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Technical Note

235

A PORTABLE RUBIDIUM-VAPOR FREQUENCY STANDARD

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U. S. DEPARTMENT OF COMMERCE
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Characteristics of Rubidium-Vapor Frequency Standard

Output Frequencies	5,000,000.000 and 100,000.000 Hz
Approximate Frequency Displacement from Nominal	Standard #1 -- +3.5 parts in 10^9 Standard #2 -- -1 part in 10^9 Standard #3 -- 0
Frequency Variation	Less than 1 in 10^{10} for periods over 1 sec.
Operating Ambient Temperature	15 to 35° C
Power Requirement	105V to 130V 50-60 Hz
Operating Time on Internal Battery	Approximately 5 to 15 hours depending on ambient temperature.
Battery Recharging Time	Approximately 24 hours.
Weight	Electronics 39 lbs. (18 kg) Power Supply 57 lbs. (26 kg)

A Portable Rubidium-Vapor Frequency Standard*

Robert J. Carpenter

Three portable optically-pumped rubidium-vapor frequency standards have been constructed. Output frequencies of 5 MHz and 100 kHz with a stability of better than $1:10^{10}$ have been realized. The weight without power supply is 18 kg and the power required, exclusive of temperature control, is about 11 watts. The power supply, which also contains batteries for up to 15 hours operation, weighs 26 kg. Sufficient detail is presented to allow the construction of similar units.

1. Introduction

Frequency stable energy level transitions have been observed in a number of materials.¹ The potential frequency stability available from the use of such transitions is such as to encourage substantial developmental effort toward frequency standards based on energy level transitions. The first type to be announced was an ammonia-vapor maser at about 24 GHz.

More recently cesium and thallium have been used in a Ramsey atomic beam apparatus. The national standard of frequency is established by such a cesium beam device at the NBS Boulder Laboratories.² Very recently work has been directed toward the development of an atomic hydrogen maser at 1420 MHz.

* This work was partially supported by the National Aeronautics and Space Administration.

¹ Reports on other work in the field of frequency standards may be found in the Proceedings of the Signal Corps Frequency Control Symposia for the years 1957 to date. See also IRE Trans. on Inst., Vol. I-11, No. 2 and 4, Dec. 62.

² Mockler, Beehler and Snider, "Atomic Beam Frequency Standards", IRE Trans. on Inst., Vol. I-9, No. 2, pp 120-131, Sept. 1960.

A suitable transition exists in optically-pumped cesium and rubidium vapor. A frequency standard based on this effect has certain advantages over the beam-type since no material is consumed in operation (resulting in longer life) and the frequency stability is not related to the mechanical length of the reaction area. Unfortunately the frequency of a practical device is influenced by the type and pressure of buffer gas, so that the optically-pumped standards are not suitable for use as primary standards.

In 1959 the National Bureau of Standards undertook the construction of three rubidium-vapor frequency standards for use in a proposed earth satellite experiment to investigate the gravitational "red shift". The nature of the experiment established certain special requirements on the standards to be built. Prime emphasis was placed on low power consumption and good long term stability, with less emphasis on small size and short term stability. The original intention was that temperature control of the environment to 45°C would be furnished by the user and would not be charged as a power requirement of the frequency standard. After a considerable effort had been expended on this project, a laboratory experiment by the Mössbauer effect established the "red shift" to approximately the same accuracy as was to be obtained by the frequency-standard-satellite experiment. Plans for the satellite experiment were deferred, but work was continued to complete the standards in a portable form so that they could be used to compare time in various locations, calibrate radio-path delays, etc.

The operation of these frequency standards, in common with that of most "atomic" frequency standards, is based on the correction of the frequency of oscillation of a quartz-crystal oscillator to a submultiple of an atomic energy level transition frequency. In the present case the transition is in optically-pumped rubidium vapor and occurs at about 6,834,683,405 Hz. The atomic transition in question can be detected by a process in which the normal population of the various energy levels is modified by the application of pumping radiation at an appropriate optical frequency. If, at the same time, radio-frequency energy at the frequency corresponding to the desired transition is applied, the amount of pumping radiation which is scattered will be increased. The scattering of the pumping radiation can either be observed directly, or as a reduction in the intensity of the radiation passing directly through the vapor cell as illustrated in Figure 1. A servo system must be provided to control the frequency of the radio-frequency energy to exactly that of the rubidium-vapor transition.

2. General Description of the System

The frequency standards may be thought of as consisting of four major sections (Figure 2):

1. The optical-microwave section in which the transition is detected;
2. The oscillator-servo system in which the microwave frequency is generated and locked to the transition;
3. The frequency translator in which the 4,996,113.6-Hz submultiple of the transition frequency is translated to 5,000,000 Hz;
4. The power supply.

2.1 Optical-Microwave Section, Figure 3

Light of the pumping wavelength is generated by an electrodeless discharge lamp excited by a vacuum-tube oscillator. The lamp contains natural rubidium and krypton at a pressure of a few torr. The spectral characteristics of the light from the discharge lamp are modified by a filter cell placed in the optical path. The filter cell contains rubidium-85 and 30 to 50 torr of argon or neon. The entire lamp and filter cell assembly was built for the National Bureau of Standards by Varian Associates. The spectral characteristic of the pumping light is further modified by an interference filter which passes the D-2 rubidium line at 7800 Å but not the D-1 line at 7947 Å. The interference filter is used because the shift in frequency with light intensity for these standards was found to be less for the D-2 than for the D-1 line.

The rubidium vapor in which the transition is to be observed is located in a TE 0 1 1 cylindrical microwave cavity which is resonant at 6.83 GHz. Due to the mode of resonance in the cavity, large openings are possible in the end faces and are used to admit the pumping light and pass the transmitted light on to the photodiode. The rubidium vapor at a pressure of about 10^{-6} torr and a buffer gas mixture at a total pressure of about 39.6 torr are contained in a quartz cell. The mixture is approximately 49.1% nitrogen and 50.9% methane, which gives maximum frequency at about 45°C. The frequency falls off quadratically above and below this point with a 2×10^{-11} deviation at $\pm 2^\circ\text{C}$ from the peak frequency temperature. After passing through the gas cell, light is focused on a silicon photo-voltaic cell by a Fresnel lens.

2.2 Oscillator-Servo System

The microwave frequency used to probe for the transition in the rubidium vapor is generated by a quartz-crystal-controlled oscillator operating at 4,996,113.6 Hz and followed by a frequency-multiplier chain. In order to sweep across the microwave frequency which results in the maximum light attenuation in the rubidium vapor, the radio frequency is sinusoidally phase modulated at about 25 Hz to a peak deviation of about 100 Hz (at 6.8 GHz). Since the speed of response of the frequency

correction loop is rather limited, the short term stability of the output frequency of the frequency standard is determined by the crystal oscillator. Since the crystal oscillator is called upon to provide excellent short term stability, while its long term drift may be reduced by the correction based on the rubidium vapor transition, the crystal drive level of the oscillator is somewhat higher than is ordinarily encountered in high stability oscillators. The oscillators used in these standards were obtained from Sulzer Laboratories³ and the Bell Telephone Laboratories.⁴ They are fitted with voltage-controlled capacitors to permit variation of the oscillation frequency on the command of the frequency-correction servo system.

The output of the crystal oscillator is fed to both the frequency multiplier and the frequency translator. In the frequency-multiplier section the first tuned circuit is shunted by a voltage variable capacitor used to apply phase modulation to the signal. Incidental phase and amplitude modulation of the radio frequency due to short term instability of the crystal oscillator and imperfections in the multiplier chain produce non-harmonically related microwave frequencies in addition to the desired harmonic. Since such modulations distribute the available microwave power among a number of frequencies variously removed from the desired harmonic, they tend to reduce the amplitude of the observed transition, broaden it, and create spurious locking points where there is sufficient mistuning for a distant modulation sideband to lie at the transition frequency.

