulated by the V_4 control amplifier and the V_7 series regulator tubes. The voltage reference is obtained from tubes V_5 and V_6. The output voltage may be varied between 300 and 420 volts dc by the 1 megohm potentiometer in the regulator circuit. The high voltage dc to the regulator is provided by a full-wave rectifier tube V_3 and a high voltage power transformer.

THE LOCK-BOX

A block diagram of the phase-lock unit appears in Figure 1. Beginning with the 5 MHz oscillator, each component will be considered in detail.

The 5 MHz crystal oscillator was designed to provide a frequency-stable reference signal for the phase-lock loop. The oscillator has very good short-term stability, the long-term stability being dependent upon the variation of ambient temperature, as the oscillator is not enclosed in a constant temperature oven.

The oscillator stage consists of a 5 MHz crystal, a transistor, Q_1, and circuitry associated with this transistor. Figure 4 is a schematic diagram of the oscillator unit. A capacitor divider circuit provides the feedback between collector and emitter in a Colpits configuration. The crystal element is used in series resonance mode and placed in series with the feedback loop.

The second stage, Q_2, serves the dual purpose of amplifying the 5 MHz signal and of isolating the oscillator stage from the next stage, the frequency multiplier.

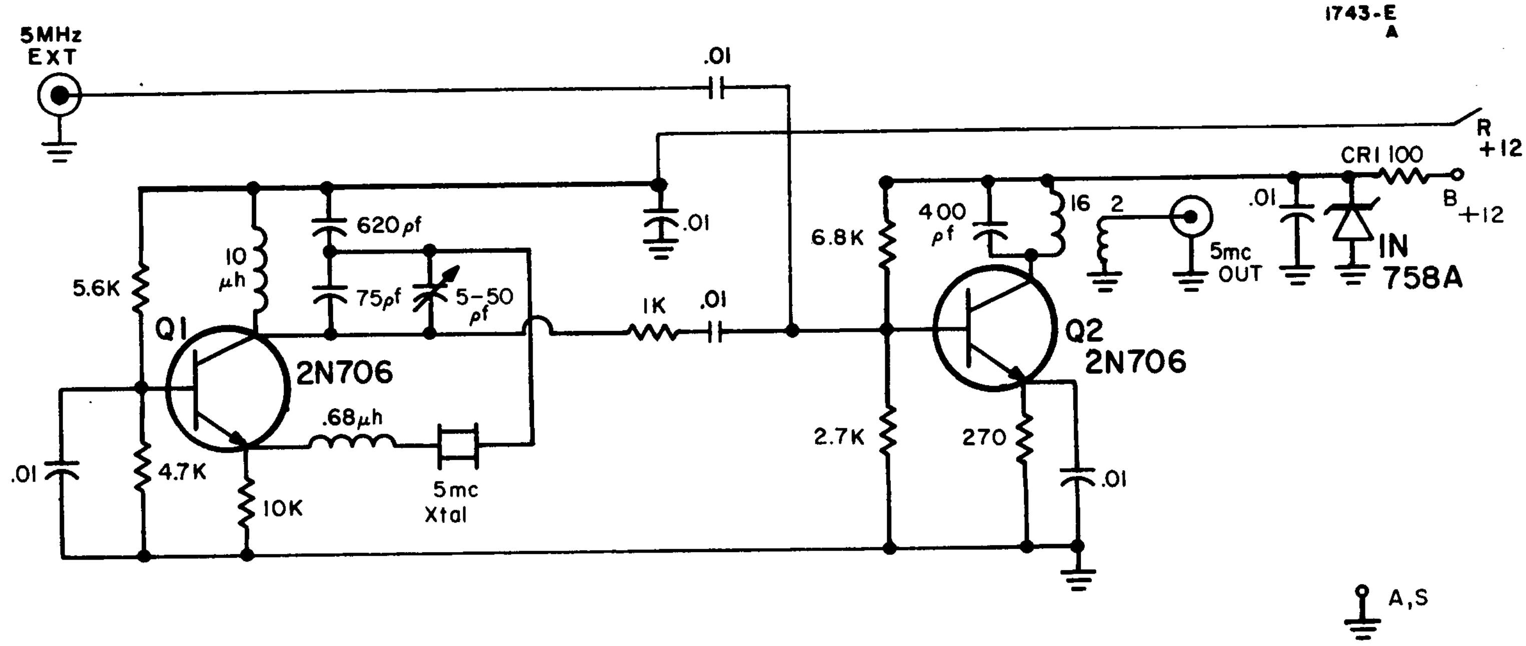


Figure 4. SCHEMATIC OF THE 5MHz OSCILLATOR

The component immediately following the 5 MHz oscillator in the block diagram of Figure 1 is seen to be a 5 to 20 MHz and a 5 to 30 MHz frequency multiplier. The schematic for this multiplier appears in Figure 5.

Both frequency multipliers are driven by a common input - the 5 MHz signal from the crystal oscillator.

The 5 - 20 MHz multiplier consists of two transistor stages, both of which are operated in class C mode. The first stage, Q_7, is a frequency quadrupler, multiplying its 5 MHz input to a 20 MHz output. The second stage serves as an amplifier. Rejection of the fundamental 5 MHz signal is accomplished in both stages by tuning the collector circuits for 20 MHz.

The 5 - 30 MHz frequency multiplier consists of four transistor stages. The multiplication is performed in stages Q_3 and Q_5, Q_4 is an idler, and Q_6 is an amplifier. The collector circuit of Q_3 is tuned for 10 MHz, that of Q_4 is tuned to 15 MHz. Q_5 receives the resulting 15 MHz signal and multiplies it to 30 MHz. Q_6 is a 30 MHz amplifier stage.

It is mentioned here that some amplitude distortions, due to the fundamental, may still be present in the 30 MHz signal, even though filtering is employed in every stage. Since this signal is fed into the phase detector, which is insensitive to amplitude distortions, the operation of the lock-loop will be unaffected by the distortions present.

The output signal of the 5 - 30 MHz multiplier is adjusted for approximately 0.5 volts (peak-to-peak), which is adequate to drive the phase detector.

Note that both outputs should be terminated in 50 ohm loads when tuning the multipliers.

Whereas the 30 MHz signal is fed directly to the phase detector, the 20 MHz output signal is multiplied up to 220 MHz in a 20 - 220 MHz frequency multiplier as shown in the block diagram. Figure 6 is a schematic of this multiplier. The principle employed here utilizes the harmonic generation characteristics of a HPA-0112 step recovery diode.

A step recovery diode is a special class of diode which has been optimized for controlled charge storage, coupled with a very abrupt transition from reverse storage to conduction cut off. When properly utilized, this diode will produce fractional nanosecond, large amplitude signals harmonically related to the drive frequency. The diode is very sensitive to temperature variation and drive level, however, and extreme care must be taken to optimize the circuitry for proper operation.

