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TH-3 Microwave Radio System:

Microwave Generator

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The TH-3 microwave generator supplies beat oscillator power for the modulators in the TH-3 radio receiver and transmitter. The design described in this paper provides a reliable low-noise source of microwave power at 6 GHz. Design considerations and performance data are presented.

I. INTRODUCTION

The microwave generator serves as a low-noise, frequency stable source of beat oscillator power for use in the microwave transmitters and receivers of the TH-3 system.[1] It supplies 140 milliwatts of output power, and can be equipped to supply any one of thirty-two different frequencies in the 5875.2- to 6334.8-MHz frequency range.*

A stable crystal-controlled oscillator operates at frequencies between 122.4 and 131.975 MHz. Three tandem transistor frequency doublers are used to multiply the oscillator frequency to 1000 MHz.† The doubler circuits utilize the collector-to-base varactor capacitance of the transistor to enhance the frequency doubling. This results in frequency doubling and power gain simultaneously. A varactor diode sextupler multiplier circuit follows the last transistor doubler to produce the required 6-GHz output power.

II. DESIGN OBJECTIVES

The microwave generator was designed to meet the objectives listed below over the normal station air-conditioned temperature range of

* This equipment is manufactured by the Western Electric Company for Bell System use only.
† In this paper 125, 250, 500, 1000, and 6000 MHz are used to denote any frequency between 122.4 and 131.975 MHz and its second, fourth, eighth, and forty-eighth multiple, respectively.

24°C ± 11°C (75°F ± 20°F) for long-haul systems. Over the range of 4°C to 60°C (40°F to 140°F) some degradation in performance is allowable.

Power Output: The 6-GHz power output must be at least +21.5 dBm (140 milliwatts). The maximum change in output power from 40°F to 140°F must not exceed 3 dB.

Frequency Stability: The frequency of the microwave generator at a main station must be maintained to within 3 parts per million over a four-month period for a constant temperature environment. For temperature variations from 55°F to 95°F and 40°F to 140°F, the frequency must be maintained to within ±4 parts per million and ±50 parts per million, respectively. At a repeater station, a single generator, together with a shift modulator, is used for the radio receiver and radio transmitter. Therefore the generator frequency error cancels, and this error does not affect the transmitted frequency. Since the tight frequency tolerance is needed for main station generators, however, and these constitute about 50 percent of the generator production, the tight frequency requirement is applied to all generators.

Carrier-to-Noise Ratio: The noise requirement for the microwave generator, as shown in Fig. 1, was established on the basis that its

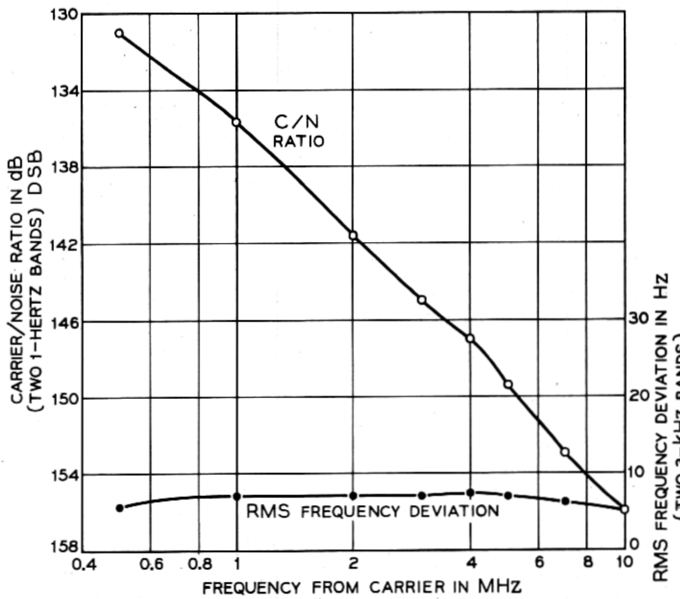

Fig. 1—Microwave generator noise requirement.

noise, when added to the other thermal noise sources, must result in a TH-3 system thermal noise not exceeding 37 dBrnc0.* The requirement is expressed as a ratio of the rms carrier power to the rms noise power in two 1-Hz bands spaced symmetrically about the carrier (DSB) and also as the equivalent rms frequency deviation caused by two 3-kHz noise sidebands.

DC Power Requirement: The microwave generator should operate from a −19-volt supply, regulated to ±0.19 volt.

Tunability: The generator should be tunable to any one of the thirty-two required frequencies. The tuning should be simple to permit easy field alignment.

Common Design: Early in the design stage a decision was made to use a common design (up to 1000 MHz) for both the 6-GHz TH-3 application and the 4-GHz TD-3 application.[2] (The TD-3 generator design uses a quadrupler at the 1000-MHz point to obtain the 4-GHz output.) The common design is feasible since the required crystal oscillator frequencies for TD-3 range from 118.125 to 128.125 MHz and thus overlap the TH-3 crystal oscillator frequencies which extend from 122.4 to 131.975 MHz. By designing the generator circuits through 1000 MHz to have a tunable bandwidth slightly greater than would be required for a TH-3 generator design alone, the same parts may be used for the two applications.