In the development of this standard, the frequency-multiplier stages originally employed varactors in three cascaded stages (X3, X2, X2) to multiply 5 MHz to 60 MHz (nominal). While the varactor multipliers could be made to operate and did not seriously widen the spectrum of the microwave energy, adjustment was very difficult. One had to be very careful to avoid a situation in which output would not resume if the input was momentarily interrupted. These difficulties, plus a problem in reproducing results from one unit to the next, led to a search for a more stable solution even if potentially less efficient. Though conventional diode multipliers are less efficient than the varactor type and might therefore be expected to be more noisy, they were investigated. The diode multiplier stages used two diodes connected so as to discriminate against odd order harmonics in the doubler stages and against even order harmonics in the tripler stage. Each multiplier was followed by a grounded-base transistor amplifier with a gain of greater than one for the complete stage. The performance of the chain of these multipliers (5 to 60 MHz) proved to be fully satisfactory. The only serious problem

³For further information contact Sulzer Laboratories, Inc., 621 Lofstrand Lane, Rockville, Maryland.

⁴W. L. Smith, "Miniature Transistorized Crystal-Controlled Precision Oscillators", IRE Trans. on Inst., Vol. I-9, No. 2, pp 141-148, Sept. 60.

encountered was in the amplitude control feedback system. Initially, reverse bias was used to reduce the gain of the input amplifier, but this resulted in the accentuation of the amplitude modulation unavoidably present on the 4.996 MHz input signal from the crystal oscillator. Under conditions of large input signal and high reverse bias the non-linearity of the gain-controlled stage generated extremely strong spurious sidebands. A change to forward bias gain control resulted in satisfactory performance. Amplification to a power level of about 30 mW follows the multiplication to 60 MHz. Multiplication from 60 MHz to 6.8 GHz takes place in a single varactor diode mounted on the gas-cell cavity located in the microwave-optical section of the standard. Even though the efficiency of multiplication by 114 in the varactor diode is extremely low, enough microwave energy is obtained to adequately observe the atomic transition.

Since the microwave energy applied to the rubidium vapor is slightly phase (frequency) modulated at a low rate, the intensity of the light after passing through the vapor also varies slightly in a related manner. If only the fundamental-modulation-frequency component of the variation in light intensity is observed, it will have essentially zero amplitude when the microwave frequency exactly corresponds to the atomic-transition frequency. A frequency error of one sense will cause light variations in phase with the applied modulation while an error in the other sense will cause light variations of the opposite phase. It is very important that the phase (frequency) modulation be sinusoidal. Any second-harmonic content in the modulation will result in spurious generation of substantial fundamental-modulation-frequency energy even when the microwave signal is centered on the peak of the atomic transition. This spurious signal will cause the servo system to balance at the point at which the error signal in one sense just equals the spurious signal in the opposite sense. The frequency-correction system which controls the crystal oscillator contains a synchronous-detection system to recover the sense of the error from the phase of the error signal. The correction signal, a direct voltage, acts to change the frequency of the crystal oscillator. The correction system is of the type in which an error must exist for a correction signal to be generated. For this reason variations in the crystal-oscillator frequency are reduced, not eliminated. The amplification of the correction system is high enough so that this type of system is acceptable.

2.3 Frequency Translator

The frequency-translator portion of the frequency standard, Figure 4, is a product of Sulzer Laboratories. In the translator a signal at 3886.4 Hz is derived from the 4,996,113.6-Hz output of the quartz-crystal oscillator. These two frequencies are added to give the desired 5,000,000-Hz output. An additional output of 100,000 Hz is available from a separate 5-MHz to 100-kHz divider.

2.4 Power Supply

The power supply for the rubidium-vapor frequency standard is a portable unit with batteries to run the standard for approximately 5 to 15 hours depending on the ambient temperature. The supply incorporates provisions for charging the batteries and operating the unit from the 117V a-c line. When operating from alternating current, the supply "floats" the batteries to maintain them near full charge. The circuit is designed so that the changeover to battery operation is automatic should the power line fail. Therefore the unit serves as an emergency power supply as well as a unit for portable operation of the standard.

The unit supplies +150V at 25 mA, regulated by a duty-cycle variation system, for the tubes in the lamp of the standard, as well as 6.3V a-c for the filaments. The transistor modules and the heater in the standard are supplied regulated direct current at +13V and -13V.

3. PLACING THE STANDARD IN OPERATION

The standard should be placed into operation in the following manner. Power is applied by connecting the two units (power supply and electronic) with the connecting cable provided and supplying 117V a-c to the power supply unit. After the thermometer on the end of the electronic unit has stabilized at about 40°C to 45°C for approximately a half hour, an effort should be made to lock the quartz oscillator to the atomic transition. With the modulation and RF level controls set to produce full RF level and half-full modulation, the 4,996,113.6-Hz frequency being fed from the multiplier to the translator sections should be measured with a digital frequency meter. Adjustment of the Volt. Adj. control on the Phase Detector section of the electronics should allow this frequency to be adjusted through the desired value. If not, insert a variable-voltage source in series with the correction voltage to the quartz oscillator. Now observe the Lissajous pattern made by the reference and error signals when the radio frequency is varied slightly by means of the above mentioned Volt. Adj. Control, or external voltage source. When the frequency is adjusted closely enough to the center of the atomic transition there will be a 1:1 pattern. The modulation should be maximized by tuning the filter on the 25-Hz Oscillator-Reference unit and the error signal should be brought into 0 or 180° phase relation to it by varying the tuning of the filter on the Tuned Amplifier unit. At this point the RF level and modulation may be reduced slightly by means of the controls on the Multiplier until a mistuning of the 4.966-MHz oscillator by a 90° rotation of the Fine Volt. Adj. control on the Phase Detector module results in a maximum error signal. Do not reduce the RF level too far; low supply voltages that may be present when operating from the batteries may result in insufficient RF energy. At this point the correction system should be operating as evidenced by the reduction of error signal to nearly zero shortly after each intentional small mistuning. The Volt. Adj. should be slowly changed, all the while keeping the system locked, to cause a

zero dc error signal from the phase detector. The 4,996,113.6-Hz oscillator is now locked to the atomic transition.

4. Details of Circuits

To the extent possible, the same circuit designs have been used in more than one place in the servo system. For example, essentially the same circuit is used as the modulation-frequency oscillator and in two filters. The same squaring-circuit design is used in both the error signal and the reference signal channels. Silicon transistors have been used extensively in the audio-frequency portion of the servo system.

4.1 Oscillator-Reference, Figure 5

A frequency of about 25 Hz is generated by the RC tuned oscillator using Q101 and Q102. The tuned network consists of the two 4.7- μ F capacitors and the 22k and 100-ohm resistors in the emitter circuitry. The waveform distortion of this oscillator is more than can be tolerated, so a regenerative RC tuned filter follows the oscillator. Except for the fact that less feedback is used, that there is no clipping, and that the frequency is variable, this circuit is identical to the oscillator. The filter supplies a modulation signal to the phase modulator in the Frequency Multiplier section of the system. In addition a reference signal is supplied to a coaxial connector on the exterior of the case to permit the observation of Lissajous patterns by comparison with the filtered error signal (from the error channel Tuned Amplifier). Since the Phase Detector section of the standard operates on rectangular waves, the sinusoidal signal from the filter is "squared" in the two 1N137 diodes between the last two transistors Q105 and Q106 of this unit.

4.2 Preamplifier, Figure 6

The error signal from the photocell in the Microwave-Optical section is at a very low level. This signal is amplified in two stages in the Preamplifier. The first stage Q401 uses a low-noise silicon transistor, type 2N2175. In order to reduce the noise output of the photocell, a DC bias current is applied to the photocell. The 100k potentiometer is adjusted until the voltage at the terminals of the photocell (measured with a VTVM at the cell voltage test point) is within 5 millivolts of ground.