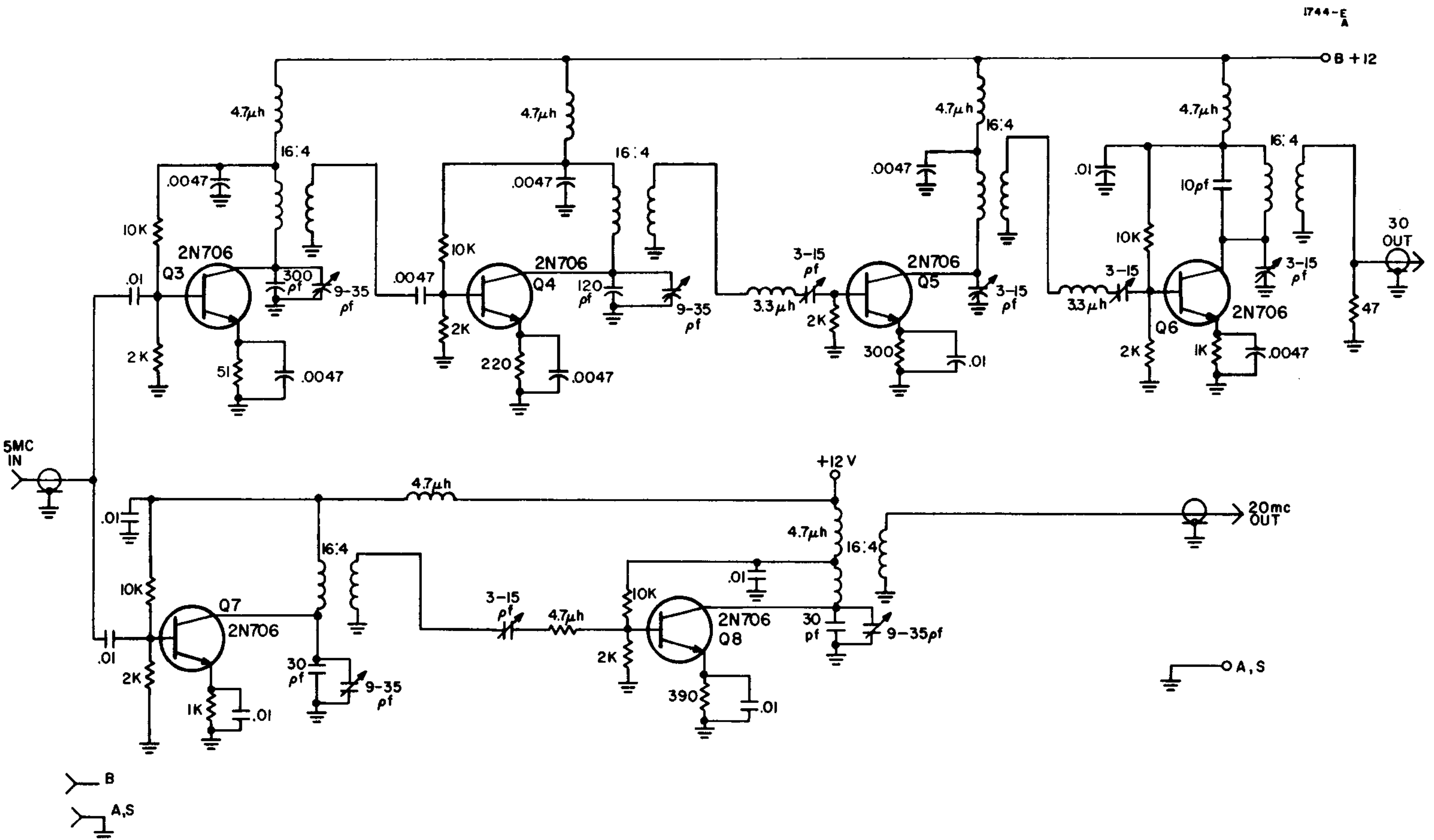


Figure 5. SCHEMATIC OF THE 5-20 AND 5-30 MULTIPLIER

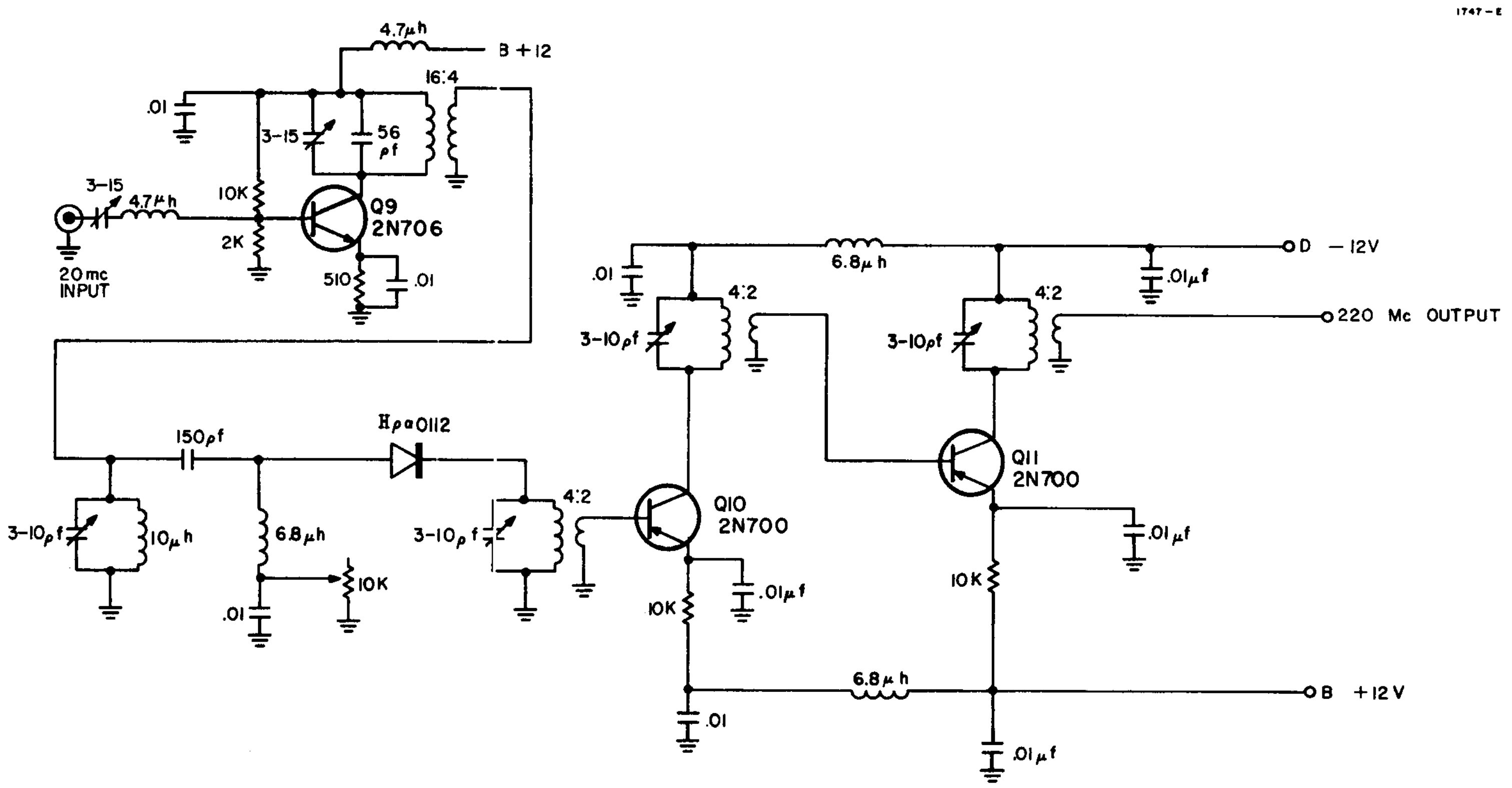


Figure 6 SCHEMATIC OF THE 20—220 MHz FREQUENCY MULTIPLIER

Q_0 serves the dual purpose of amplifying the 20 MHz input and of rejecting other frequency harmonics. The circuitry preceding the diode is tuned to 20 MHz, the 10K potentiometer and 6.8 microhenry coil serves as a bias circuit for the diode, and the circuit following the diode is tuned for the desired output frequency, 220 MHz. The two following stages serve as amplifiers and filters. The 220 MHz output frequency is used as the local oscillator for the laser.

If the collector circuits of Q_{10} and Q_{11} are not properly tuned, the output signal will contain more than one frequency component and the operation of the lock-box may be impaired.

Figure 7 is a schematic diagram of the next lock-box component, the 250 MHz to 30 MHz converter, wherein the 250 MHz signal from the laser detector is beat down to a 30 MHz IF signal. This is accomplished by beating the laser signal against the 220 MHz local oscillator signal from the preceding frequency multiplier. Both signals are coupled into the base of the 2N2996 transistor, Q_{14}. All the transistors are of the 2N2996 type, which are known to have excellent signal-to-noise characteristics at high frequencies. The sensitivity of the converter is -60 dbm and dynamic range is 40 db.

The 250 MHz signal is applied to the base of Q_{12}. A tuned circuit is included to improve selectivity. Whereas Q_{12} and Q_{13} are 250 MHz amplifiers, they serve also as buffer circuits to prevent the local oscillator signal from feeding back to the optical detector.

The input circuit from the local oscillator contains two tuned circuits which serve as impedance matching circuits for the 220 MHz signal. The two signals are mixed at the base of Q_{14} and the collector circuit is tuned for 30 MHz. The following two stages are IF amplifiers with a bandwidth of 4 MHz.

Since the overall circuit exhibits high gain, care must be exercised when tuning the circuit to prevent self-oscillation.

Figure 8 is a schematic for the next component in the lock-box, the 30 MHz amplifier-limiter.

The input signal from the converter is amplified and two separate outputs provide a monitoring point and an input to the following phase detector. The circuit consists of one common amplifier stage Q_{17}, the output of which is divided into two channels to be further amplified, each by its own transistor stage. Each of these latter are similar except that the gain of Q_{18} is greater and the 2N1142 transistor can handle higher power. This arrangement is necessary to prevent feedback from the phase detector. If the two outputs were picked off from a common

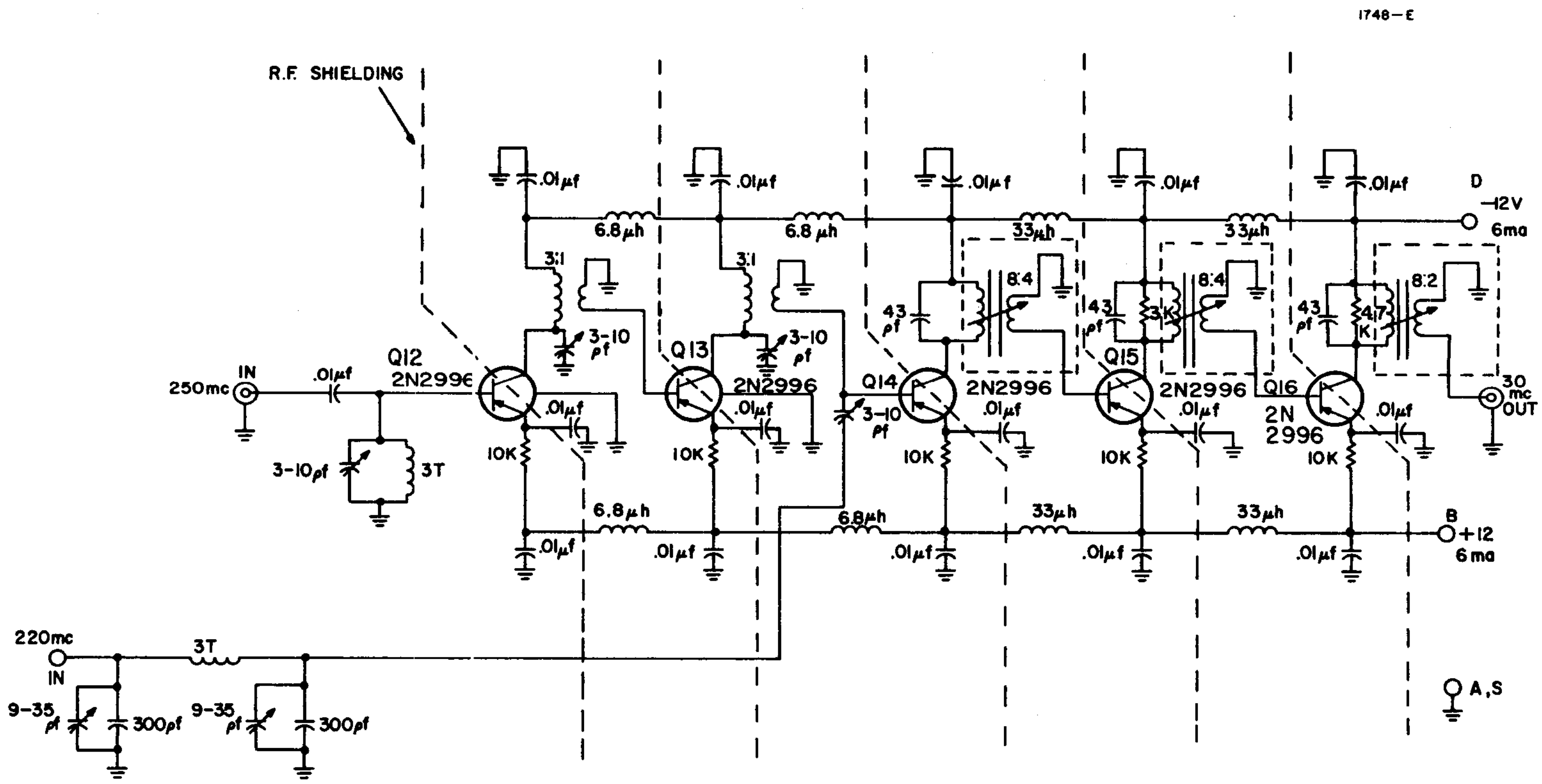


Figure 7 SCHEMATIC OF THE 250-30MHz CONVERTER

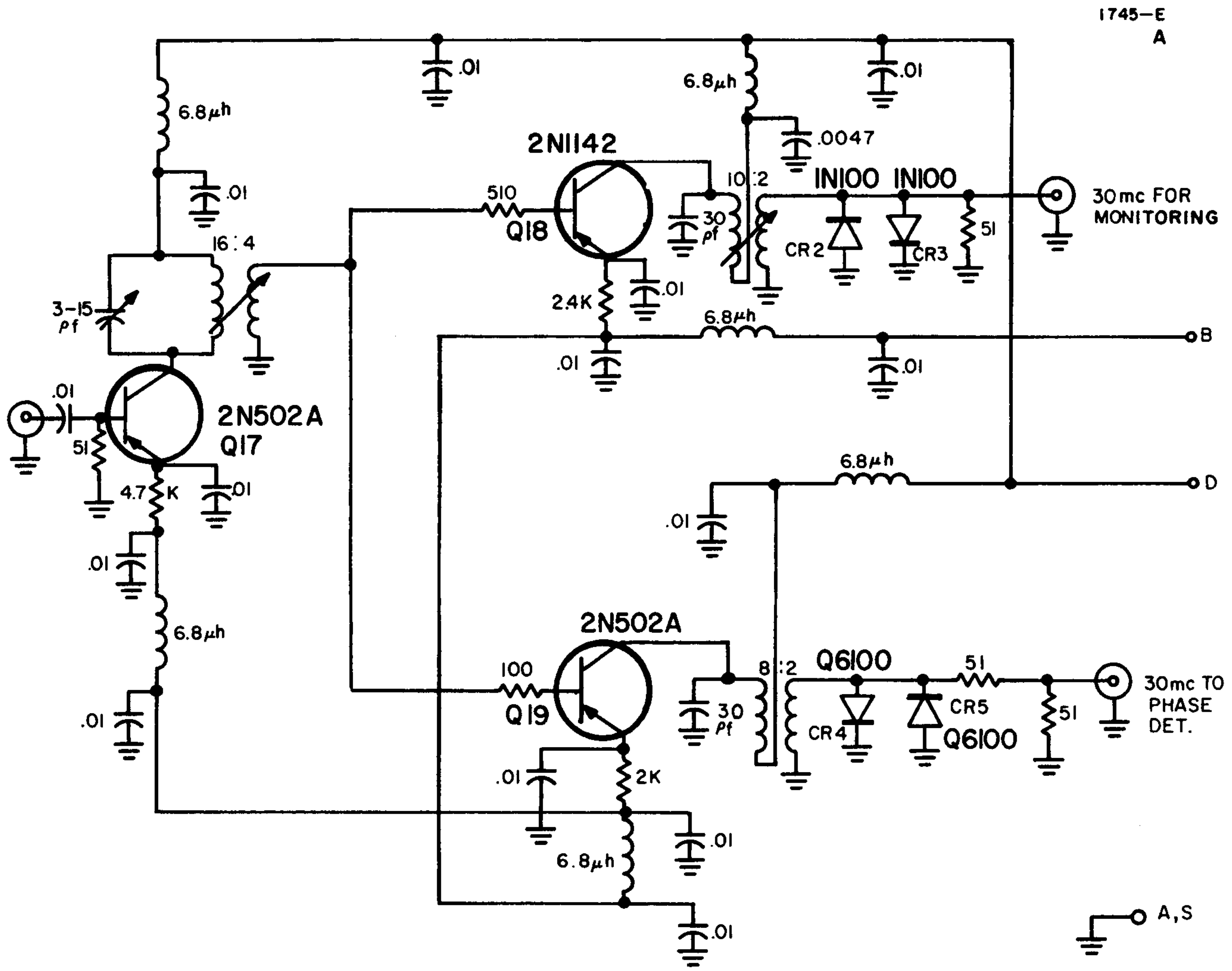


Figure 8. SCHEMATIC OF THE 30MHz AMPLIFIER-LIMITER

point, modulation on the monitoring line would be observed due to the reference signal in the phase detector.

The diodes in the output circuit limit the output signal amplitude to less than one volt.

The final component in the lock-box is the phase detector, the schematic of which appears in Figure 9.

The phase detector module actually consists of two parts; the phase detector proper and a high gain dc amplifier.

The phase detector is a coincidence device in which the output is proportional to the phase difference of the two input signals. The two transformers add the two input signals in one channel and subtract them in the other. The two diodes, together with the low-pass filter, constitute a peak voltage detector. As the phase between the two input signals varies, the amplitude of the voltage in one channel will vary from a maximum when they are in phase to a minimum when they are 180° out of phase. The two channels are always 180° out of phase with each other.

The phase detector circuitry is followed by a dc coupled differential amplifier, Q_{20}. Q_{20} is followed by another differential amplifier consisting of Q_{22} and Q_{23}. Each of the latter differential amplifiers are biased by current generators, Q_{21} and Q_{24}, to provide constant bias current and eliminate drift.

Q_{25} is a high gain amplifier stage containing an ac gain potentiometer in the emitter circuit. Q_{26} reduces the loading effect on the previous stage and Q_{27} is the driver stage capable of handling high power at high bias voltage. The 20K potentiometer is used for zeroing the null meter.

CAUTION: A high dc voltage is present at the output of this final stage. On the lock-box this output is marked "ERROR SIGNAL".

Figure 10 is a wiring diagram of the lock-box.