III. OVERALL DESIGN FEATURES

As mentioned above, a crystal-controlled oscillator is used as the frequency determining unit. The frequency was chosen to be as high as possible to minimize the FM noise multiplication factor in reaching the 6-GHz output frequency. About 150 MHz was the highest frequency for which crystals were available to meet the stability requirements needed for TH-3. The oscillator is designed to operate with plug-in crystals having frequencies from 118.125 to 131.975 MHz, with a specific frequency in the range 122.400 to 131.975 MHz being used for each of the channel frequencies of the TH-3 radio system. The oscillator frequency is multiplied by a factor of 48 (125 MHz × 48 = 6 GHz).

The block diagram of Fig. 2 shows the multiplier plan used. The first three circuits following the oscillator-amplifier are frequency doubler stages each using a transistor as the active element. In these

* 150 repeaters, 4000-mile system.

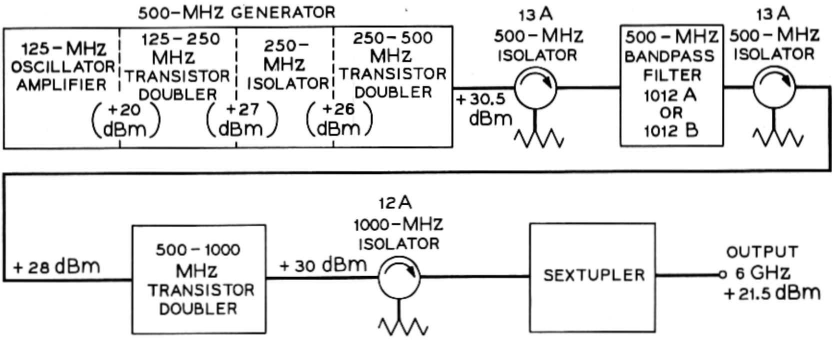

Fig. 2—Microwave generator block diagram.

circuits, the nonlinear collector-base capacitance of the transistor is used as a varactor to improve the multiplication gain over that provided by a conventional transistor doubler. A varactor diode sextupler instead of a transistor multiplier circuit is used to obtain the 6-GHz signal because high power transistors with cutoff frequencies greater than 2 GHz were not available at the time of this development. All units shown in Fig. 2 were designed to operate at a 50-ohm impedance level to facilitate testing in manufacture.

In a microwave generator which uses frequency multiplier stages, the FM index for the noise sidebands increases as $20 \log_{10} N$ where N is the multiplying factor. Thus the FM noise goes up 6 dB for every doubling action. Also, each transistor and diode frequency multiplier stage contributes noise of its own in addition to increasing the index of modulation of noise from the previous stage. An ideal method of improving the output carrier-to-noise ratio would be to employ a sharp bandpass filter at the 6-GHz output to reduce the noise about the carrier. Noise measurements made on a filterless TH-3 generator (curve A of Fig. 3) show that 9 dB of loss relative to the carrier is needed at 0.5 MHz from the carrier frequency to meet generator noise objectives. Using a single-cavity bandpass filter at the output frequency would require a filter with a loaded Q of 16,800. This Q is so high that use of such a filter becomes impractical because of temperature sensitivity problems.

It was determined that 500 MHz was the highest frequency at which a practical filter, from a size and loss stability standpoint, could be provided. The 500-MHz filter employed uses a capacitively loaded quarter-wavelength cavity. The cavity is made of Invar and the filter has an insertion loss of 2 dB with a loaded Q of 1600. Although locat-

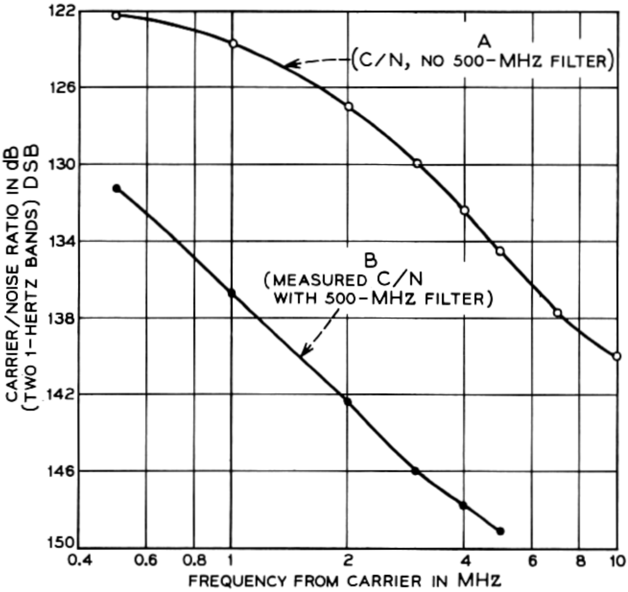

Fig. 3—Microwave generator carrier/noise ratios.

ing the filter at 500 MHz has disadvantages in that noise introduced by subsequent stages is not attenuated, substantial improvement was obtained as shown by curve B of Fig. 3.