4.3 Tuned Amplifier, Figure 7

The signal from the Preamplifier is delivered to the Tuned Amplifier section of the servo system. It is further amplified by the first stage using Q201. The next two transistors Q202 and Q203 form an RC tuned regenerative filter similar to that used in the Oscillator-Reference Section. This filter is tuned to the fundamental-frequency component of the error signal from the Optical-Microwave assembly by adjustment of the 100-ohm variable resistor connected to the emitter of Q202. The

sine-wave output of this filter is supplied to a panel connector and is used in a 1:1 Lissajous figure comparison with the Reference signal to permit visual observation of the performance of the servo system, particularly when the system is being put into operation. The sine-wave is also supplied to the next stage Q204, which is a simple amplifier. This stage drives a double-diode clipper using type 1N137 silicon diodes. The approximately rectangular wave signal from the clipper drives Q205, the output amplifier from this unit. The output signal from this unit forms one input to the Phase Detector unit.

4.4 Phase Detector, Figure 8

The Phase Detector unit of the servo system produces the correction voltage to be applied to the 4,996,113.6-MHz oscillator on the basis of the relative phases of the error signal (from the Tuned Amplifier) and the reference signal (from the Oscillator-Reference). The error signal is further clipped by the 1N137 silicon diodes at the Signal Input of the Phase Detector unit. This signal is then passed through Q301 which amplifies the signal. A phase-inverted replica of the output of Q301 is produced by Q302. Thus the outputs of Q301 and Q302 form a push-pull error signal. The output of the Oscillator-Reference unit drives Q303, an emitter follower.

The phase-detector proper is formed by Q304 and Q305. The collectors of both of these transistors are driven by the reference rectangular wave through Q303. This rectangular wave has limits of about ± 12 V. The error rectangular wave (from Q301 and Q302) is fed in push-pull to the bases of the phase-detector transistors. The phase-detector transistors conduct fully when the error-signal input is negative; thus if the reference is negative at this time (in phase with the error signal) the phase detector will produce a negative output. When the error and reference signals are opposite in phase the phase-detector output will be positive.

The output of Q304 and Q305, in the form of positive or negative pulses is then passed through a long time constant RC filter. Due to the demands of size and weight, a tantalum electrolytic capacitor had to be used. Unfortunately a polarizing potential, provided by a 4-V mercury battery, is needed for the capacitor. A further potential must be subtracted from the voltage across the electrolytic capacitor before it can be applied to the crystal oscillator as the frequency-correction signal. This further potential, also from a 4-V mercury battery, is made adjustable by a multiturn 1-megohm resistor with fine adjustment by a 10k ohm resistor. In practice the 10k ohm resistor is set at mid-scale and is used primarily to produce small frequency offsets when adjusting for optimum system operation. The setting of the 1-megohm resistor is made so that the battery-induced potential maintains the oscillator at the proper average frequency and the correction signal from the phase detector is only needed for small errors. An external meter indicates the output of the phase-detector transistors so that the

1-megohm resistor may be adjusted for an average zero output from the phase detector.

4.5 Frequency Multiplier, Figure 9

The frequency-multiplier unit takes the 4,996,113.6-MHz output of the crystal oscillator, phase-modulates it, and multiplies the frequency to approximately 60 MHz. At the input of this unit the 4.996-MHz signal is amplified to Q502. This transistor amplifier is gain-controlled to hold the 60-MHz output signal at a constant amplitude. "Forward" AGC is used.⁵ The tuned circuit in the collector of Q502 is shunted by a voltage-variable capacitor which produces phase modulation at the reference frequency due to a signal from the Oscillator-Reference unit. Frequency multiplication takes place in three stages of diode multipliers, each followed by a grounded-base transistor amplifier. The first multiplier is a tripler. The output of this stage at 15 MHz is amplified by Q504. The next multiplier is a doubler, followed by an amplifier Q505 at 30 MHz. The final multiplier, also a doubler drives the 60-MHz output amplifier Q506. The output amplifier is matched to the load exhibited by the varactor multiplier in the Optical-Microwave section by a very small capacitor in series with the output coaxial transmission line. The value of this capacitor must be determined for each unit. The RF potential on the output tank circuit is measured by a diode detector with a back-bias to control the level at which detector output begins. Output level is varied by adjusting the detector bias. The detector output is filtered to DC and applied to the two-stage amplifier Q501, Q503, and controls the bias and therefore the gain of Q502, the 4.996-MHz input stage.

An isolating amplifier, Q507, provides a 4.996-MHz output signal to drive the Frequency Translator section of the frequency standard. In one of the units this stage is contained in a separate box.

4.6 Power Supply, Figure 10

The +13V and -13V are supplied by identical independent supplies. The Stancor RT202 power transformer is used both in a full wave bridge-rectifier circuit to supply -34V, and in a full wave center-tapped circuit to provide -17V. The -34V is used to supply base bias to the 2N174 (Q801) series-regulating transistor and with the 25-ohm, 25-watt resistor to provide a current source for charging the battery. The -17 volts supplies the collector of the 2N174. With the charging switch in the normal operating position, the output voltage is approximately equal to the battery voltage which is kept from exceeding 14V by the 14V, 10-watt zener diode. In the charging position "C", the zener diode sets the output voltage at about -14V and the battery voltage is allowed to reach a

⁵John C. Sinclair, "Forward or Reverse Transistor AGC?", Electronic Design, Vol. 11, No. 22, pp. 64-69; Oct. 25, 1963

maximum of about 15.3V due to the forward drop in the 1N3208 silicon diodes. The battery voltage will approach this value when fully charged. The charging rate is 0.8A and the charging time is about 24 hours.

The +150V and 6.3V are obtained from a 2kHz transistor oscillator supply (Q803, Q804) operating from the +13V and -13V d-c supplies. The output of the oscillator is controlled by a feedback circuit which varies the low voltage direct current supplied to the oscillator. The oscillator output is stepped down by the Merit A2814 transformer with a 1000-ohm wire-wound variable resistor in the primary to control the output level. The high voltage from the Triad TX89 transformer is rectified by the full wave bridge and filtered to provide +150V d-c.

The +150V feedback regulating circuit consists of a blocking oscillator (Q807) which produces positive pulses which turn on Q808. This discharges the 1μf capacitor between the collector and ground. The capacitor then begins to charge toward the supply voltage until it is again discharged by the next pulse. The result is a sawtooth. The 1N100 diode is forward biased until the voltage becomes more positive than that on the anode of the diode which is obtained from a voltage divider across the +150V. This produces a sawtooth which is clipped at the top. The level of this clipping ultimately determines the voltage applied to the oscillator transistors (Q803, Q804). The clipped sawtooth is amplified and applied to a Schmitt trigger (Q811, Q812) which produces pulses with a duty cycle that is dependent on the clipping level. These pulses are amplified by Q813 and Q814 and then used to switch Q815. When Q815 is on, its collector is at +13V. When it is off, its collector is at -13V and current is supplied through the 1N2071 diode. The collector output is then filtered and the resulting direct current supplied to the oscillator transistors (Q803, Q804).

Transistors Q805 and Q806 control the heater in the standard. The mercury thermostat in the standard opens for heat and closes for cooling.

4.7 Lamp - Microwave Assembly

The lamp, its exciting oscillator, a gas filter cell, and their package were made for this standard by Varian Associates. The circuit diagram of the exciting oscillator is reproduced as figure 11.

In order to verify that the lamp is operating, one may measure the output of the Hoffman-type 110C photovoltaic cell. If the connection between this cell and the Preamplifier is disconnected, the cell voltage is a measure of the lamp output as attenuated by the filter cell and microwave-cavity gas cell. When the system is at normal operating temperature the cell voltage is 50 to 100 mV as measured by a VTVM. A larger voltage is present before the system reaches operating temperature.