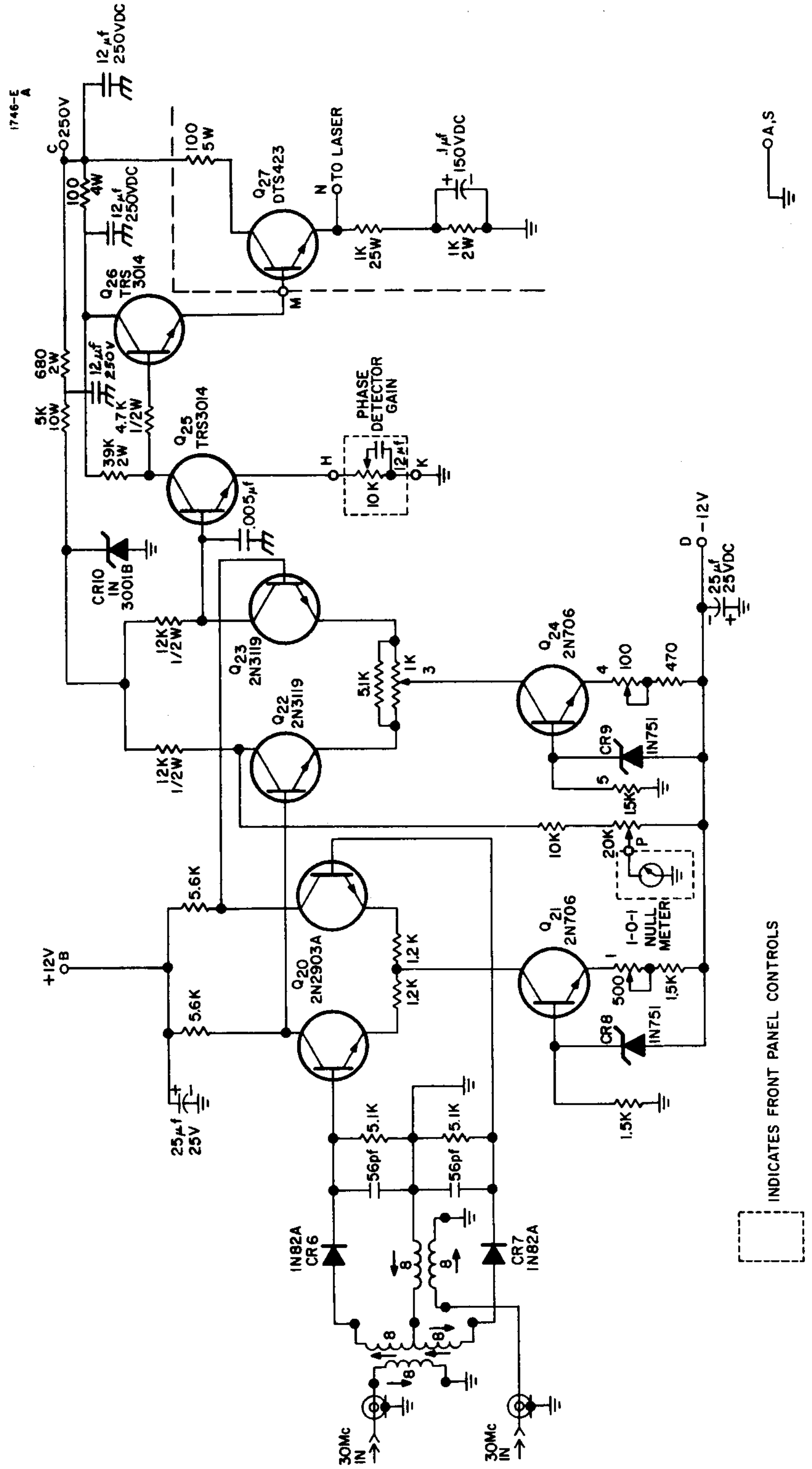


Figure 9. SCHEMATIC OF THE PHASE DETECTOR

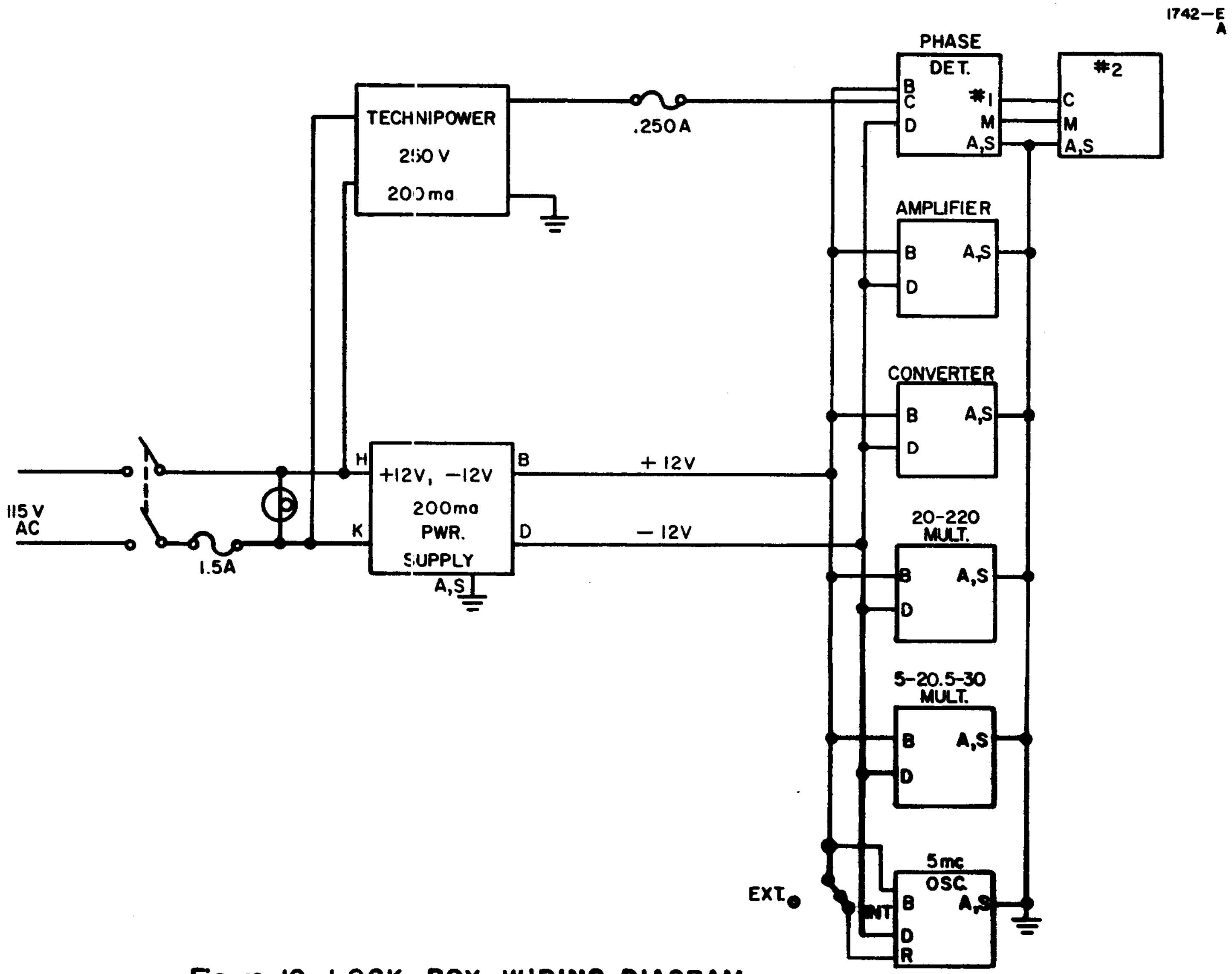


Figure 10. LOCK-BOX WIRING DIAGRAM

EXPERIMENTAL RESULTS

The initial stages of the experimental program involved the testing of certain commercially available gas lasers in order to evaluate their noise characteristics and adaptability to stabilization. This led to the design and construction of a laser which would have good inherent stability and which would be capable of being electronically tuned. This laser was then tested. On the basis of these tests, a second laser was designed and built such that the inherent stability and the tuning capability were both improved. The second laser was then tested.

Figure 11 is a block diagram of the system used to make short-term stability measurements on the various lasers tested in the early stages of this investigation. The laser was adjusted and driven such that the beat frequency between two axial modes could be extracted by directing the laser beam into a square law optical detector. An RCA 6102 multiplier phototube was used for this purpose.

The electrical output signal from the detector was input to a converter whose purpose was to refer the instabilities of the laser to a standard stable frequency, but without simultaneously introducing new sources of instability. The converter consisted of a crystal oscillator, multiplier, and mixer. In some cases, the exact crystal necessary was not available, so an HP 608 signal generator was used as the local oscillator.

The system represented by Figure 11 was tested by making a control plot wherein an HP synthesyzer was substituted for the laser detector input to the converter. This control plot is presented in Figure 12.

Figure 13 is a plot made with a commercially available laser which used invar rods as the main structural element. Similarly, the plot of a laser having a metal structural housing appears in Figure 14, while that of a laser constructed about a quartz cylinder is presented in Figure 15. These three plots show noise and sidelobe structure considerably worse than that shown in the control plot of Figure 13, thus indicating the amount of instability due to the laser and detector combination.

Since Figure 15 indicates the most stable type of laser construction, the quartz cylinder was decided upon as the basic structural element in the lasers to be built under this contract.

The laser used to develop the plot shown in Figure 15 was then used in conjunction with the circuit depicted in Figure 16 in an attempt to stabilize this laser. A plot of the result is shown in Figure 17 and a control plot of the system, made by substituting a crystal oscillator for the laser, is shown in Figure 18.

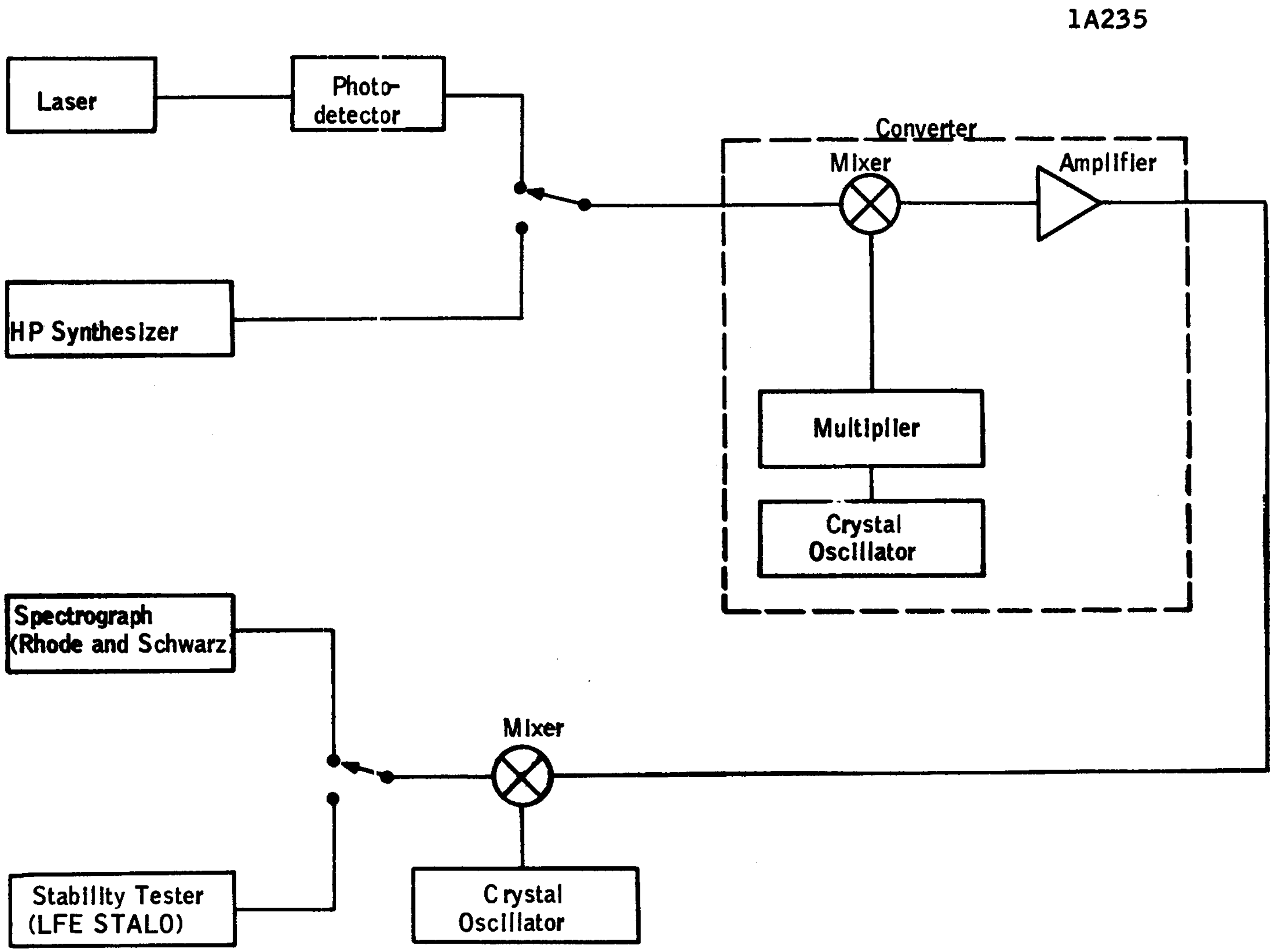


FIGURE 11. A BLOCK DIAGRAM OF THE SYSTEM USED TO MAKE SHORT TERM STABILITY MEASUREMENTS ON THE VARIOUS LASERS TESTED IN THE EARLY STAGES OF THE INVESTIGATION.