IV. CIRCUIT DESIGN FEATURES

4.1 *Oscillator*

The crystal oscillator shown in Fig. 4 is a modified Butler circuit. The base of the oscillator transistor is bypassed to ground at the frequency of oscillation by capacitor C7. The crystal is a 5th overtone unit operating at series resonance. Capacitor C1 is used to adjust the oscillator to exactly the desired frequency. Inductor L1 centers the tuning range of C1. Inductor L3 resonates with the case capacitance of the crystal at the frequency of oscillation and thus the feedback network has two impedance poles which are equally spaced about the impedance zero at the frequency of operation. Capacitors C5 and C6 provide impedance matching to the buffer amplifier stage. The combination of L2, C2, and the transformed input impedance of the second stage provides a parallel tuned circuit at the collector.

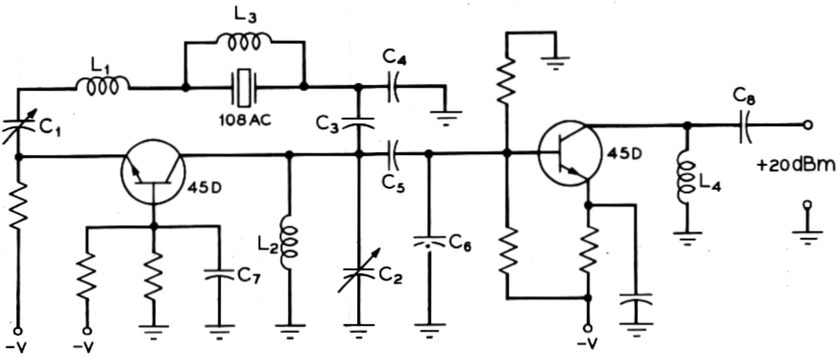

Fig. 4—Oscillator-buffer amplifier circuit.

The carrier-to-noise ratio of the oscillator is limited by the maximum permitted dissipation of the crystal and the noise figure of the transistor. The ratio remains constant as the oscillator output power is varied assuming that the feedback through the crystal is limited by the crystal dissipation. However, it is desirable to have the oscillator output power as high as possible to minimize the noise contribution of the following stages. The oscillator provides approximately +10 dBm of output power to the buffer amplifier. The latter operates as a class A common-emitter amplifier and provides an output of +20 dBm.

4.2 *Transistor Doublers*

Three transistor frequency doubler circuits are used to multiply the 125-MHz output of the oscillator-amplifier to 1000 MHz. Figure 5 shows a circuit diagram which basically is common to all three doublers. The doubling action is enhanced by using the varactor capacitance properties of the transistor collector-to-base junction, C_{bc}.[3] In order to obtain gain in this operating mode, the circuit should

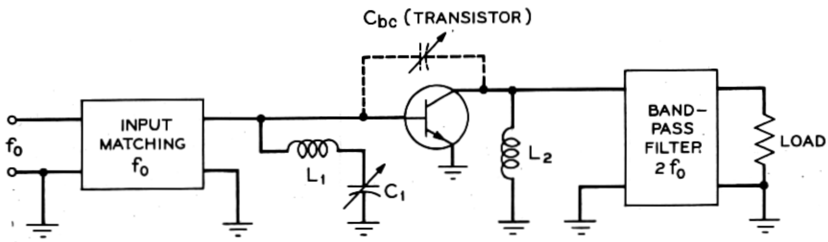

Fig. 5—Typical transistor multiplier circuit.

have at least 3 to 4 dB gain at the input frequency. This requires that a relatively high impedance be presented to the collector at the input frequency, f_o. Since base-to-emitter impedance is small, a high collector-to-ground impedance is provided by selecting L2 to resonate, at f_o, with the collector-to-base capacitance C_{bc}. Thus, a large voltage swing is developed across C_{bc}. Due to the nonlinear action of C_{bc} higher-order currents will flow if a path is provided. Inductor L1 and capacitor C1 series resonate at $2 f_o$ and provide the base-to-ground path. The load provides such a path in the collector circuits.

The 125- to 250-MHz doubler circuit uses a Western Electric 62C overlay type transistor with 72 emitters and a minimum f_t of 500 MHz. The 250- to 500-MHz doubler uses a Western Electric 62A overlay type transistor with 110 emitters. The 500- to 1000-MHz multiplier circuit has the emitter bypassed by using a quarter-wavelength open circuited transmission line. The 1000-MHz output circuit uses a coaxial cavity with probe coupling to the load. A Western Electric 46F overlay type transistor, which is similar to the 62A except that it does not have a tab type heat sink, is used in this circuit.

4.3 *Sextupler*

This unit, which multiplies the output frequency of the 500- to 1000-MHz transistor doubler to the final output frequency of 6 GHz, uses a varactor diode as the active element. The diode is mounted in a structure comprised of coaxial and waveguide elements as shown by the cross-section view of Fig. 6.