The microwave cavity is magnetically shielded to reduce the effect

of external shields. An internal solenoid adds a fixed field of about one microtesla to swamp out the small remaining external fields.

4.8 Other

The circuit diagrams of the Sulzer 4.9961136 MHz oscillator and the 5 MHz to 100 kHz frequency divider are included as figures 12 and 13.

Acknowledgement

This report reflects the work of a number of persons at the National Bureau of Standards. Major contributions were made by the following:

Earl C. Beaty
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Sachio Saito
Robert O. Stone
Kenneth W. Yee

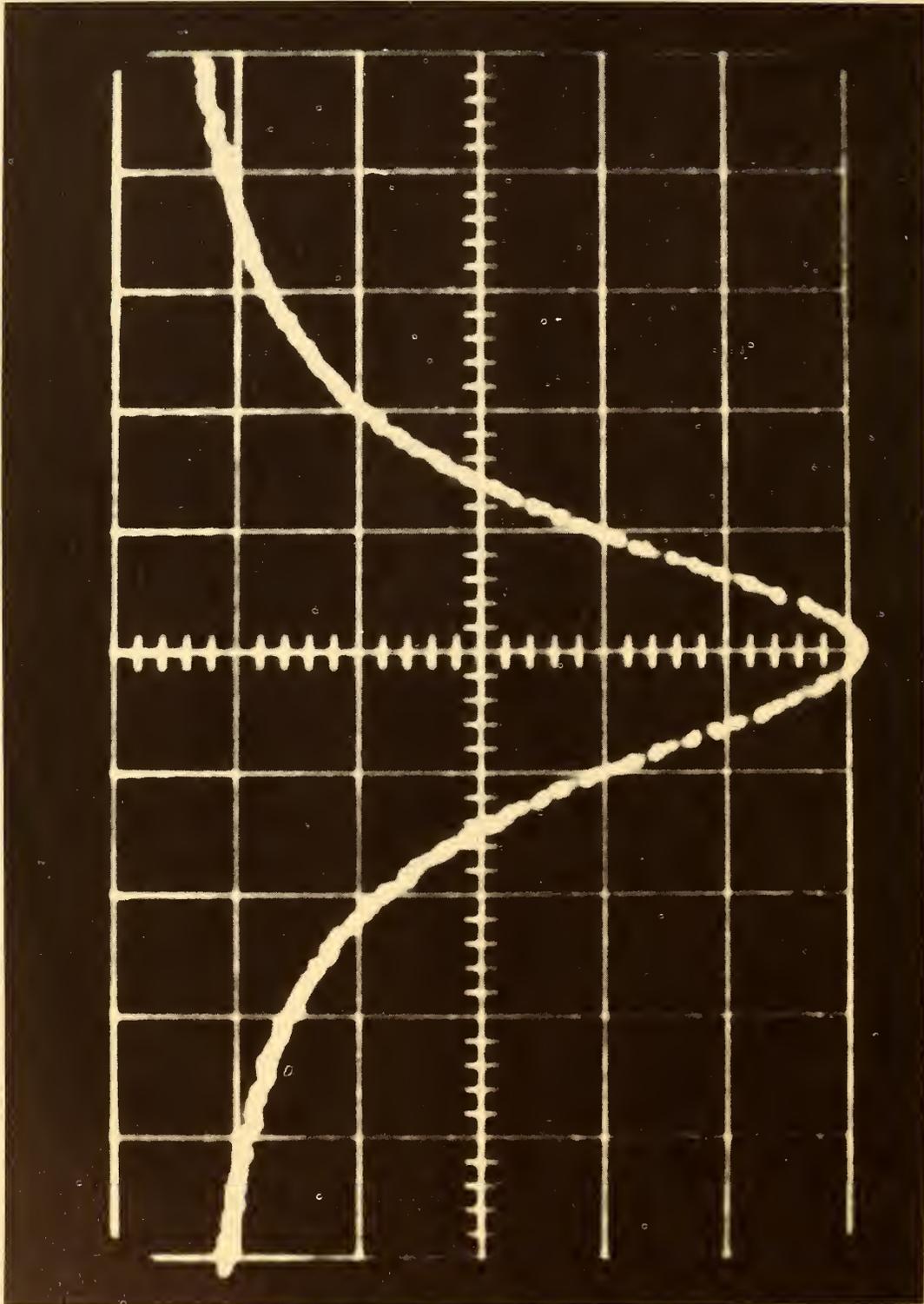


Figure 1

The rubidium-vapor transition line. The larger abscissa divisions are three parts in 10^9 .