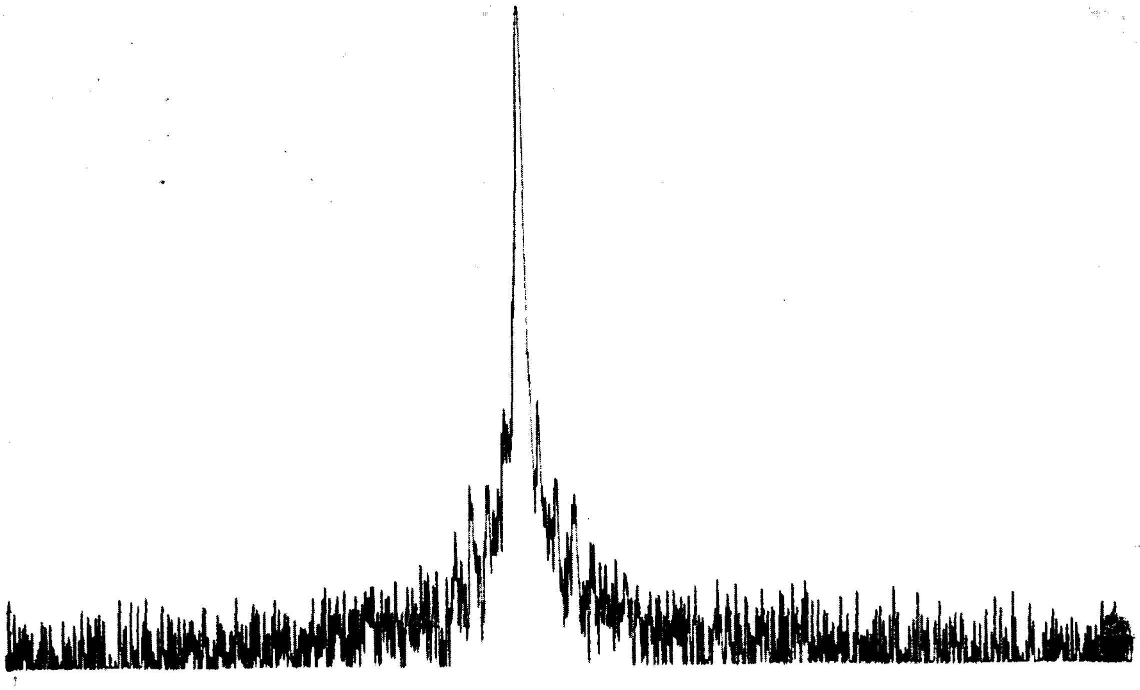


FIGURE 12. CONTROL PLOT OF CIRCUIT DEPICTED IN FIGURE 11 WITH AN HP SYNTHESIZER SUBSTITUTED FOR THE LASER-DETECTOR COMBINATION. THE SCALE IS 200 Hz/cm.

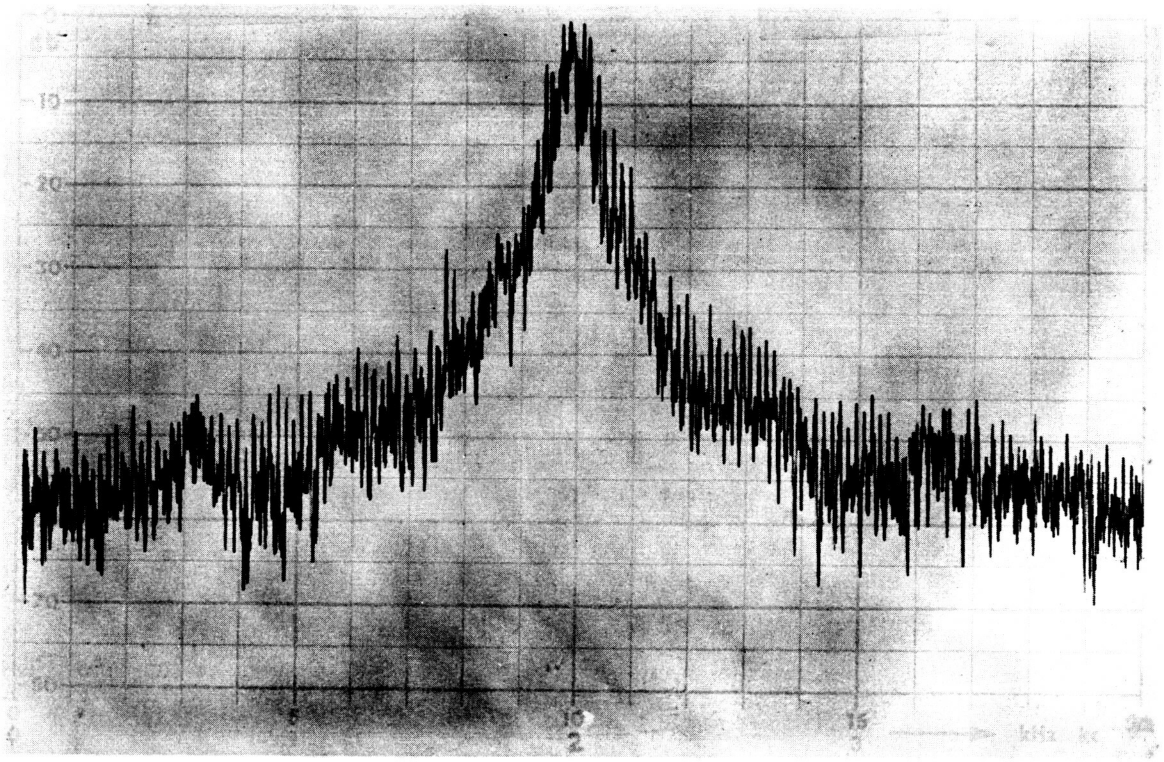


FIGURE 13. STABILITY PLOT OF A COMMERCIAL LASER WHOSE MAIN STRUCTURAL ELEMENTS WERE INVAR RODS. HORIZONTAL SCALE IS 200 Hz/cm.

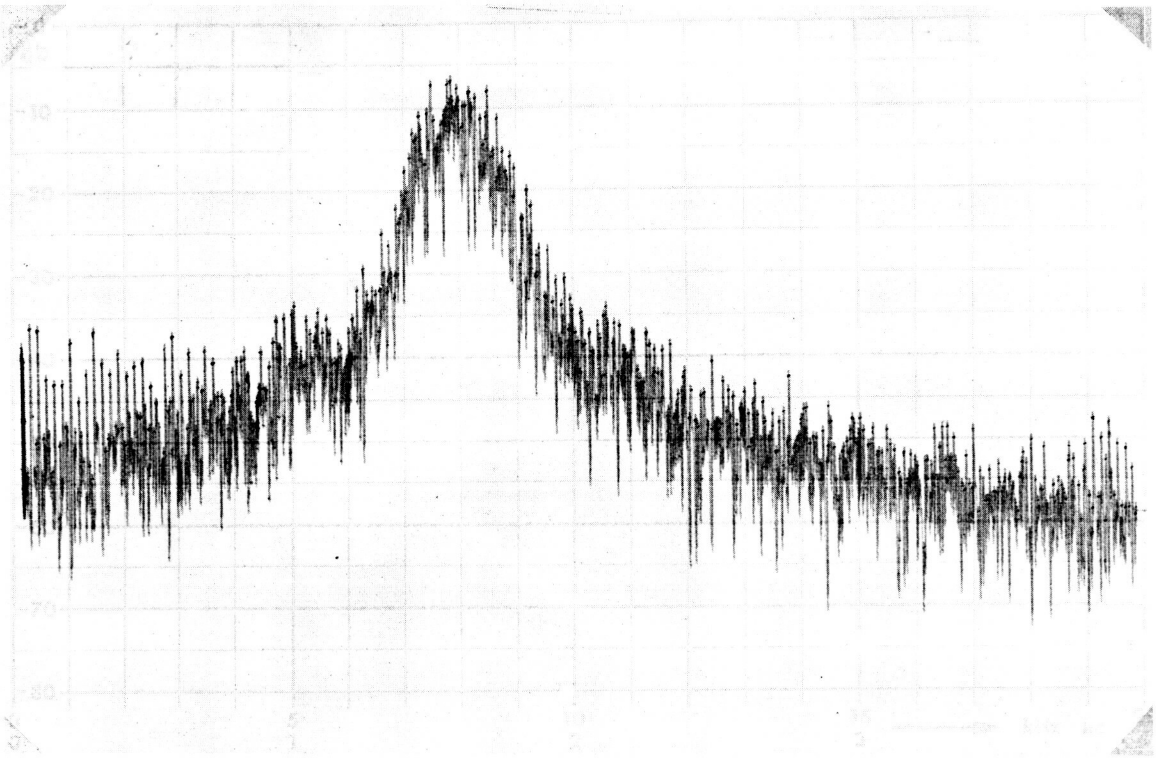


FIGURE 14. SPECTRAL PLOT OF A COMMERCIAL LASER WHOSE STRUCTURAL INTEGRITY WAS DERIVED FROM A STEEL HOUSING. HORIZONTAL SCALE IS 200 Hz/cm.

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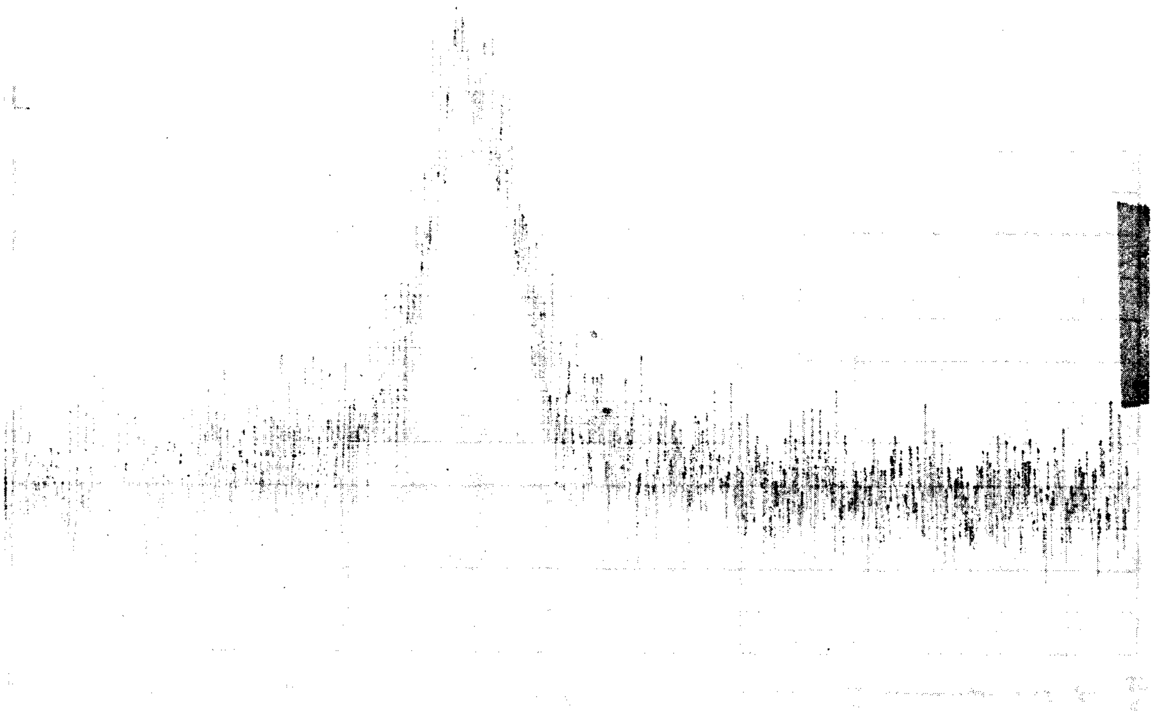

FIGURE 15. SPECTRAL PLOT OF A COMMERCIAL LASER WHICH WAS CONSTRUCTED ABOUT A QUARTZ CYLINDER. HORIZONTAL SCALE IS 200 Hz/cm.