The coaxial transmission line input circuit consists of an impedance transformer in the form of a quarter-wave resonant coaxial cavity tuned to 1000 MHz, a low-pass filter to isolate harmonics of 1000 MHz from the input, a varactor diode, and a shunt resistor for self-bias. The tunable resonant cavity (a) has a loaded Q of 100 and transforms the diode impedance to 50 ohms. The cavity uses magnetic input and capacitive output couplings. The center conductor (b) is made of Invar to achieve the desired degree of temperature stability. The bias resistor (c) is connected between the center conductor of the low-pass filter (d) and ground at a low impedance point to minimize resistor losses at both 1000 MHz and 6 GHz. To insure the proper reflection phase for the 6-GHz signal generated in the diode (e) a suitable length of line (L1) is inserted between the diode and the low-pass filter.

The output circuit, which uses coaxial transmission line and waveguide elements, consists of a tunable coaxial-to-waveguide transducer and a tunable waveguide bandpass filter. The coaxial line (L2) pro-

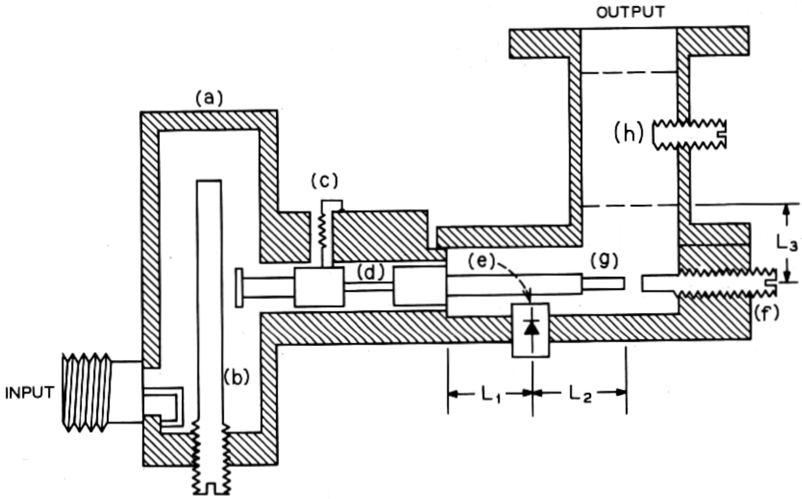

Fig. 6—Sextupler circuit.

trudes into the output waveguide to provide coupling. A capacitive tuning screw (f) opposite the probe (g) in the waveguide optimizes the coupling at the output frequency. A tunable waveguide bandpass filter (h) having a loaded Q of 35 is spaced by a distance (L3) from the probe. It passes the 6-GHz carrier and reactively terminates adjacent harmonics generated by the 1000-MHz drive signal. The output waveguide is used as a high-pass filter to suppress harmonics of the 1000-MHz drive signal at frequencies below the 6-GHz carrier. With an input power of +29 dBm at 1000 MHz, the output power at 6000 MHz is approximately +22 dBm. The varactor diode is a Western Electric 473A diode[4] with typical characteristics as follows: breakdown voltage of 60 volts, series resistance of 1.1 ohms, and capacitance at zero bias of 5 picofarads. This graded junction device is driven into the forward charge storage region and therefore available design theory could not be applied.[5] The multiplier circuit was developed by making use of experimental design techniques to achieve the desired performance. The diode is biased to operate near breakdown. At frequencies between 0.5 and about 3 MHz from the carrier the C/N performance of the multiplier is limited by both the threshold noise associated with the diode breakdown voltage and noise generated in the driving circuit. The selectivity of the input cavity provides some reduction of the noise from the driving circuit.

Additional filtering is provided at the output for tones located ± 500 MHz and ± 1000 MHz from the carrier frequency by a 1349 type bandpass filter.[1] The 500-MHz bandpass filter removes tones which may be present at 125 MHz and 250 MHz from the carrier.

4.4 *Generator Tuning*

To achieve the goal of providing simple alignment procedures, power monitors have been placed in all stages through 500 MHz. Each monitor circuit samples the power output of its corresponding stage, and a diode detector provides a current which may be read on a test meter of the TH-3 transmitter-receiver bay. Thus, these stages may be tuned by observing the response on the bay meter.

Four circulators are used in the generator chain as shown in Fig 2. These circulators were required to obtain coincidence of maximum power and minimum noise. Without the circulators, parametric oscillations occurred under certain tuning conditions.

Tuning of the 500- to 1000-MHz doubler circuit is done by monitoring the transistor collector current. The collector current is adjusted so that the transistor is operated within its dissipation limits.

The sextupler is tuned by adjusting the controls for maximum output power as observed on an external power meter.

The output power of the generator is adjustable over approximately a 5-dB range. The power adjustment is achieved by adjusting the dc bias on the 125- to 250-MHz and the 250- to 500-MHz doublers.

V. PERFORMANCE

5.1 *Power Output Variation with Temperature*

Figure 7 shows the power output as a function of temperature. Curve A gives the performance at the output of the 500- to 1000-MHz stage, curve B at the 6-GHz output frequency. The performance is within the design objectives of 3 dB maximum variation from 4°C to 60°C (40°F to 140°F).

5.2 *Frequency Variation with Temperature*

Figure 8 shows a typical change of crystal oscillator frequency with temperature. The variation in generator frequency is completely dependent on the crystal oscillator stability. The curve indicates that design objectives for frequency stability of the generator are satisfied.