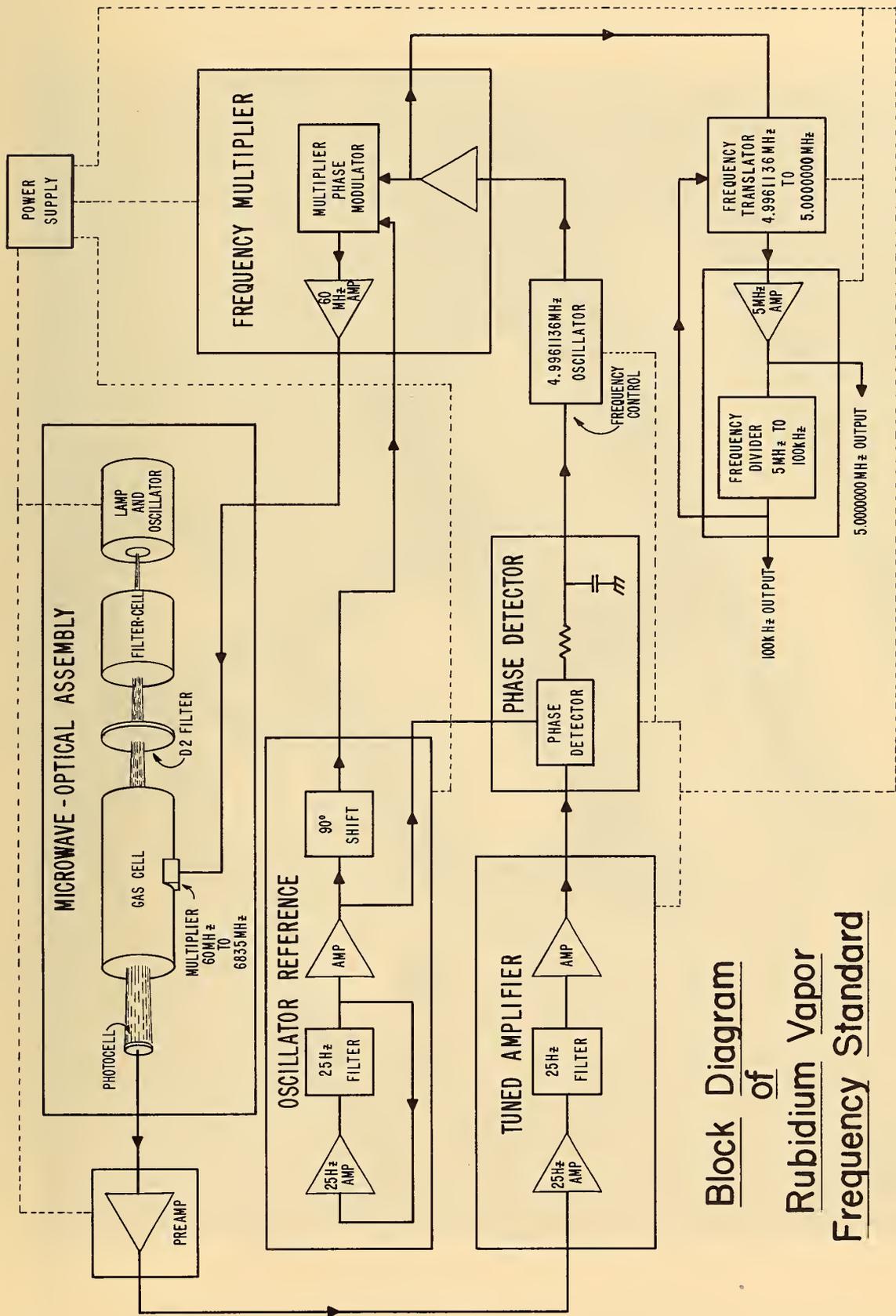


Figure 2 Block Diagram of System

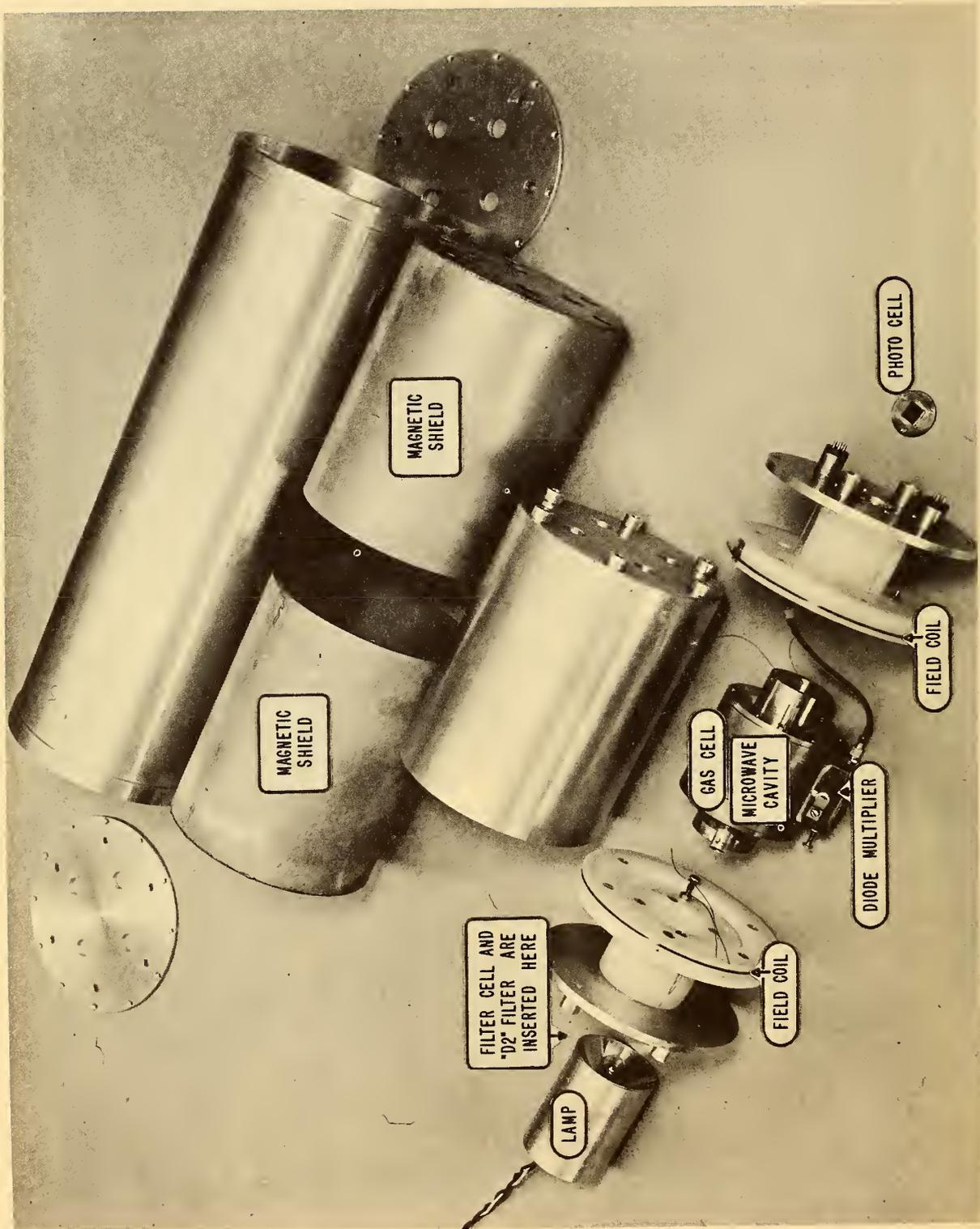


Figure 3

Photo of Optical Microwave Section

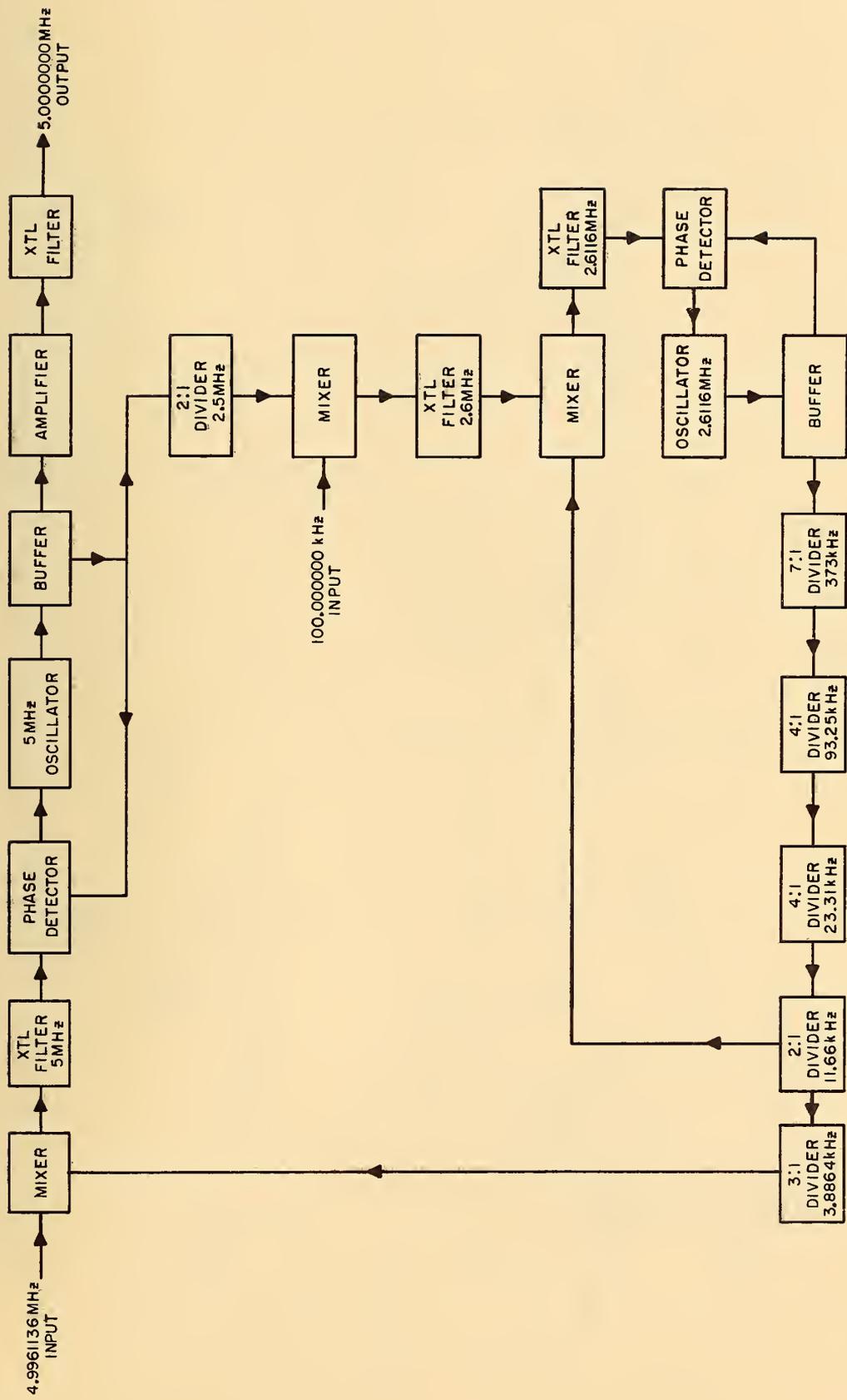