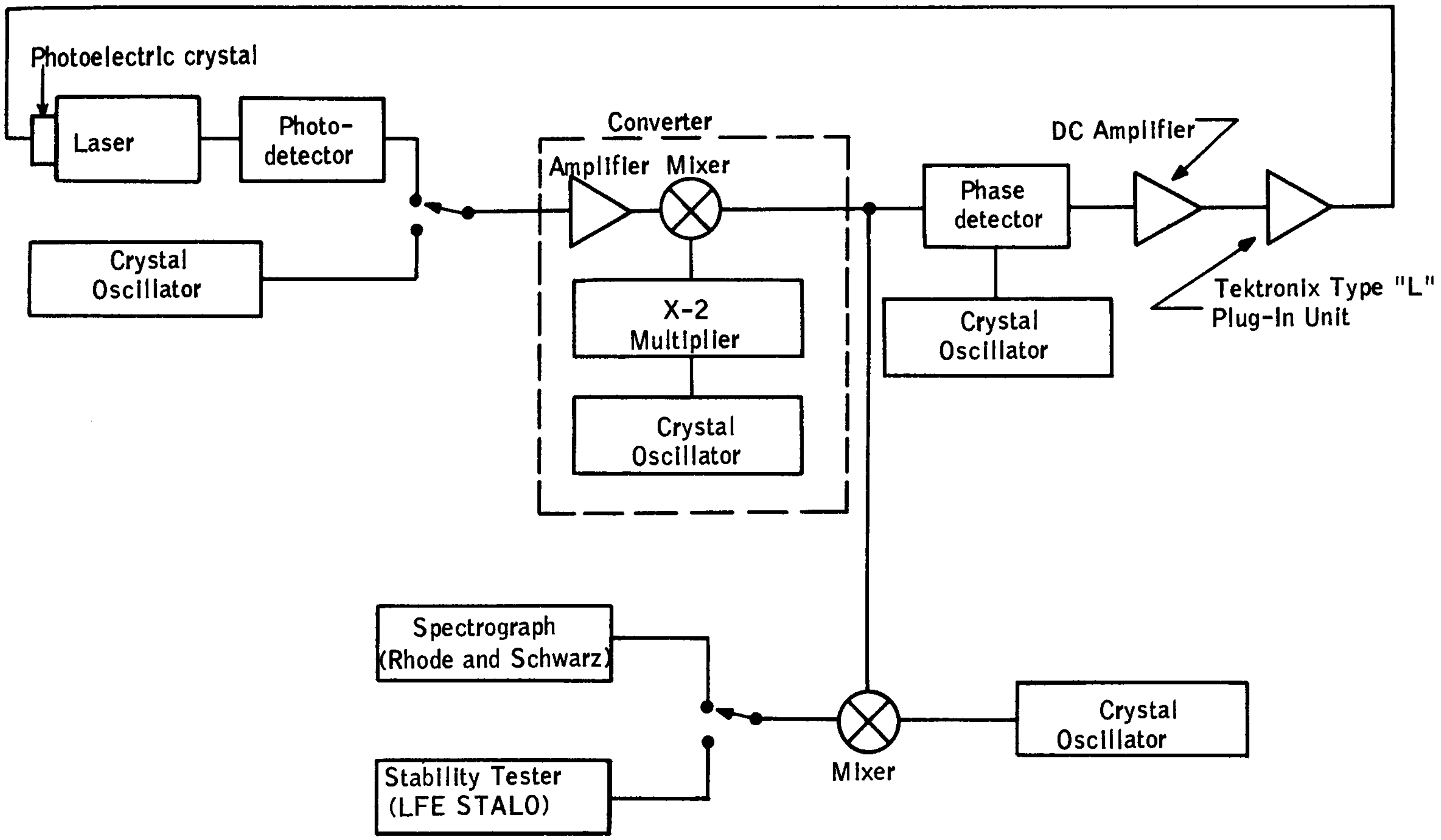

FIGURE 16. BLOCK DIAGRAM OF FIRST PHASE-LOCKING STABILIZATION CIRCUIT. THIS CIRCUIT WAS USED IN CONJUNCTION WITH THE LASER FROM WHICH THE PLOT IN FIGURE 15 WAS DEVELOPED.

1A179

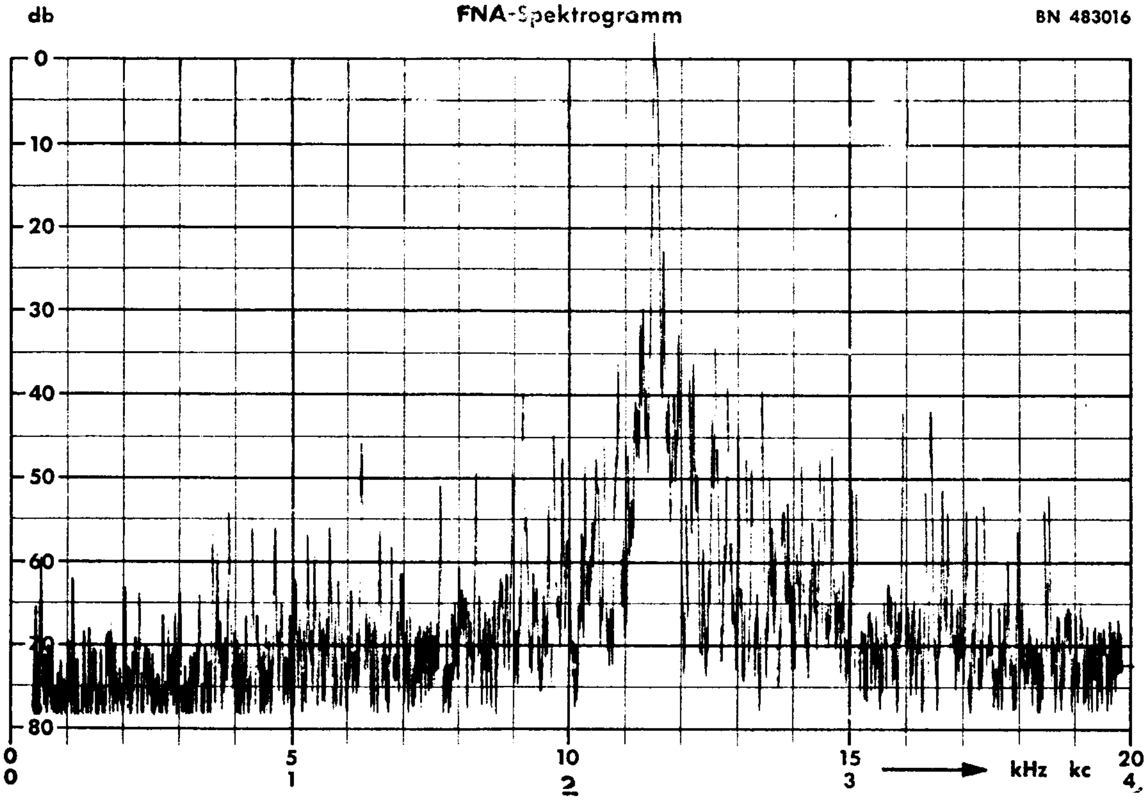

FIGURE 17. A STABILITY PLOT OF THE FIRST ATTEMPT TO PHASE-LOCK A LASER USING THE CIRCUITRY SHOWN IN FIGURE 16. THE SAME LASER WAS USED TO GENERATE THIS PLOT AS WAS WAS USED TO OBTAIN THE PLOT SHOWN IN FIGURE 15. HORIZONTAL SCALE IS 200 Hz/cm.

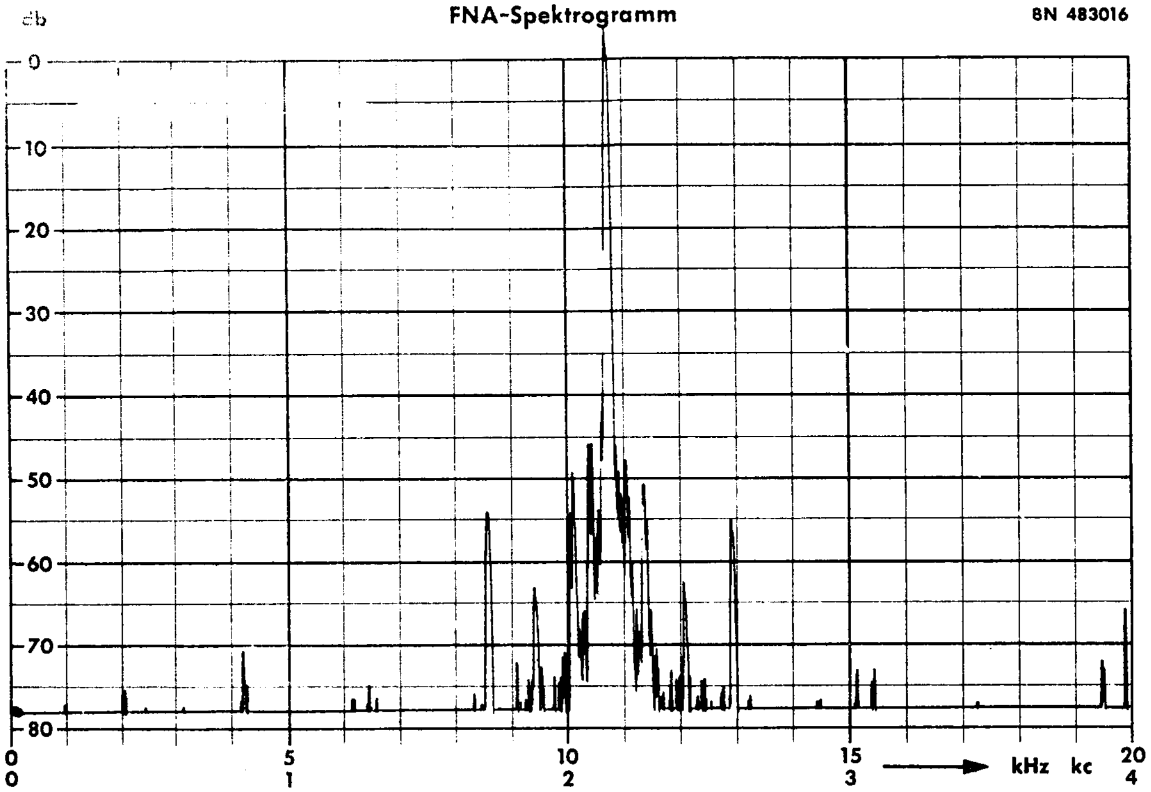

FIGURE 18. A CONTROL PLOT OF THE CIRCUIT SHOWN IN FIGURE 16. THIS PLOT WAS MADE BY SUBSTITUTING A CRYSTAL OSCILLATOR FOR THE LASER. HORIZONTAL SCALE IS 200 Hz/cm.

Comparison of Figures 17 and 15 shows the improvement in spectral purity to be gained by phase-locking while comparison of Figures 17 and 18 shows that there is still a considerable amount of laser derived noise present. It was obvious that improvements in the laser design and in the phase-lock loop were necessary.

A block diagram of the phase-lock circuit used to stabilize the first NASA/SURC laser is shown in Figure 19. The spectral plot of this phase-locked laser appears in Figure 20. The improvement which resulted from the redesign of the lock-loop and from the special construction of the first NASA/SURC laser is evident upon comparison of Figures 20 and 17.

Based upon the education obtained by building the first phase-locked laser system, the design and construction of an improved version were undertaken. The phase-locking circuitry is shown in Figure 21, the spectral plot of the locked laser in Figure 22. Again the improvement achieved is indicated by the comparison of Figures 22 and 20.

Figure 23 is another plot of the spectral purity of the second NASA/SURC phase-locked laser but with a different horizontal scale value. In this figure the 15 kHz width of the phase-lock loop is clearly evident.