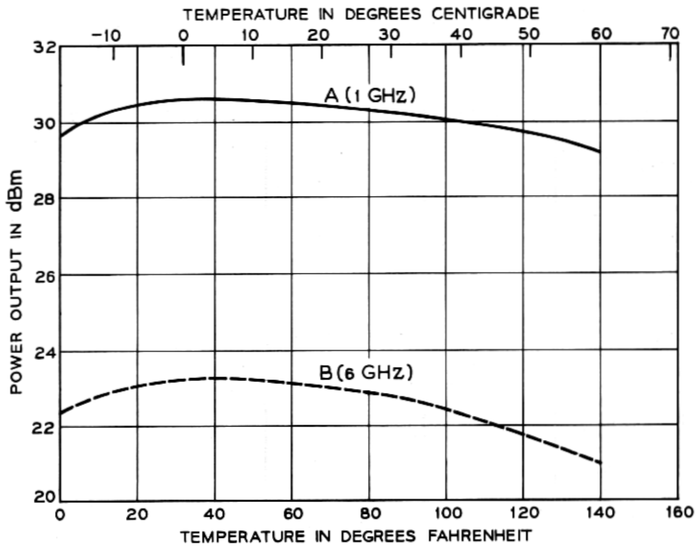

Fig. 7—Microwave power output vs temperature.

5.3 *Carrier-to-Noise Performance*

5.3.1 *Noise Measurement Method*

The carrier-to-noise ratio of the 6-GHz output signal was measured using the equipment shown in Fig. 9. Essentially the arrangement applies the output of the generator being tested to the inputs of two paths, one path (Path A) leading to the signal port of a down converter, the other (Path B) to the beat oscillator port of the converter. The output of the converter, at a frequency of 70 MHz, is applied to an FM receiver which recovers the FM noise at baseband frequencies. The noise is then measured using a tunable, frequency selective, power meter. Since the noise present at the output of the generator is very low, some method must be used to increase it so that it is not masked by the noise of the measuring equipment. This is done by using a highly selective filter to suppress the carrier in the signal path, thus, in effect, degrading the signal-to-noise ratio and increasing the FM index of noise modulation.

The beat oscillator signal for the down converter is supplied in Path B. Path B shifts the frequency of the generator under test by 70 MHz. The output of the shift modulator in Path B is filtered by a sharp

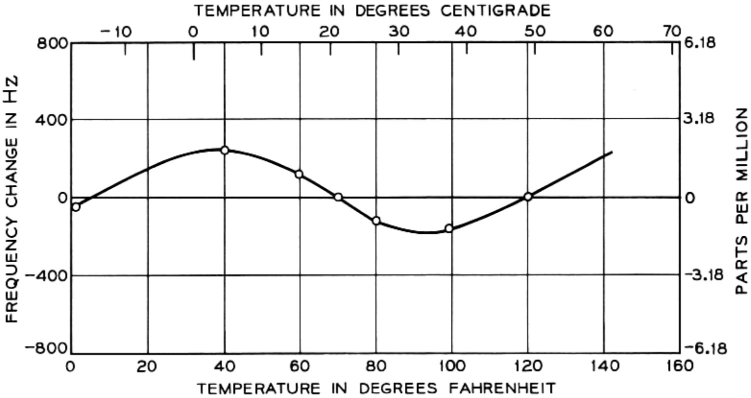

Fig. 8—Crystal frequency vs temperature.

bandpass filter (3-dB points ±0.75 MHz). This filtering essentially removes any noise which might enter the down converter via the beat oscillator port. This test set must be capable of measuring carrier-to-noise ratios as high as 154 dB (1-Hz band, DSB). With the carrier power at +21.5 dBm, the noise power to be measured is −138.5 dBm/Hz. A receiver modulator with a 10-dB noise figure will introduce noise of only −164 dBm/Hz and, therefore, will not produce any significant error.

The FM terminal receiver sensitivity is such that an input carrier-to-noise ratio of 153 dB (DSB) (at a 10-MHz baseband frequency) produces an output equal to the residual FM terminal noise.[6] By increasing the FM index (decreasing the carrier-to-noise ratio) of the signal being measured, the desired output will override the residual noise of the FM receiver. The circulator and sharp bandpass filter, as shown in Path A of Fig. 9, are used to reduce the carrier by approximately 20 dB. The noise at frequencies removed from the carrier suffers little or no attenuation. The carrier-to-noise ratio is decreased by the amount of carrier absorption.

Using the measurement equipment shown in Fig. 9, it can be shown that

$$C/N_{DSB} = -8 + 20 \log FM + 10 \log B - P_{out} + R_1 *$$

* The FM terminal receiver measures the FM index which in effect measures the noise on both sides of the carrier (double sideband).

