SOLID STATE MICROWAVE POWER GENERATION

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Introduction Significant advances have been made in the state-of-the art capability of RF power transistors and varactor diodes. This progress coupled with the recent demand for microwave telemetry transmitters particularly at S-band - has created a large potential market. Other requirements exist at L, C, X, and KU band, although presently not as active as those at S-band. Even though much research and design has been car ried on over the past four to five years in this area, such transmitters still demand considerable experience and ingenuity from the designer if a unit capable of production is desired. The purpose of this paper is to discuss the current capabilities of microwave transmitters, the problem areas associated with their design, and the techniques developed which have resulted in production oriented equipment. Typical circuits of the various stages of a transmitter are also presented along with photographs of developed hardware.

Basic Microwave Transmitter Concept Basically, a microwave transmitter consists of the building blocks as exemplified by the block diagram of Figure 1. A signal source which can be anything from a simple crystal oscillator to a sophisticated wide band FM modulator, develops an RF signal usually at low power and at a frequency under 100 mc. This signal is raised in frequency and power to some intermediate value by an RF exciter. A Power Amplifier follows the Exciter and develops the necessary input power for the varactor chain. The varactor chain follows the power amplifier and consists of the required doublers or triplers in the correct combination to achieve the desired output frequency. Often a DC to DC converter-regulator is added which gives the transmitter protection from variations and transients existing on the primary power source. The frequencies and power levels shown in Figure I are representative of an all solid state X-band transmitter currently under development.

Power Available vs Frequency Figure 2 is a graph which displays the state-of-the-art power output capability of currently available solid-state devices as a function of frequency. The varactors are manufactured by Motorola while the 3TE440 and TA2675 transistors are manufactured by IT&T and RCA respectively. At frequencies below 1000 mc it is practical to use parallel transistors and balanced varactor multipliers to increase the available power. However, above 1000 mc where distributed constant circuits must be used, the use of more than one varactor per multiplier necessitates somewhat cumbersome and tedious techniques which leave much to be desired from a practical viewpoint.

Besides the devices shown, some work has been performed recently on a technique which combines the function of a transistor amplifier and, varactor multiplier in one device. The device is referred to as a "Transistor Parametric Multiplier". Basically the transistor is driven by an RF signal in the base circuit in a conventional fashion, and the collector circuit made to function as both an amplifier and varactor multiplier by utilizing the transistor collector-base capacity non-linearity over the RF cycle. The overall performance approaches that of the separate amplifier-varactor combination and has less power output potential. Simplicity and cost are its main attractive features.

Even though the transistor curve in Figure 2 extends up to 500 mc, superior performance in efficiency and simplicity of microwave transmitters can be achieved when the transistors are operated in the 250 mc to 350 mc range. This improved performance is due to the high efficiency obtainable from varactor multipliers at frequencies below 1000 mc coupled with the superior gain and efficiency of the transistors.

Problem Areas and System Requirements A number of system requirements and problems confront the designer of microwave transmitters, each of which must be dealt with and solved if an adequate design is to be achieved. The most significant of these are:

> The transmitter must be free from parametric instabilities under all conditions of operation.
>
> The transmitter must be free from lock-up phenomena by which full power output is never reached during initial turn on and other transient conditions.
>
> The transmitter must be protected against significant VSWR conditions at its output terminal.
>
> Primary power source variations and transients must be prevented from adversely affecting the operation.
>
> The type of modulation to be transmitted must be considered and the design treated accordingly.
>
> Design techniques must consider environmental requirements such as temperature, shock, vibration, acceleration, altitude, etc.

If the design is to have production potential the factors of cost and reproducibility must be considered.

Stability The problem of maintaining the transmitter free from spurious responses is one of the most difficult the designer faces. These spurious responses can occur in the RF exciter, the power amplifier, or in the multipliers, and if present in any module, are multiplied upon cascading with the other modules. The instabilities create such spurious responses by introducing amplitude modulation of the main carrier at any rate from a few cycles to many megacycles. Since this instability cannot be predicted and thereby removed by appropriate filters, it must be minimized.

Figure 3 displays the swept passband response of an L-band transmitter as viewed on an oscilloscope and shows the effect of a typical instability. Figure 4 shows the RF spectrum of the same instability viewed on a spectrum analyzer when the transmitter is operated in the cw mode.

While these spurious responses were originally being investigated, it was observed that they were affected by a variation in power level, a variation in frequency, and a variation in circuit tuning. Therefore, it was decided to align the transmitter using a swept frequency display of the bandpass characteristic. In addition, if the swept response is observed under various drive levels, two of the three types of variations are simulated. Also an effort is made to make each stage free from bandpass response breakup within as large a tuning range as possible. By performing this stability criteria on a stage by stage basis and then applying the same criteria to the complete transmitter, a significant improvement in stability is realized. Figure 5 is a series of photographs which display the transmitter bandpass under various drive levels and shows no evidence of breakup.