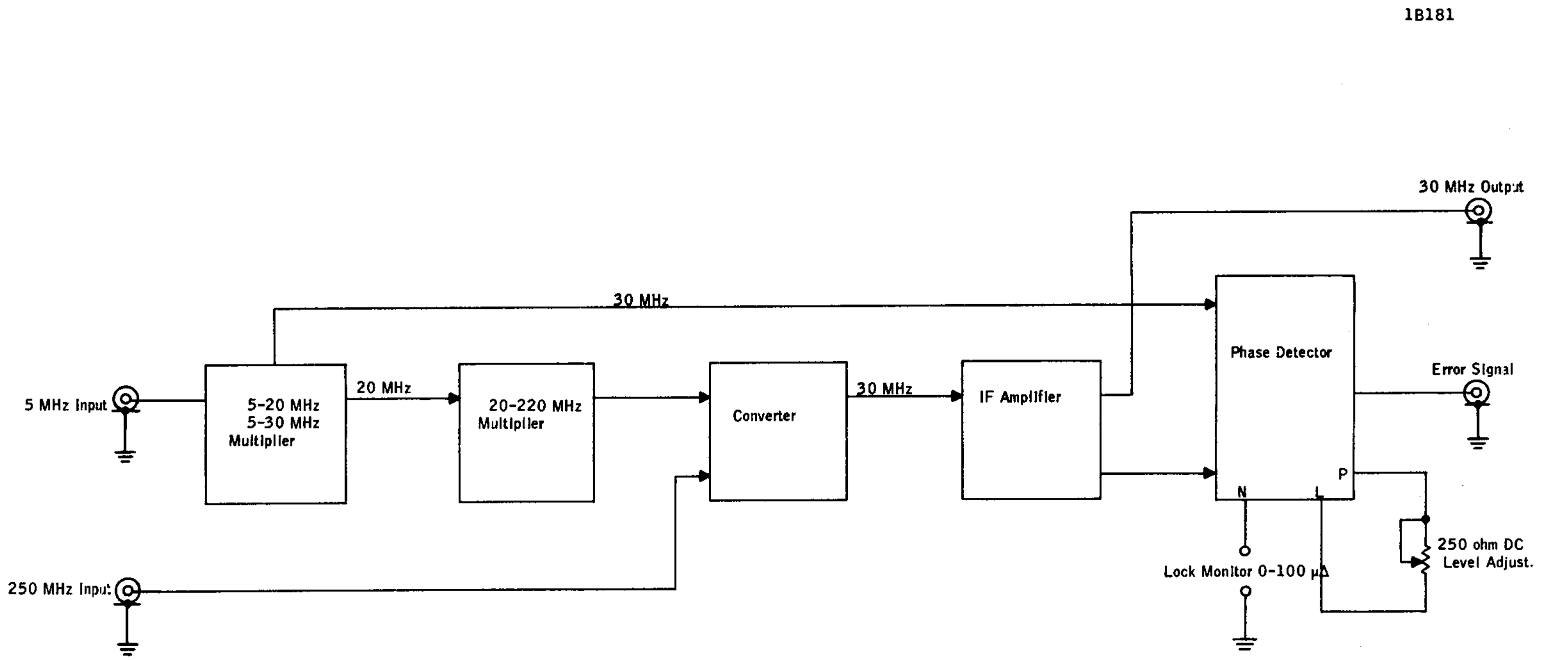

FIGURE 19. PHASE-LOCK CIRCUIT FOR FIRST NASA/SURC LASER SYSTEM.

1A182

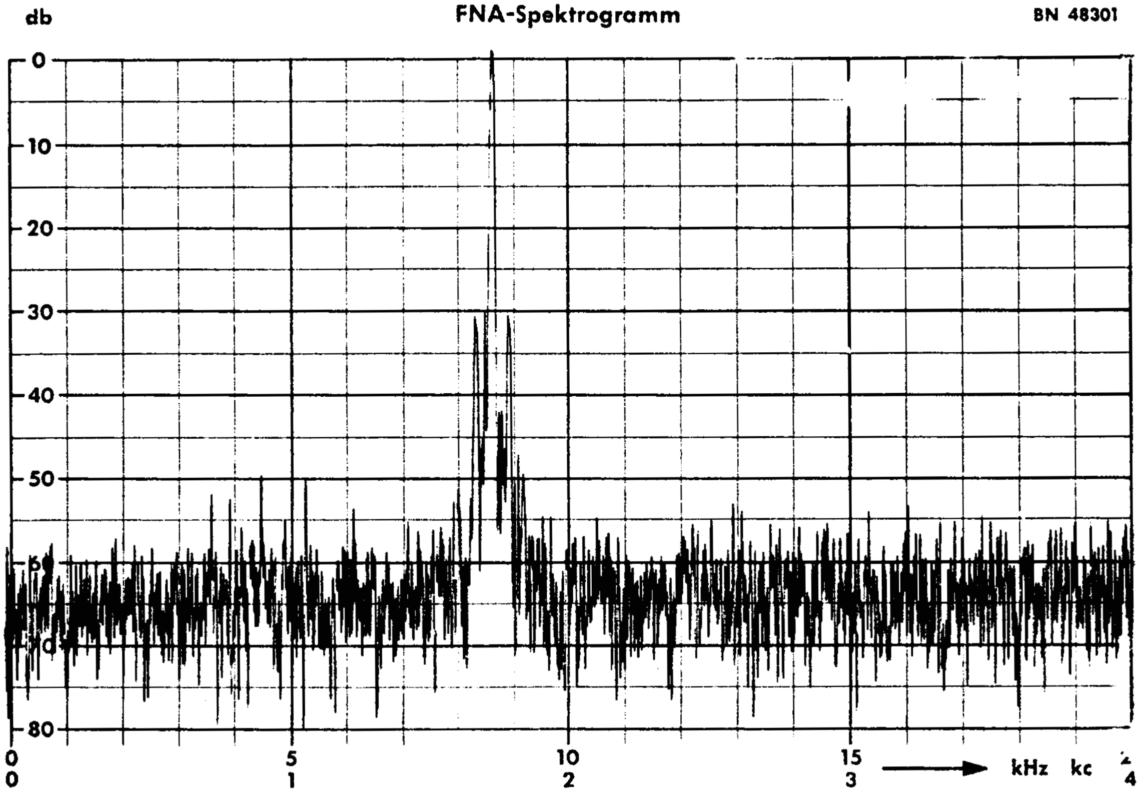

FIGURE 20. A STABILITY PLOT OF THE FIRST PHASE-LOCKED NASA/SURC LASER SYSTEM. THE CIRCUITRY SHOWN IN FIGURE 19 WAS USED TO LOCK THE LASER. HORIZONTAL SCALE IS 200 Hz/cm.

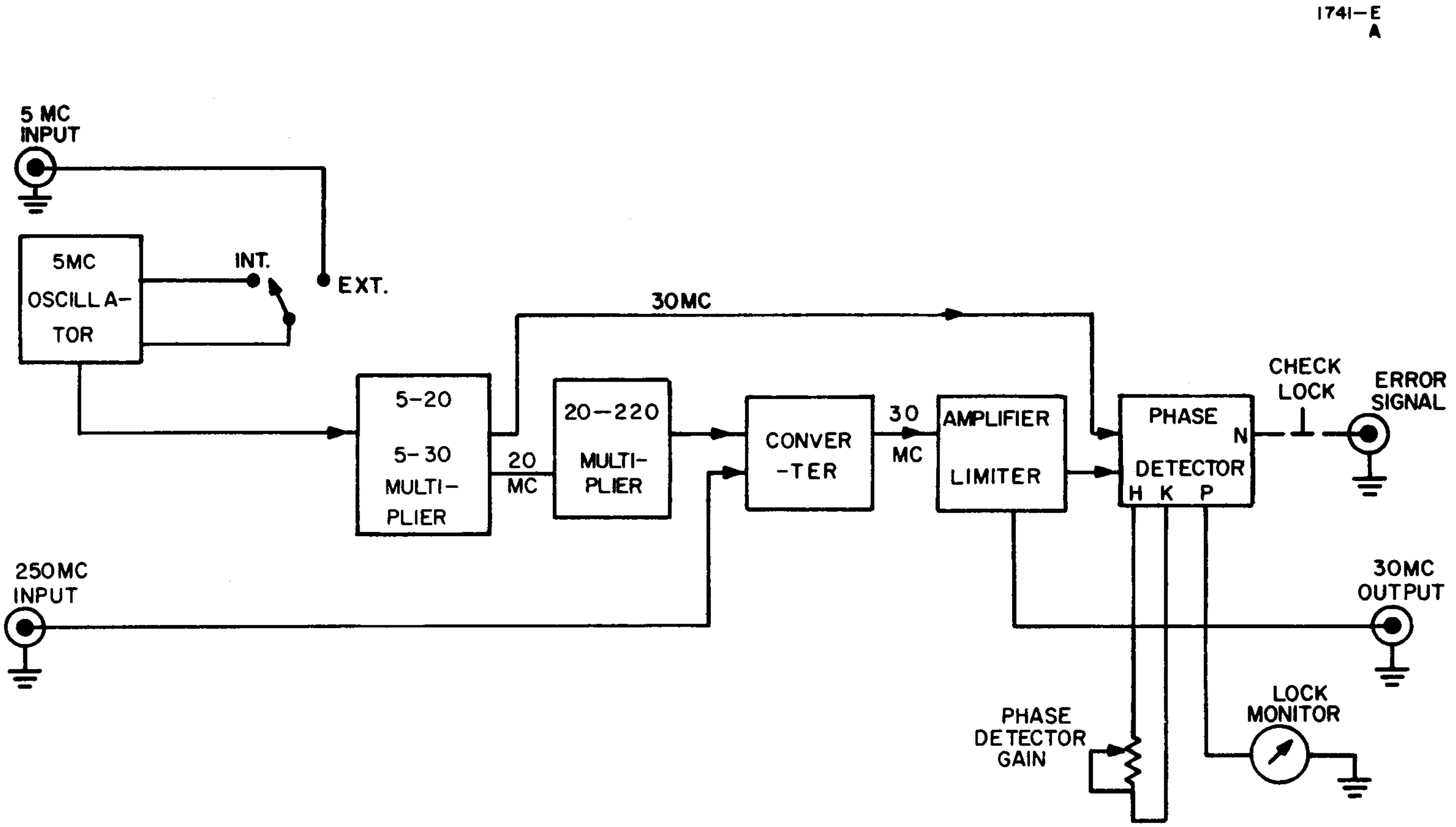

Figure 21. PHASE-LOCK CIRCUIT FOR 2nd NASA/SURC LASER SYSTEM

1A183

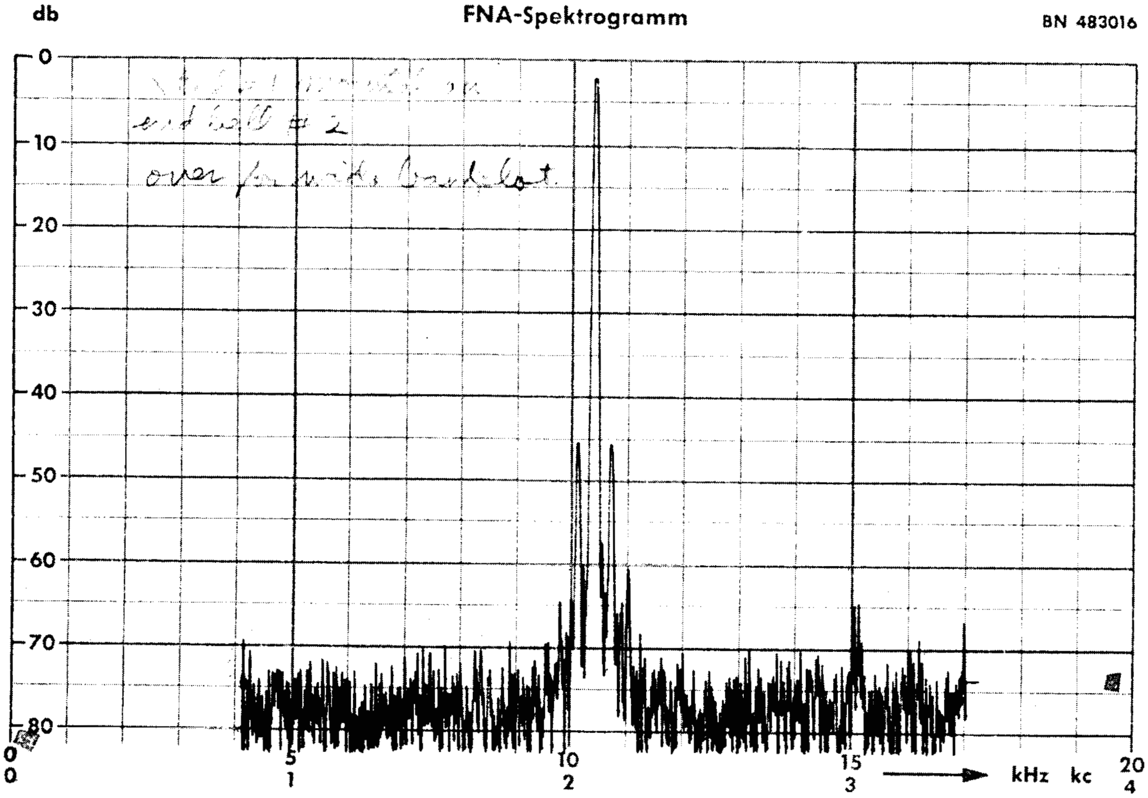

FIGURE 22. A PLOT OF THE SPECTRAL PURITY OF THE SECOND PHASE-LOCKED NASA/SURC LASER SYSTEM. HORIZONTAL SCALE IS 200 Hz/cm.