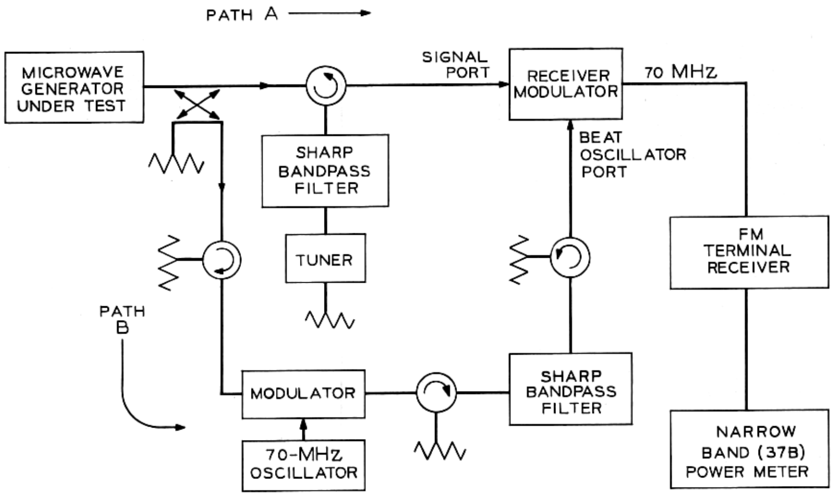

Fig. 9—C/N measurement setup.

where

R_1 = carrier absorption in dB,
FM = baseband frequency (frequency from carrier), in MHz,
B = bandwidth of 37B power meter in Hz, and
P_{out} = baseband output power indicated by the 37B (dBm).

5.3.2 *Carrier-to-Noise Performance*

Curve B of Fig. 3 shows the carrier-to-noise performance of the TH-3 generator.

VI. PHYSICAL DESIGN FEATURES

All units of the microwave generator but the sextupler are mounted in an assembly which measures 21 by 11 by 7 inches. The oscillator-amplifier, the first two transistor multiplier stages, and the 250-MHz isolator are contained in one package, designated the "500 MHz Generator." It and the other major units are shown in Fig. 10. The major components are interconnected using miniature semi-rigid cable (0.141 inch outer diameter), which simplifies the equipment layout and minimizes RF leakage.

The sextupler (designated the "6 GHz Multiplier"), as shown in Fig. 11, is mounted adjacent to the carrier distribution network in the TH-3 bay to minimize cable loss at 6 GHz. The 1000-MHz

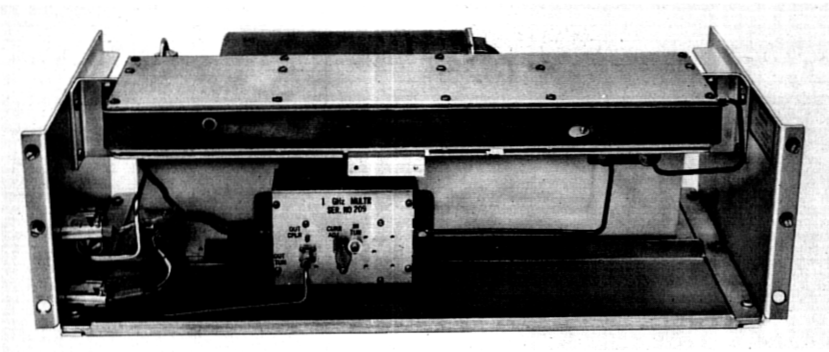

Fig. 10—Microwave generator (without sextupler).

carrier power is fed to the sextupler through a 6-foot low-loss coaxial cable (0.325 inch outer diameter).

The oscillator, two transistor multipliers, and the 250-MHz isolator are housed in the compartmentalized die-cast frame shown in Fig. 12. Printed wiring techniques are employed to achieve controlled wiring essential at these frequencies. Distributed parameters of inductance and capacitance are controlled by path width and length on the printed wiring boards. A separate compartment is provided for decoupling of the power supply leads. Access to the tuning controls and the frequency monitor point is provided on the front surface. The two sheet metal covers and braided gasket material provide complete RF shielding.

A somewhat different approach was employed in the physical design of the 500- to 1000-MHz multiplier, as shown in Fig. 13, because of the higher frequencies at which it operates. At the 500-MHz input end a combination of lumped elements and microstrip was found to provide the required accuracy for control of distributed capacitance and inductance. At the 1000-MHz output end the coaxial cavity approach provided the best realization of the circuit objectives. A small die-cast housing again provides the shielding and decoupling features found in the 500-MHz unit.

The physical embodiment of the sextupler is illustrated by the cross-section diagram of Fig. 6. As indicated in the circuit description of this multiplier each physical part of the structure is an electrical parameter of the circuit. The coaxial transmission line section at the input and the waveguide structure at the output were established by the electrical requirements for the design. Almost every phase of the physical design has a direct bearing on the electrical performance of the end product. The removable diode holder and adjustable tuning