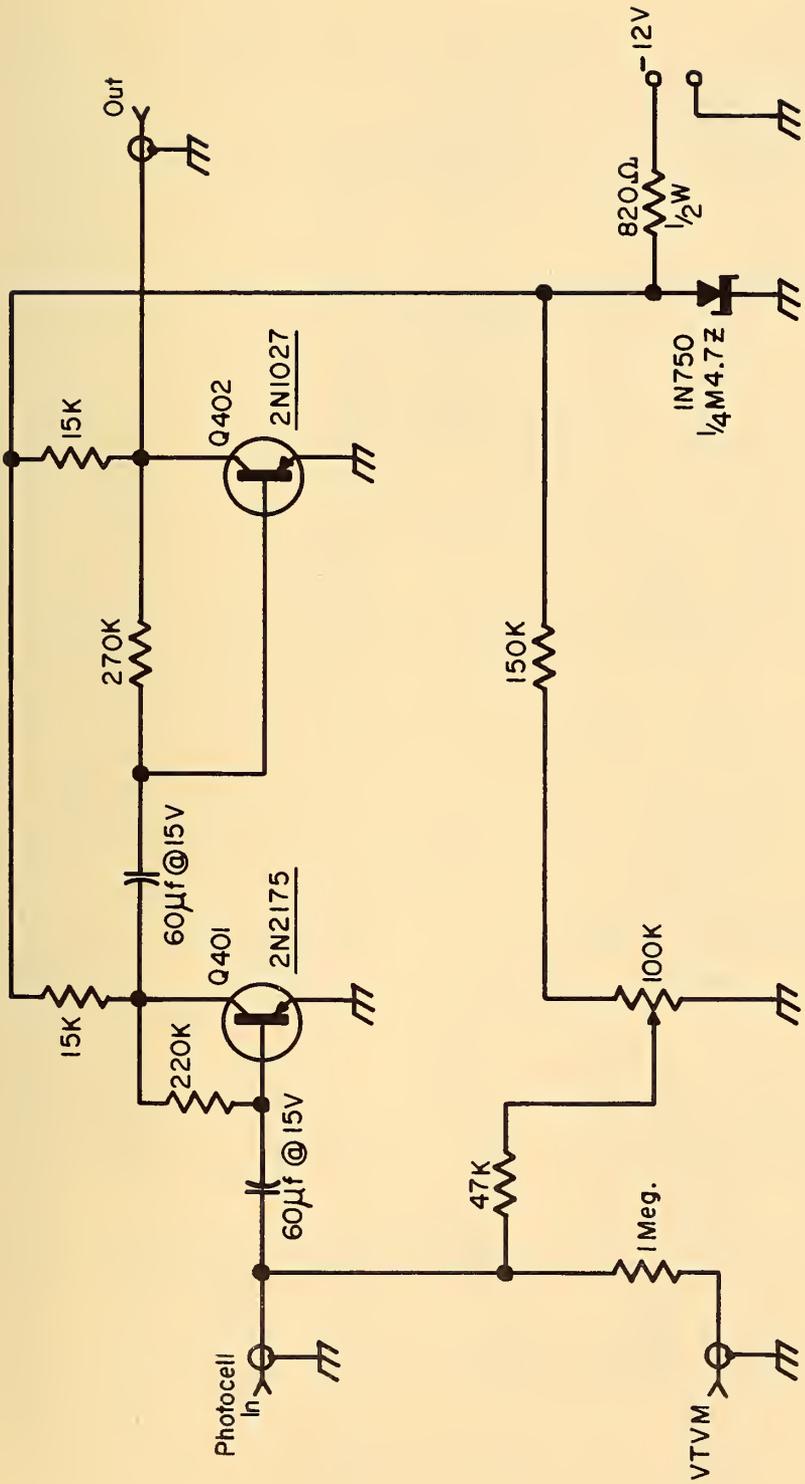


Figure 4 Translator Block Diagram

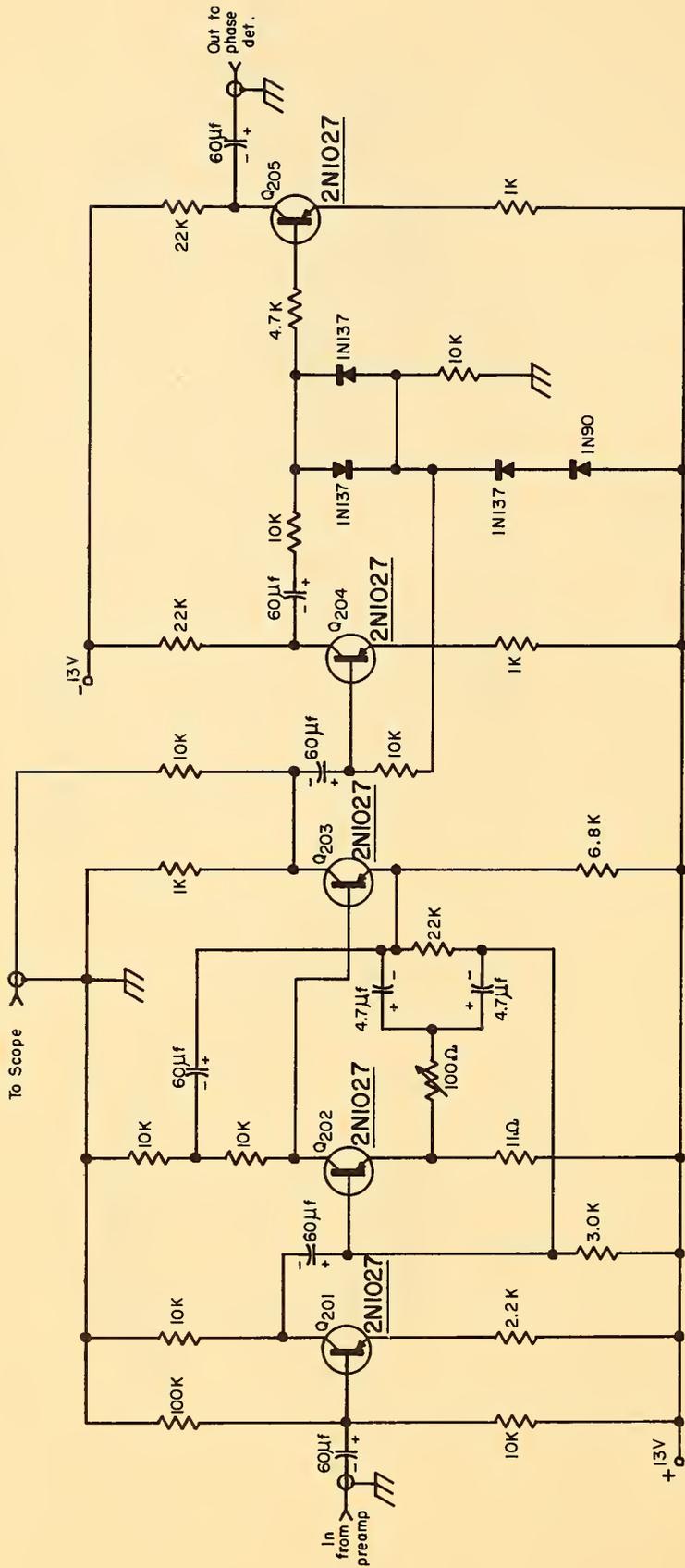


Note:
Resistors 1/4 watt unless
otherwise noted.