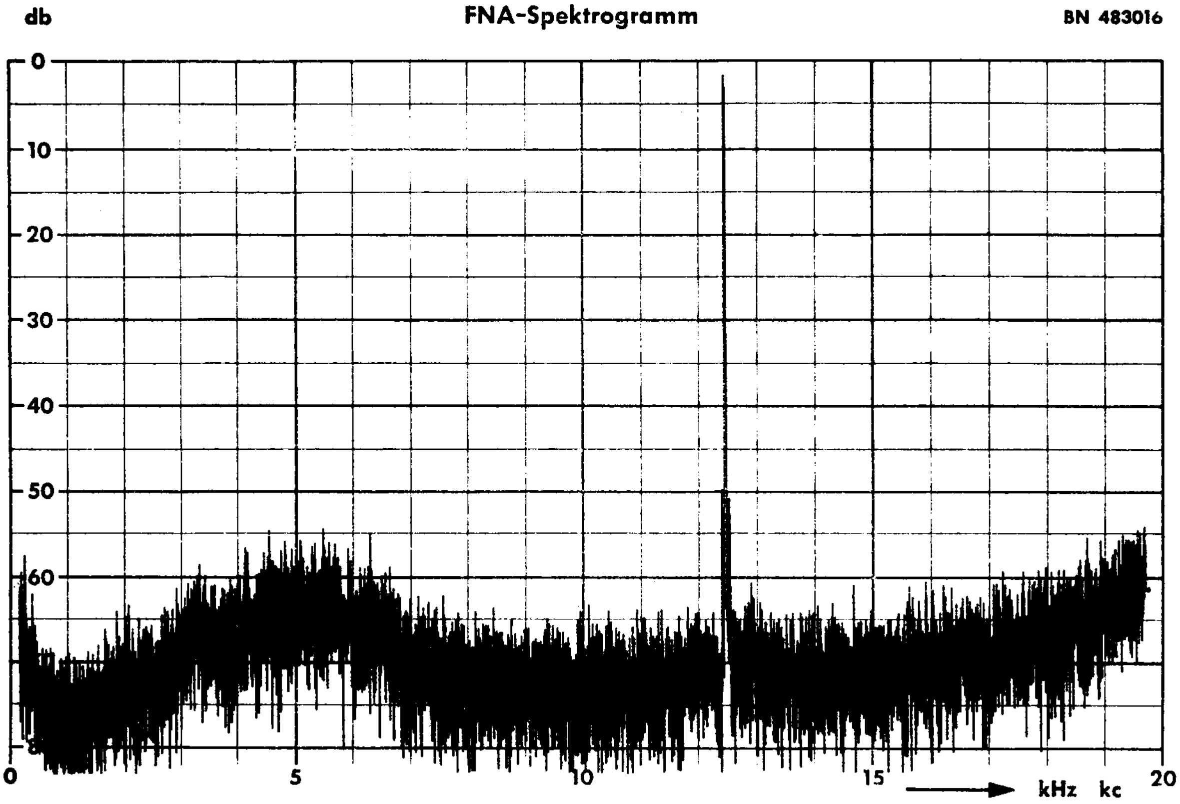

FIGURE 23. A PLOT OF THE SAME INFORMATION DEPICTED IN FIGURE 22, BUT WITH A CONTRACTED HORIZONTAL SCALE. NOTE THAT THE 60 Hz SIDEBANDS ARE 50 db DOWN AND THAT THE SYSTEM BANDWIDTH IS 15 kHz. HORIZONTAL SCALE IS 1000 Hz/cm.

CONCLUSIONS AND RECOMMENDATIONS

It is concluded that these two laboratory prototypes have proven the feasibility and practicality of the phase-locking scheme employed. Based upon these models, a very stable phase-locked laser system could be built if certain modifications were incorporated into the design. It is recommended that the mirror mounts be redesigned to incorporate high precision micrometer drives so that certain mechanical instabilities be alleviated. Considerable difficulties have been encountered due to the mechanical play in the "end-bells", which, while not considered severely excessive by mechanical standards, can produce drastic alterations in the optical cavity modes of oscillation.

It is further recommended that the electro-mechanical properties of these piezoelectric stacks be given further consideration, particularly as regards the fact that the heavy mirror is suspended on the end of the cantilever beam formed by the crystal stack.

It is believed that the use of a 30 MHz crystal for the reference oscillator, instead of a 5 MHz crystal multiplied up to 30 MHz, should alleviate some of the noisy harmonic oscillation problems encountered in this development. A sevenfold multiplication up to 210 MHz, combined with a 62.5 cm laser cavity to produce a 240 MHz beat signal would provide the two phase-detector inputs; or, other combinations could be used without affecting the overall scheme.

APPENDIX I

OPERATION AND TROUBLESHOOTING MANUAL

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

APPENDIX I.
OPERATION AND TROUBLESHOOTING MANUAL

1. The 24 MHz Laser Exciter.

The laser exciter is a 24 MHz, crystal controlled, 40 watt RF transmitter employing the third harmonic of an 8.000 ±.01%MHz crystal. Voltages necessary for operation are contained within the unit and only conventional 60 Hz, 115 volt external power is required.

Once the exciter has been tuned for a specific load, it should not be necessary to make further adjustments for each use, except possibly for a slight adjustment of the PLATE TUNE control which controls the output of the final power tube. Load impedance matching is controlled by the PLATE CURRENT control. The power delivered to the laser is variable by manipulating the GAIN control. The more precise the tuning of the former two controls, the lower the gain setting required to achieve proper lasing action.

The exciter should never be turned on with no load on the output. If it is desired for any reason to operate the exciter without the laser, a 60 to 150 watt light bulb is useful as an alternate load.

To excite the laser, the following procedure is recommended.

1. Connect the laser to the output of the exciter with an appropriate length of coaxial cable. If the same cable is used consistently for this purpose, the adjustments required for each use will be minimized. A three-foot cable, or shorter, is recommended.
2. Plug the exciter power cord into a conventional 60 Hz, 115 volt wall outlet.
3. Check that the RF switch is "OFF", that the GAIN control is turned down (CCW) as far as possible, and that the switch below the milliamp meter is in the PLATE position.
4. Move the power switch to "ON". The red panel light should come on.
5. Wait 30 - 45 seconds for filament warmup.
6. Move the RF switch to "ON". The meter needle should move slightly upscale from zero.

7. Increase the GAIN until the plasma tube fluoresces, but do not exceed 10 milliamps on the plate-current meter. The tube will usually light at about 5 milliamps indicated. If the tube does not light, go to step 11.

8. Continue increasing the GAIN until lasing action occurs. When the exciter is properly tuned, this should occur with a plate-current reading of 6 to 7.5 milliamps.

9. Adjust the PLATE TUNE control for a dip on the plate-current meter. Adjust the PLATE CURRENT control for the brightest fluorescence from the plasma tube. Dip the meter again using the PLATE TUNE control. Repeat this sequence for optimum tuning.

10. Any GAIN setting may be used when operating the laser, but the plate-current meter should never be allowed to indicate over 10 milliamps.

11. If the plasma tube does not fluoresce during step 7, decrease the GAIN until the meter reads less than 7 milliamps and slowly rotate the PLATE TUNE control throughout its complete range. If fluorescing occurs, proceed as in step 9 for fine tuning and increase the GAIN until lasing action occurs.

12. If the plasma tube does not light during step 11, turn the PLATE CURRENT control CCW as far as possible and slowly turn the PLATE TUNE control through its complete range until the meter dips. Turn the PLATE CURRENT control a few degrees clockwise (CW) and dip the meter again with the PLATE TUNE control. Continue this process until the plasma tube lights, then fine-tune as in step 9. Increasing the GAIN should bring on lasing action. If not, the laser itself may be misaligned, or the mirrors may be dirty. This will be covered in the next section.

2. The Laser.

The laser itself is a conventional He-Ne, hemispherical-cavity gas laser with a mirror separation (variable) of 60 cm. The spherical mirror has a radius of curvature slightly in excess of 60 cm so that laser oscillations will not cease when the mirrors are adjusted to have maximum cavity dimensions. As a result, modes of order higher than the TEM_{00} mode can be easily excited, but should be eliminated for phase-locking purposes. This is easily accomplished by manipulation of the gain control on the exciter and of the mirror positioning controls on the ends of the laser.

The plane mirror is mounted on a stack of hollow piezoelectric crystals[1], and is adjustable axially by rotating a large brass positioning screw. About one inch of travel is allowed, with the 60 cm position near the center of the travel range.

The spherical mirror is mounted such that it may be tilted in two planes by manipulation of the three positioning screws on the spherical mirror mount.

The plasma tube is terminated by Brewster angle windows to reduce undesirable reflections and to induce linear polarization in the output beam. The enclosed gases are excited by RF coupling around the plasma tube.

If the plasma tube fluoresces brightly, but no lasing action is observed, there are three immediate possibilities to be investigated; mirror misalignment, dirty optics, and plasma tube aging.

An autocollimator is required to accurately align the plane mirror normal to the axis of the plasma tube. Aligning screws are located around the base of the piezoelectric crystal stack, and by bore-sighting down through the tube and using standard autocollimator techniques the plane mirror may easily be adjusted. This mirror, however, should not need adjusting unless the laser is completely disassembled in order to replace the plasma tube, etc.

Assuming the plane mirror is aligned normal to the plasma tube axis, the spherical mirror may be aligned by observing that the image of an axial object placed at the center of curvature of a concave spherical mirror will coincide with the object itself. Thus, to align the spherical mirror, the following procedure may be followed:

1. Cause the plasma tube to fluoresce very weakly by reducing the gain of the exciter and by detuning it slightly using the plate-tune control. It is desired that only one or two small sections of the plasma tube be lit. With such weak fluorescence, it will be impossible for the laser to lase.

2. Turn the brass driving screw such that the plane mirror is driven along the laser axis until a mirror separation of less than 60 cm is assured. Care must be taken that the mirror surface does not come in contact with the sharp edge of the Brewster window on the end of the plasma tube as damage will surely result.

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[1] PZT-5A, Clevite Corporation, Piezoelectric Division, Bedford, Ohio.

3. Peer down the length of the plasma tube by placing your eye at the spherical end of the cavity. Since the mirror is not 100 percent reflective, you will be able to look through the spherical mirror and see the plane mirror mounted on the piezoelectric crystal stack at the other end of the laser. Since the mirrors are peaked to reflect strongly near 0.63 microns, but nowhere else, and since a considerable amount of blue and ultraviolet light is emitted by the fluorescing gases, it is advisable to hold a red filter in front of your eye when performing this aligning sequence.

4. If the optical cavity of the laser is aligned, you will be able to observe a small bright spot of red light superimposed upon the plane mirror at the other end of the laser. It is not necessary that this spot of light be centered on the plane mirror. The system is adequately aligned if the spot can be observed at any position. The position of the spot can be varied by manipulating the three adjusting screws on the spherical end of the laser.

5. If the spot of light cannot be observed during steps 3 and 4, the spherical mirror is misaligned and must be realigned by manipulating the three mirror-tilt adjusting screws. There is no set procedure for achieving this, and it may be necessary to spend a considerable amount of time looking for the spot. While searching, periodically, check the amount of fluorescence from the tube and keep it very low so as to prevent accidental lasing into your eye. If the mirrors are badly misaligned, no movement at all will be observable at the plane mirror when peering down the length of the tube. Whenever any motion is observed, however, the laser is close to alignment and only fine adjustments should be made to all three screws until the spot appears. As stated previously, once the spot is visible the system is capable of lasing and the eye should be removed from the output of the laser, the exciter should be retuned and the gain increased until lasing action occurs.

If the plasma tube is fluorescing brightly, the mirrors are known to be aligned, and yet no lasing action occurs, it is possible that the mirrors or Brewster windows have a film of oil or smoke or dust on them. They can be cleaned only be removing the mirror mounts from the ends of the laser, and should be cleaned using only optical quality cotton and a solvent such as acetone. "Q-Tips" may be used if care is exercised not to apply excessive pressure on the mirror surfaces. The Brewster windows are not coated so they may be cleaned often and thoroughly without danger of damage, provided that the care usually given any optical component be given them. It is recommended that a soft optical quality camel's hair brush be used to remove any dust and lint before trying to clean the mirrors with the acetone-dampened cotton swab.

Whenever a mirror mount is removed from the laser, care should be taken that it be reinstalled without rotation, particularly the mirror mount holding the plane mirror and piezoelectric crystals. If this is rotated it may be necessary to realign the plane mirror normal to the laser axis using an autocollimator.

If the laser is known to be optically aligned and the optics are known to be clean, and yet the laser still will not lase when the tube is fluorescing brightly, then it may be suspected that the plasma tube has been subject to outgassing and aging. There is no convenient test to determine the amount of outgassing to which a plasma tube has been subjected, but the tube should be good for several hundred hours of operation before it is necessary to replace it. The most convenient indication of an exhausted plasma tube is to observe the color of its fluorescence in close proximity to another plasma tube which is known to be still useful. The good tube will exhibit a rich, slightly orange hue, while the exhausted tube will be a bright pink. It is noted that the lasing medium may be unfit to sustain lasing oscillations even though it might fluoresce very brightly.

3. The Photodetector-Mixer

Any square-law optical detector capable of responding to the 0.6328 micron laser beam may find use as the optical detector-mixer in the phase-lock loop of this system. Two detectors which have found acceptance in this respect are the RCA 7102 photo-multiplier tube and the Philco L4501 solid state photodetector diode. We prefer the photo-multiplier tube for this application.

Care must be taken that the proper negative bias voltage be applied to the detector and that the detector be so positioned in the output beam from the plane mirror end of the laser that the beam is not reflected from the detector surface back down the axis of the laser.

When using the 7102 multiplier phototube, the phase-lock loop will exhibit less noise if the voltage is maintained somewhere between 600 and 800 volts, although the phototube can be operated with higher values of bias voltage.