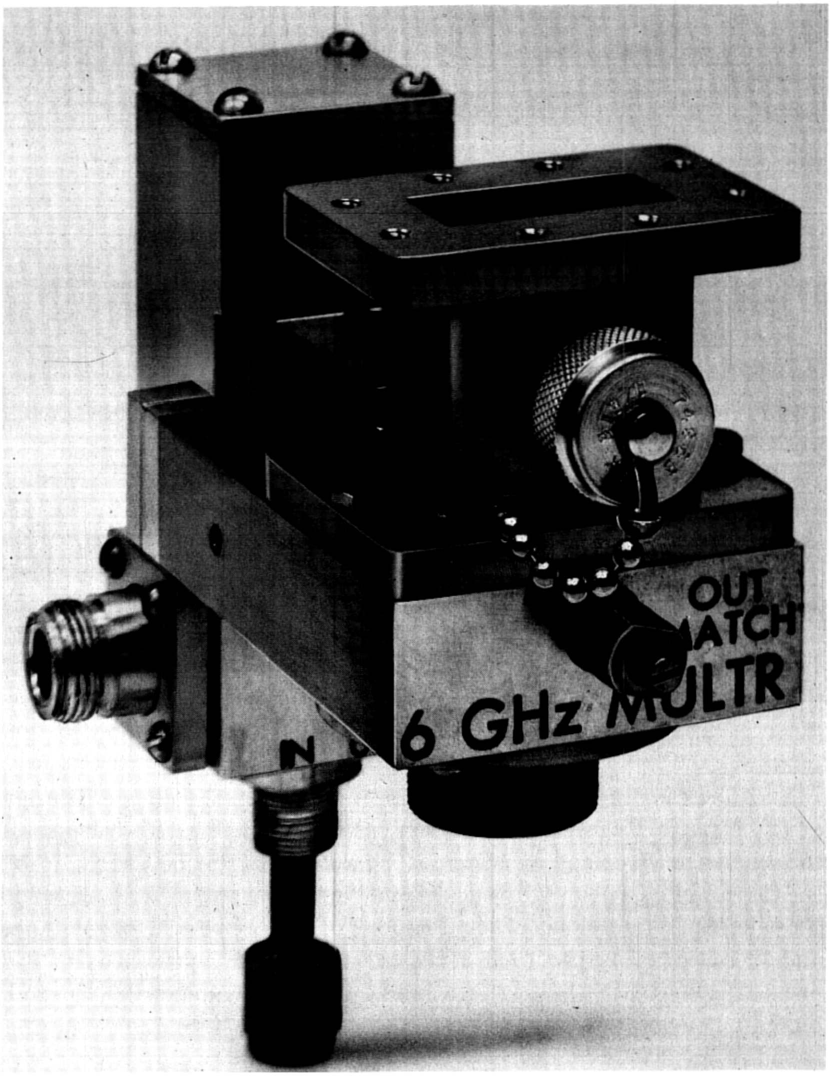

Fig. 11—Sextupler.

screws are specific details that required special design effort to insure good electrical contact pressures and to eliminate RF leakage paths.

During the development of the generator, a great deal of effort was spent to assure that the unit would exhibit high reliability in service. Much of this effort was directed toward achieving high reliability for the transistors. Figure 14 shows a curve of fits (1 failure in 10^9 hours) as a function of junction temperatures for the type of transistor used

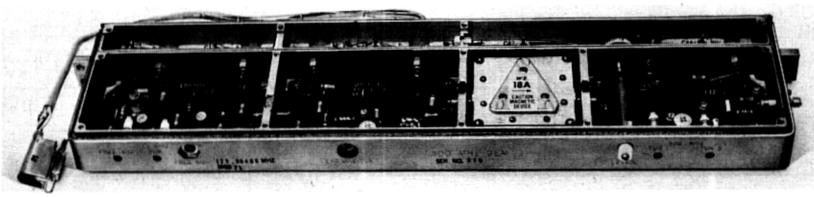

Fig. 12—500-MHz generator.

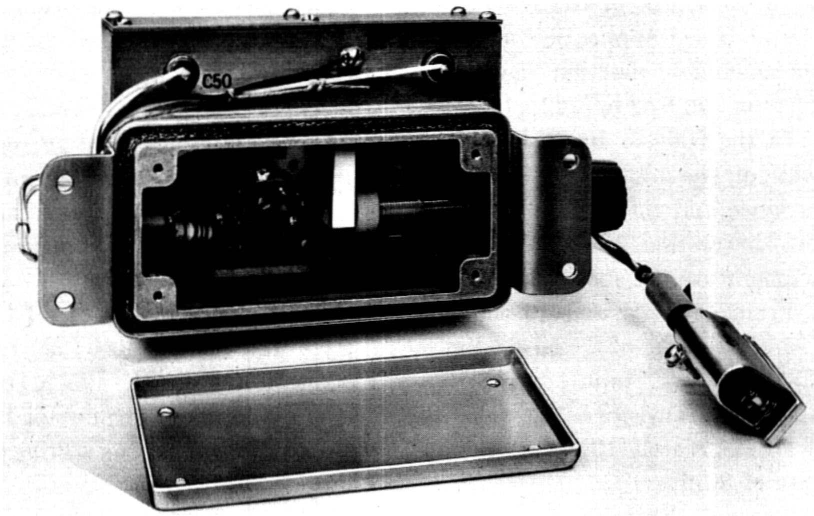

Fig. 13—500-MHz to 1000-MHz multiplier.