PRE - AMP

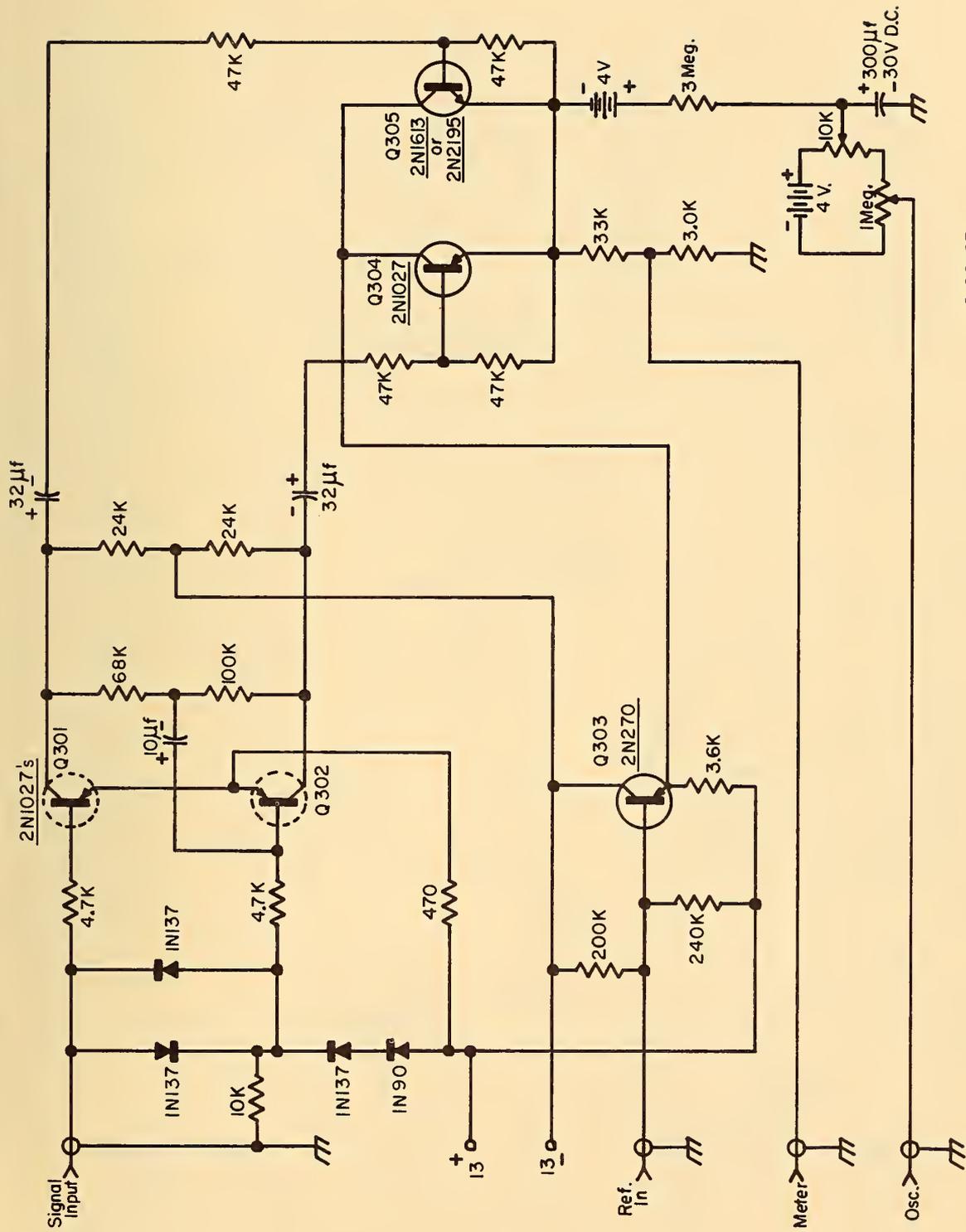
7-19-62

Figure 6 Circuit of Preamplifier



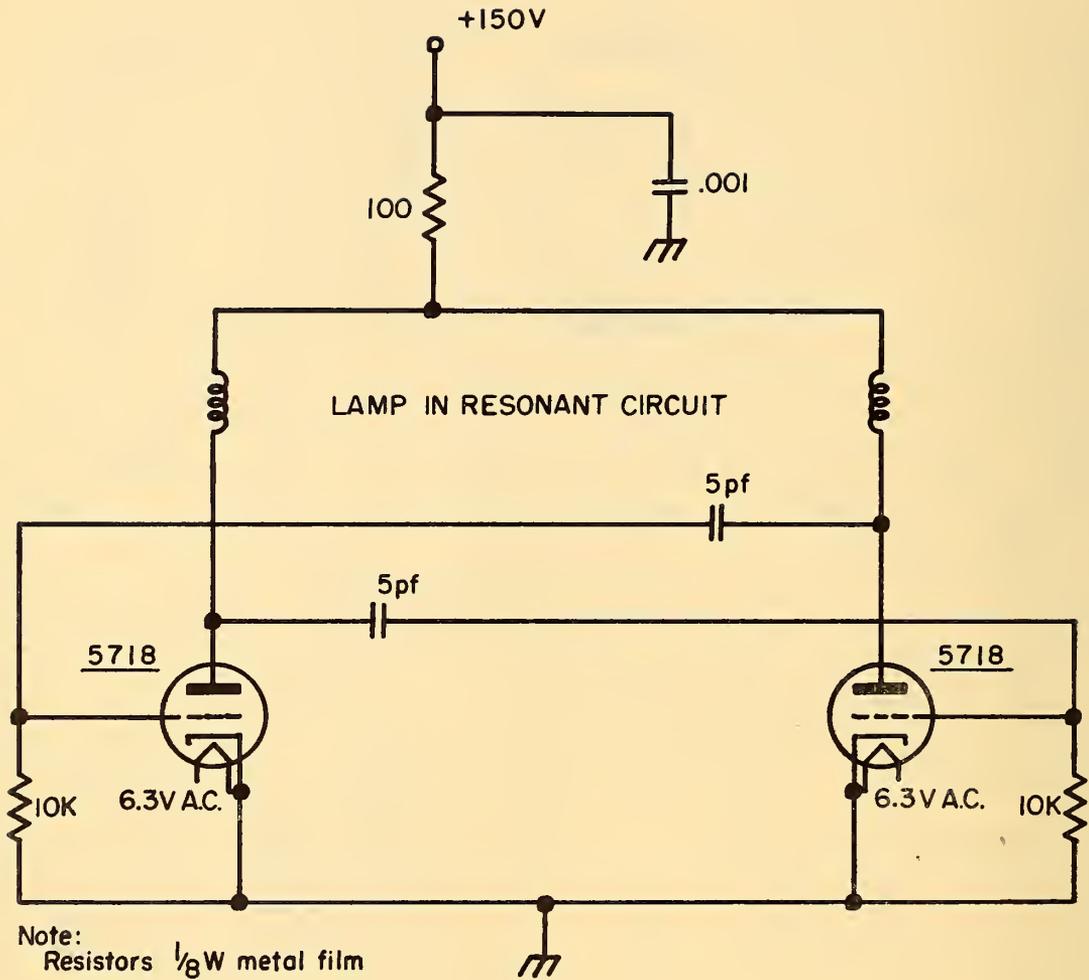
Note:
All resistors $\frac{1}{4}$ W, 5%

Figure 7 Circuit of Tuned Amplifier



6-20-63

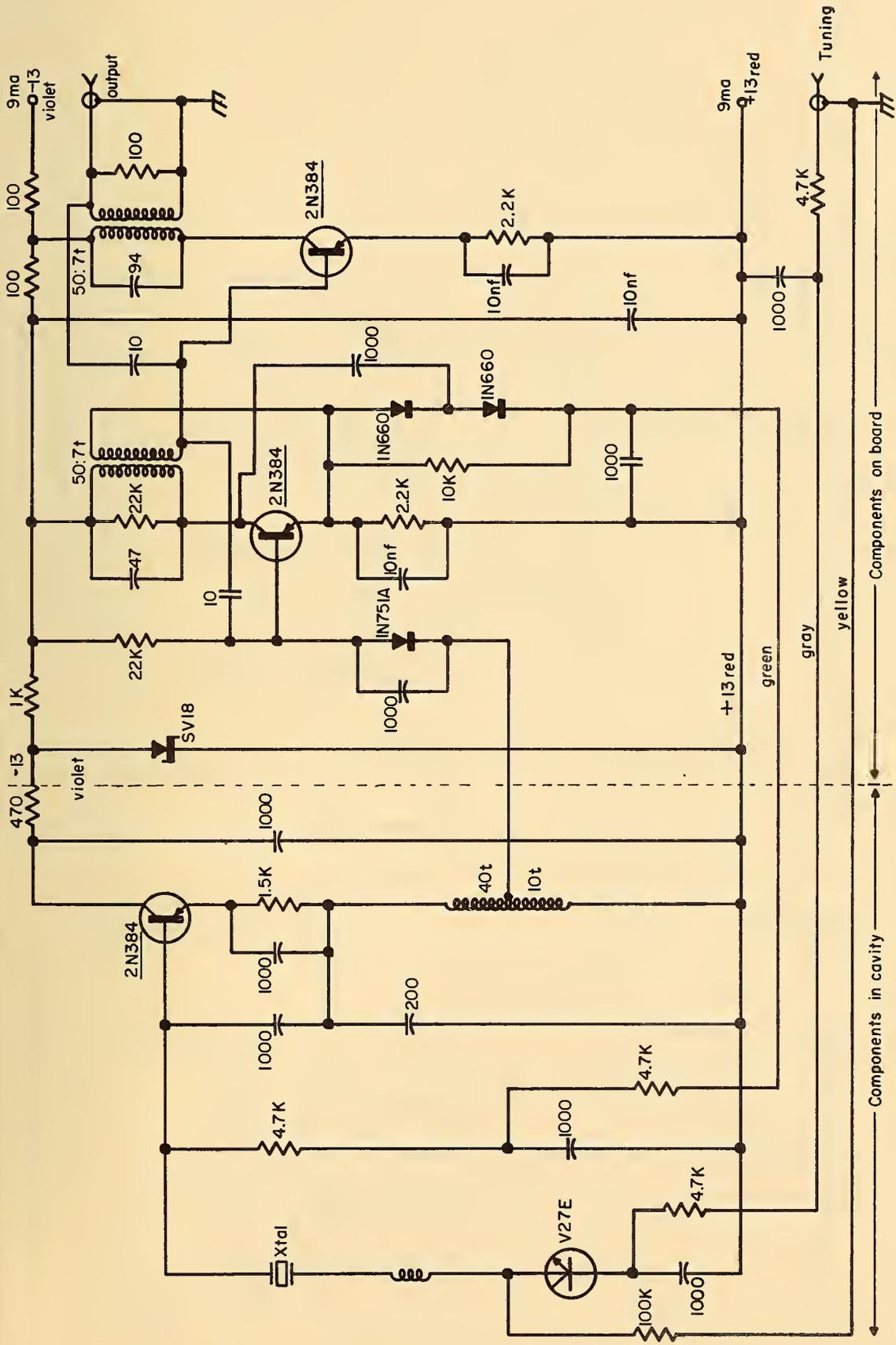