Turn-On When power is first applied to the transmitter, a transient condition exists during which the supply voltage sweeps up from zero to its nominal value. If an unstable condition is encountered during this time, a lock-up can occur in which full power output is never reached. Often, the final power amplifier draws excess current and a catastrophic failure can result. Since it is difficult to ensure freedom from unstable modes during such extreme variations, a simple delay technique should be incorporated in which the RF drive to the amplifier chain is disconnected until the supply voltage is established. If an FM modulator using an AFC loop is employed as a frequency source another technique can be adopted. It makes use of the fact that the FM modulator is initially off frequency by an amount in excess of the bandpass of the RF exciter. If the lock-in time of the modulator AFC loop is in excess of the power supply charging time, RF drive to the power amplifier is delayed until the power supply is completely charged.

Output VSWR Protection VSWR at the transmitter output in excess of 2:1 can cause parametric instabilities as well as excess dissipation in the power amplifier. In order to prevent this from occurring, an isolator is recommended between the transmitter output and the intended load. The penalties are insertion loss, size, weight and cost. At 2.25 GHz the insertion loss of such a device is about 0.3 db, the isolation is 20 db, the size is about 6 in^3, and the cost is about $300.00.

Power Source Variations and Transients It is virtually impossible to design a transmitter of this type capable of withstanding large variations in supply voltage, line surges, line interference, etc. without resorting to a DC to DC converter-regulator. When a converter-regulator is used the result is that the above mentioned power source characteristics have no effect on the transmitter' s performance. The further advantages of ground isolation and freedom in choice of voltages for the transmitter design are also achieved. The penalty is only a 10% increase in the required input power when a state-of-the-art design is used.

Modulation

Amplitude Modulation Because of the non-linearity of microwave transmitters, linear AM must be implemented by a scheme similar to that shown in Figure 6. Here the carrier level of the transmitter is coupled into a absorption type modulator whose average carrier output is one -fourth of the input power. The modulator loss then follows the modulation input waveform. The scheme suffers from an efficiency standpoint since the average carrier output is reduced.

A non-linear AM system is shown in Figure 7. In this scheme the RF signal is switched on and off into the RF exciter, thus utilizing the full peak power of the transmitter. The only consideration necessary here is that alteration of the switching time is not of consequence and that spurious which may be generated during the switching interval do not adversely influence the system. In addition the various stages must have sufficient bandwidth if faithful reproduction of the modulation waveform is to be obtained.

Single Sideband Single sideband cannot be transmitted directly by a microwave transmitter because of the amplitude non-linearity as well as the frequency multiplication involved. Instead a power up converter is normally employed as shown in Figure 8. The system shown is representative of state-of-the-art results.

Frequency Modulation and Phase Modulation Microwave transmitters are best adapted to handling FM or PM type of modulation. The deviation ratio of the fundamental frequency source is multiplied by the total multiplication factor of the transmitter, and the full average power of the transmitter can be utilized. The primary problem in the scheme is in the design of the frequency source. For wide band systems the lower frequency exciter stages must be designed to have sufficient bandwidth to pass the intelligence or distortion will occur.

Environmental Considerations

Temperature Characteristics Excessive variation in output power and efficiency over a wide temperature excursion can be minimized by a number of techniques. The results are illustrated in Figure 9. Over a temperature range of -20° C to +80°C, the power output varies less than 1.5 db while the efficiency varies from 20% down to 14%. Among those techniques employed are:

> Adequate derating of all semiconductors to prevent power output drop-off at high temperatures.
>
> Low Q multi-pole filter circuits to prevent excessive mistuning in temperature.
>
> Operation of the transistor driver stages into slow saturation, thereby minimizing gain changes in temperature.
>
> Temperature compensation of low-level transistor stages to reduce changes in gain.
>
> Use of step recovery varactor diodes which have a minimum variation in efficiency with temperature.

Shock, Vibration, Acceleration, Etc In addition to close attention to mechanical strength of the package and parts layout, it is helpful to pot the parts of the transmitter which operate at frequencies below1000mc. Available compounds reduce the movement of components under stress immeasurably and result in negligible loss to RF circuits. At frequencies above 1000 mc, the use of combine and interdigital multipole wideband filters results in far less incidental AM and PM than that created by narrow band cavity filters.

REPRESENTATIVE CIRCUITS

RF Exciter A schematic diagram of an RF exciter is shown in Figure 10. Amplifier Q1 has a gain of 17 db at an input frequency of 83 MHz. With 0.1 mw input from the signal source, amplifier Q1 delivers 5 mw to the frequency tripler. Varactor frequency tripler CR1 is operated in the series configuration and provides 2.5 mw at 249 MHz to amplifier

Q2 which has a power output of approximately 30 mw. These three stages are contained in the top (low level) section of the RF exciter module shown in Figure 11.

Amplifier stages Q3 and Q4 raise the power output to a nominal value of 0.7 watts. Adjusting the forward bias on Q3 varies the power output above or below this value. The two stages are constructed in the bottom,(high level) section of the RF exciter module as shown in Figure 12. The high and low level section are then bolted together to form a 1-1/4" x 1-1/4" x 2-1/2" module. Careful shielding and decoupling have made the RF exciter a high performance module which is easily manufactured. The unit operates with over 40 db of gain and an efficiency of 33%. Power output up to 3 watts can be obtained by increasing the operating voltage of the bottom section from +16 VDC to +28 VDC.