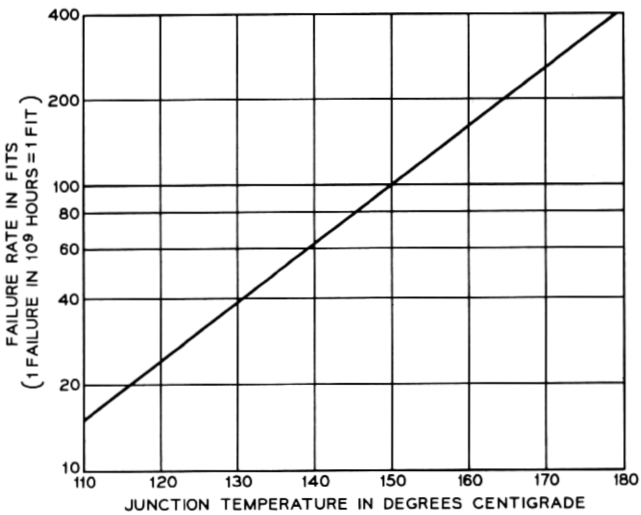

Fig. 14—Failure rate vs junction temperature for 62A, 62C, and 46F transistors.

in the generator. To obtain low junction temperatures, heat sinks were used on the transistors of the frequency multiplier circuits. The 125- to 250-MHz doubler transistor (62A) has a tab-type heat sink which connects to the framework. Use of the tab-type heat sink was desirable as it was compatible with printed circuit boards which were used through 500 MHz. The tab-type heat sink, which was developed by J. E. Clark of the Allentown Laboratory, is shown in a printed circuit board application in Fig. 15. In Fig. 16 the upper curve shows the calculated junction temperature as a function of ambient temperature for the 62C and 62A transistors using the tab-type heat sinks.

In the 500- to 1000-MHz circuit, the transistor is mounted in the wall of the aluminum front plate. This provides low thermal impedance and thus the 46F transistor operates at a junction temperature lower than the 62C and 62A. The calculated values of junction temperature are shown as the lower curve of Fig. 16.

From Figs. 14 and 16 the failure rate at a temperature of 36°C (95°F) for the 62A and 62C is 30 fits each and for the 46F (500 to 1000 MHz) the failure rate is 15 fits. The failure rate for the 125-MHz amplifier transistor is about 30 fits and for the oscillator transistor it is approximately 10 fits. The diode in the sextupler circuit has a failure rate of 30 fits.

The failure rate for those passive components in the generator which would cause loss of service is estimated to be about 900 fits. Since the failure rate for active devices is 145 fits, the total for the generator is 1045 fits which corresponds to a mean time for failure of 109 years.

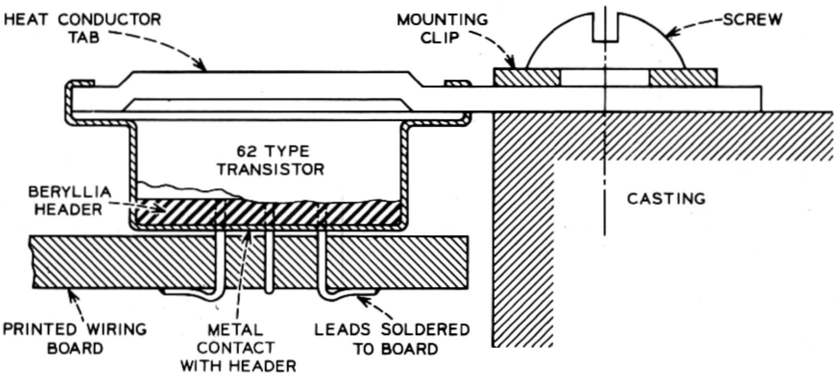

Fig. 15—Tab-type heat sink.

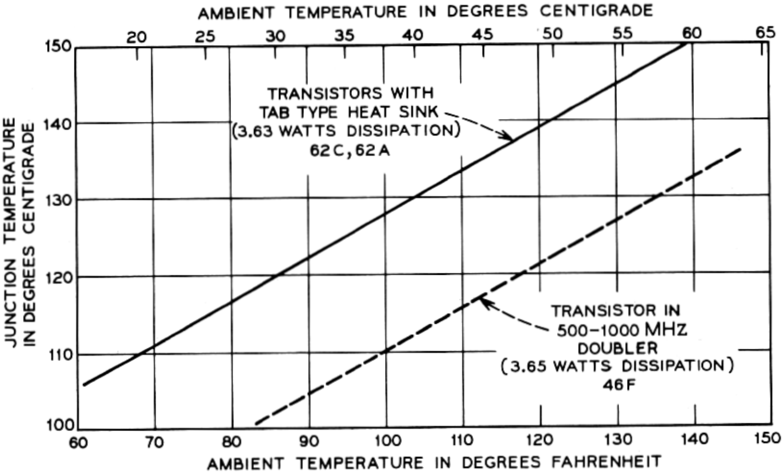

Fig. 16—Junction temperature vs ambient temperature for microwave generator transistors.

VII. ACKNOWLEDGMENTS

The microwave generator could not have been developed without the cooperation and contributions of many people. W. J. Schwarz, J. A. Gerrish, and O. Giust contributed to much of the circuit design. Also, thanks are due to J. Wiley of the Allentown Laboratory for his help with transistors. We also wish to thank R. E. Sherman for encouragement and support.

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