Figure 8 Circuit of Phase Detector



LAMP

Figure 11

Circuit of Lamp Oscillator



Designed by Sulzer Labs.

Figure 12 Circuit of Sulzer Crystal Oscillator

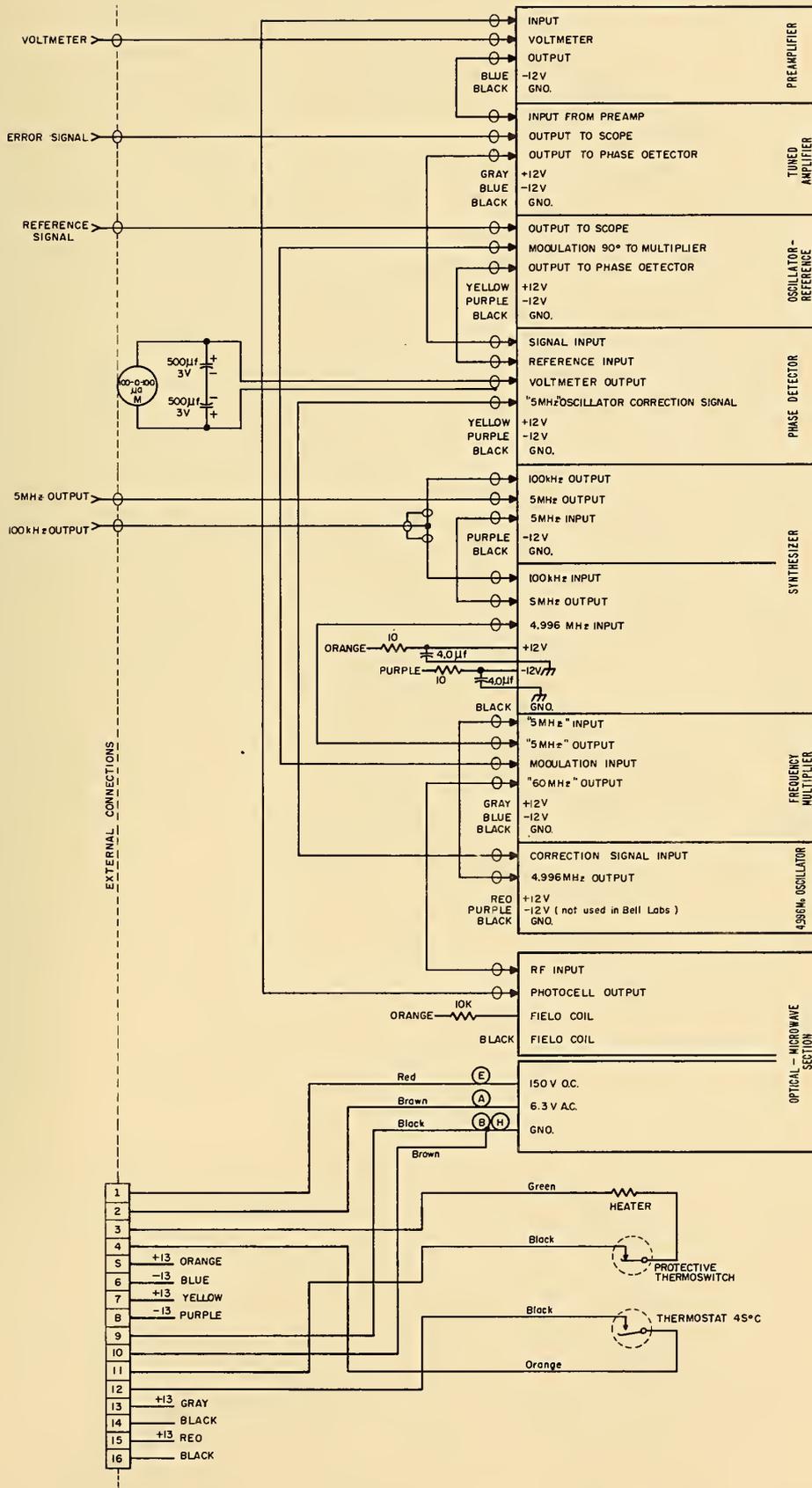


Figure 14

Interconnection Diagram



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