4. The Lock-Box

The lock-box for the first phase-locked laser system has neither a self-contained power supply nor an integral 5 MHz crystal oscillator. The lock-box for the second system has both. The second system will be discussed here with the understanding that an external 5 MHz stable signal and a 100 volt and ± 12 volt power supplies will have to be provided if the first lock-box is used.

Even though the second system contains its own 5 MHz crystal oscillator, an input jack is provided should it be desired to bring in an external 5 MHz signal. In this case the EXTERNAL-INTERNAL switch should be switched to EXTERNAL to circumvent the crystal oscillator built into the lock-box. Otherwise, leave the switch in the INTERNAL position.

Both boxes have ERROR-SIGNAL and 30 MHz output jacks. The latter is provided for monitoring purposes, the former for both monitoring purposes and for connection of the error signal to the piezoelectric crystals in the laser. When monitoring the system during operation it is recommended that both the error signal (by use of a coaxial "T") and the 30 MHz signal be displayed simultaneously on a dual-trace oscilloscope. It is necessary to display both signals as it is possible for the 30 MHz signal to go to zero, thus causing the error signal to go to zero also. If the error signal goes to zero but the 30 MHz signal does not, however, this is a positive indication of lock. Figure 1-1 is a photograph of the scope face when the system is not locked. Figure 1-2 shows the scope face under locked conditions.

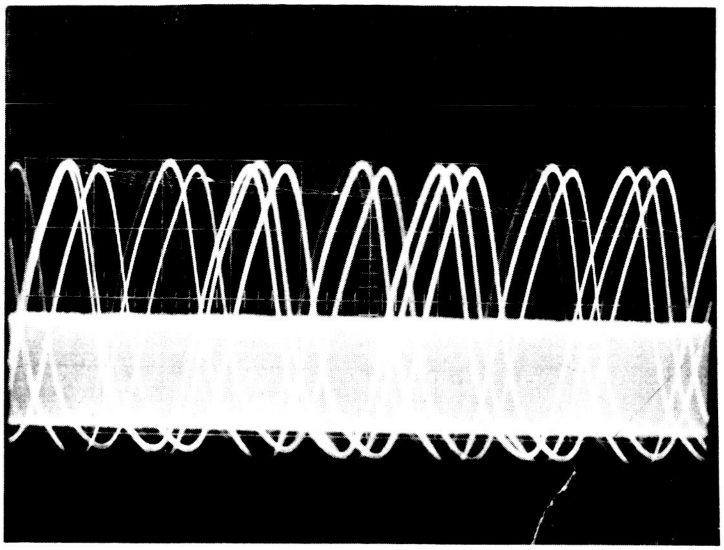
A PHASE DETECTOR gain control knob on the second system allows the gain of the phase detector module to be varied. It has been determined in practice, however, to leave this control at a very low setting, even in the extreme CCW position, at all times as noise amplification is prevalent when the phase detector gain is increased too much.

The lock-box for the second system also contains a PUSH-TO-TEST-LOCK momentary disconnect push button below the milliamp meter. When the system is locked the meter needle may be deflected away from the zero scale reading and may be observed to swing slowly about as the system maintains the lock. The needle will also move slightly when the system is near a locked condition and is searching for, or reaching for a lock. When it is suspected that a lock has been established, depressing the push button momentarily should cause the needle to swing back to some neutral position, which will not necessarily be scale zero. If the needle does not behave as just described, the system is not locked. This method of testing for lock is not as reliable or as informative as is the dual trace oscilloscope method.

The output of the laser photodetector should be connected to the 250 MHz input of the lock-box and the ERROR SIGNAL output of the lock-box to the piezoelectric crystals in the laser. This completes the phase-lock loop.

To activate the lock-box, plug the power cord into a conventional 60 Hz, 115 volt wall outlet and turn on the POWER switch. Observe that the pilot light comes on and that the meter deflects full scale only momentarily.

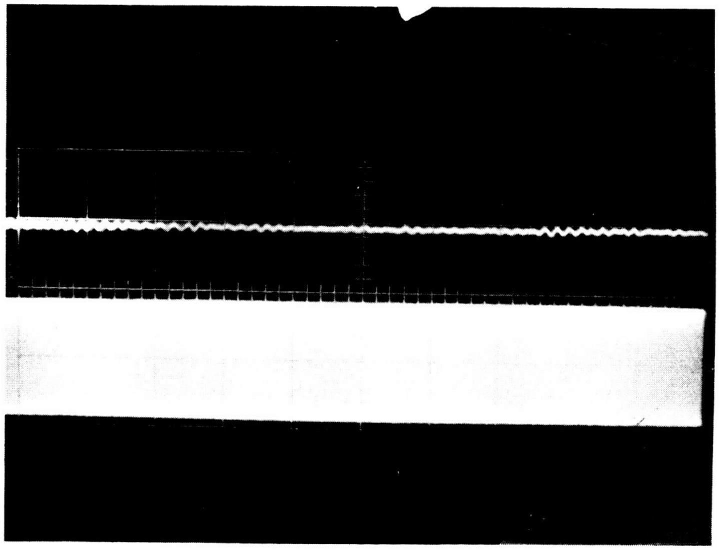
IA185



Error Signal
10 v/cm, 1 ms/cm

30 MHz beat signal
0.5 v/cm, 1 ms/cm

FIGURE 1- 1. OSCILLOSCOPE TRACES OF ERROR SIGNAL AND 30 MHz SIGNAL WHEN SYSTEM IS NOT LOCKED.



Error Signal
10 v/cm, 1 ms/cm

30 MHz Beat Signal
0.5 v/cm, 1 ms/cm

FIGURE 1-2. OSCILLOSCOPE TRACES OF ERROR SIGNAL AND 30 MHz SIGNAL WHEN SYSTEM IS LOCKED

Should the meter deflect full scale and refuse to return to a neutral position on the meter when the system is first turned on, rapidly flick the POWER switch off and on. The meter should return to a neutral reading after two or three seconds.

If the meter deflects full scale when the lock-box is first turned on and flicking the POWER switch will not return it to a neutral reading, open up the lock-box and check the voltages on the ± 12 volt power supply plug-in module. If these check out, the problem lies in the differential amplifiers within the phase detector module.

5. Operation of the Entire System

1. Plug the laser exciter, the photomultiplier power supply, and the lock-box into a conventional 60 Hz, 115 volt wall outlet. NOTE: All parts of the system requiring power should be plugged into a common power line, and this line should be well regulated. Power line fluctuations affect the system in a very adverse manner.

2. Connect the laser to the exciter output with coaxial cable. Similarly, connect the output of the photodetector to the 250 MHz input of the lock-box. Connect a coaxial "T" to the ERROR SIGNAL output of the lock-box, one arm of the "T" being connected to the piezoelectric crystals on the end of the laser, the other arm going to one trace of a dual trace oscilloscope. Connect the 30 MHz output of the lock-box to the other oscilloscope trace input.

3. Locate the photodetector such that it is in front of the plane mirror end of the laser (the end with the piezoelectric crystal stack), but place it temporarily in such a position that the laser beam will NOT strike the photosensitive surface of the detector. NOTE: When the laser is first turned on it may have a very strong output beam. If the system is all aligned and operating this sudden burst of energy can adversely affect the components in the lock-box.

4. Turn on the lock-box, the photodetector power supply, the laser exciter, and the dual-trace oscilloscope.

5. Observe the output beam from the opposite end of the laser and manipulate the exciter GAIN control and the spherical mirror tilting screws until a single clean spot is observed. The presence of a pattern in the output beam is an indication that higher order modes are being excited within the laser. Such modes are detrimental to the operation of the system. NOTE: If the plane mirror is positioned

along the laser axis such that the optical cavity length is considerably less than 60 cm, it will be rather difficult to suppress these higher order modes and achieve a single spot in the output beam. Therefore, once the laser is lasing, the plane mirror should be backed away from the end of the plasma tube, if necessary, such that a combination of plane mirror, spherical mirror, and exciter gain settings can be found which will result in a single output spot. A considerable reduction in exciter gain over that necessary to first fire the laser is usually required.

6. Position the photodetector in the laser beam such that the laser light reflected from the detector sensitive surface is not directed back along the laser axis. Such reflected light should always be prohibited from re-entering the laser when phase-locking is being attempted.

7. The coarse adjustment of the position of the plane mirror can now be performed. This may be done either with or without the error signal being applied to the crystals. In the latter case, the brass positioning screw is rotated until the error signal trace on the scope is observed to decrease in frequency and increase in amplitude to the point where any further rotation of the screw in a given direction tends to increase the frequency again. The error signal may then be applied to the crystals and the fine tuning procedure begun.

   To perform the coarse adjustment with the error signal applied to the crystals, rotate the brass adjusting screw until the error signal increases in amplitude then suddenly begins jumping about in an erratic fashion. This will be accompanied by much "sputtering, squeaking, and squealing" from the crystals. This is an indication that the system is approaching the lock position. In fact, if the other variables in the system are in agreement, the laser may pull itself into lock and remain there. NOTE: Due to harmonics, more than one position of the plane mirror can be found such that the system gives indications of attempting to lock. One indication is much stronger than the others, however, and this is the position to be used. NOTE: At all times when adjusting the plane mirror care must be taken that the mirror does not come in contact with the sharp Brewster window end of the plasma tube.

8. The system may now be fine-tuned. First, check the output beam and re-adjust the laser for a single spot output. Now decrease the exciter GAIN control until the 30 MHz signal disappears from the scope. This is an indication that the laser threshold has been raised to an excessively high level such that the cavity is not oscillating in at least two uniphase modes. Now increase the GAIN control on the exciter again until the 30 MHz signal reappears. The gain may be increased slightly above this setting if desired, but should be kept at a fairly low setting.

   It will probably be observed that the trace of the 30 MHz signal is rather noisy. It can be, and should be cleaned up by adjusting the voltage being applied to the photodetector. An optimum voltage can usually be found somewhere in the range from 600 to 800 volts.

9. By making small adjustments to the brass positioning screw on the laser it should be possible to now bring the system into a stable lock. It may be necessary to make further fine adjustments to the photodetector voltage supply, the PLATE TUNE and GAIN controls on the exciter, and the spherical mirror positioning screws if considerable difficulty is encountered in establishing a stable lock. A couple of hours of experience with the system is the best teacher at this point.

It will become obvious that the laser is extremely sensitive to any mechanical side thrust applied to the brass mirror positioning screw. In the final adjustment to obtain phase locking then, a very light touch is recommended.

It will also become obvious, upon experimentation, that the PHASE DETECTOR gain control on the lock-box must be kept at a very low setting. It is recommended that this control be turned down as far as possible and left there as the system becomes quite noisy with excessive phase detector gain. The inherent gain in the phase detector has been adjusted for optimum effect without adversely affecting the bandwidth of the system.

Figures I-1 and I-2 show, respectively, the oscilloscope traces when the system is unlocked and when it is locked. A further test for lock can be made by depressing the PUSH-TO-TEST-LOCK momentary disconnect push button below the meter on the lock-box. The phase-lock indications are discussed in detail in Section 4 of this appendix.

Be informed that the system cannot be expected to remain phase-locked over long periods of time until it has been in operation for at least three hours. Short term stability may still be good, but the crystal controlled oscillator will drift slowly for several hours, even days. Containing the crystal in a temperature controlling oven would improve the long term stability of the system.

This slow drift may be easily monitored by feeding the 30 MHz output from the lock-box into a frequency counter. The last digit, i.e., the 1-9 cycle figure, will be observed to change by not more than a few cycles when the system is locked, but will change by many cycles over an hour's time as the crystal warms up. Note, however, that the last figure on the counter is not significant anyway, and that it reflects the stability of the crystal, not of the laser.

The method which we have found most useful to check the frequency response of the system when locked is to make a frequency plot on the Rohde and Schwarz Audio Frequency Spectrograph. The 30 MHz monitor signal is mixed with a 30.010 MHz signal from a precision converter-oscillator. The difference frequency, 10 kHz, is then plotted using both 20 kHz and 4 kHz scale widths. The former provides a clear graph of the bandwidth and the noise levels outside and within the bandwidth. The latter shows the fine structure surrounding the 10 kHz spike. The 60 Hz sidebands can be shown to be lower than -45 db, with noise levels as low as -70 db.

An LFE STALO Stability Tester has also been quite useful in checking out the system.

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13. ABSTRACT

This is the final report on Contract No. NAS 5-3927, "Stabilized Gas Laser Oscillators". This contract involved the design, development, fabrication, evaluation, and delivery of two phase-locked, frequency-stabilized gas lasers.

The contract was awarded by the National Aeronautics and Space Administration, Goddard Space Flight Center, to the Electronics Research Laboratory, Syracuse University Research Corporation, Syracuse, New York.

The phase-locking scheme employed utilized the comparison of the frequency of a signal derived from a crystal oscillator to the frequency of the self-beat signal of the laser in order to generate an error signal which would minimize the difference frequency. The first system was delivered on 2 April 1965, the second system on 21 June 1966.

It is concluded that these two laboratory prototypes have proven the feasibility and practicality of the phase-locking scheme employed.

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Stabilized Laser						

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13. ABSTRACT: Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as *(TS)*, *(S)*, *(C)*, *or (U)*.

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