Power Amplifier A power amplifier module is shown schematically in Figure 13. The 249 MHz input from the RF exciter is amplified to a level of 20 watts in two stages. The amplifier uses a 2N3375 driver transistor for Q1 and a pair of 2N3632's as the final amplifier. In order to achieve 40 watts at 249 MHz, Q2 and Q3 could be replaced by either the RCA TA 2675 or the ITT 3TE440, both of which are capable of this performance.

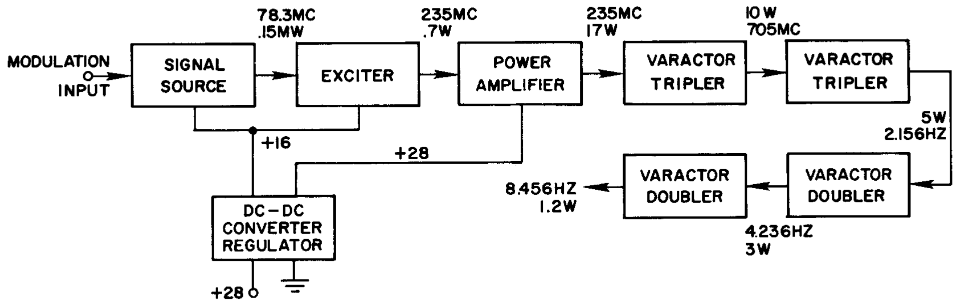
The driver amplifier circuit is quite conventional, but the final amplifier uses a unique arrangement in which the two transistors are combined in a hybrid output circuit. The hybrid provides isolation between the collectors of the two transistors, thereby preventing interaction if the outputs are not matched. A significant improvement in stability and performance has been achieved with this technique over arrangements using direct paralleling, push-pull, or paralleling with separate output circuits. The gain of the two stages is 14 db and the efficiency is about 55%. Figure 14 shows the packaging of the power amplifier.

250 MC to 750 MC Tripler Figure 15 is a schematic and Figure 16 is a photograph of a 250 mc to 750 mc varactor tripler which uses the MV 1807C varactor. A power output of 13 watts can be achieved with a conversion efficiency of 65%. A 750 mc three section comb line filter is used in the output but the input filter and output matching from varactor to filter are lumped constants. The comb line filter is used following the lumped circuitry in order to achieve sufficient filtering of harmonic freuencies above 750 mc. Lumped circuitry tends to become self resonant somewhere in the vicinity of 1000 mc and thereafter provides poor filtering. The bandwidth of the multiplier filter combination is approximately 10% thereby providing non-critical performance under the various operating conditions expected. Broadband operation also minimizes packaging problems and RF voltage build up created by narrow band, high Q circuits.

S-Band Tripler Figure 17 is a schematic diagram of an S-band tripler which utilizes a lumped input circuit at 750 mc and a lumped idler at 1500 mc. Lumped circuitry is practical in the input circuit of the multiplier since the filtering requirements are not as severe as in the output of the 750 mc tripler. The 1500 mc idler is implemented by the self resonant frequency of a Johanson .8 - 10 uufd trimmer capacitor in series with a short connection directly to the MV 1808B varactor. A five section comb line filter with a 10% bandwidth is used as the output filter at 2.25K mc The varactor is mounted directly between the matching post of the filter, which incorporates a dc block, and the wall of the cavity. Excellent heat conduction and mechanical rigidity for the varactor are achieved in this arrangement. A photograph of the tripler is shown in Figure 18. The multiplier operates with a conversion efficiency of 45% and can deliver output power in excess of 5 watts. Spurious suppression at S-band is greater than 70 db.

C-Band Doubler Figure 19 is a photograph of a C-band doubler operating at an output frequency of 4200 mc and capable of delivering greater than 3 watts of power. Its multiplication efficiency is approximately 60%. Atwo section comb line filter is used for the input and a three section interdigital filter is used for the output. The varactor is mounted directly between the common matching stub and the cavity wall. A DC block is built into the stub. The interdigital filter is superior to a comb line at 4.2K mc by means of its lower insertion loss. In addition the width of the cavity is made the same for both input and output filters thereby providing for an efficient package configuration.

Summary In summary, microwave transmitters have emerged from the research era into one of practical use for those applications of a few watts or less. High reliability, small size, crystal stability, and environmental ruggedness are among their primary attributes. Compared to their non-solid state counterparts - cavity amplifiers and oscillators, TWT' s, BWO's, Amplitrons, etc, they are inferior in efficiency, power output, and degree of complexity. The rapid advance of microwave transistors however, is rapidly closing the gap particularly in the areas of efficiency and complexity. For instance, a current development is under way to produce a 15 watt 1 KMC transistor. By using such a device as a frequency stabilized oscillator, the efficiency of an S-band transmitter would be increased and the complexity decreased significantly. In short, the future of solid state power generation at microwave frequencies is brighter than ever before.



BASIC MICROWAVE TRANSMITTER

Figure 1

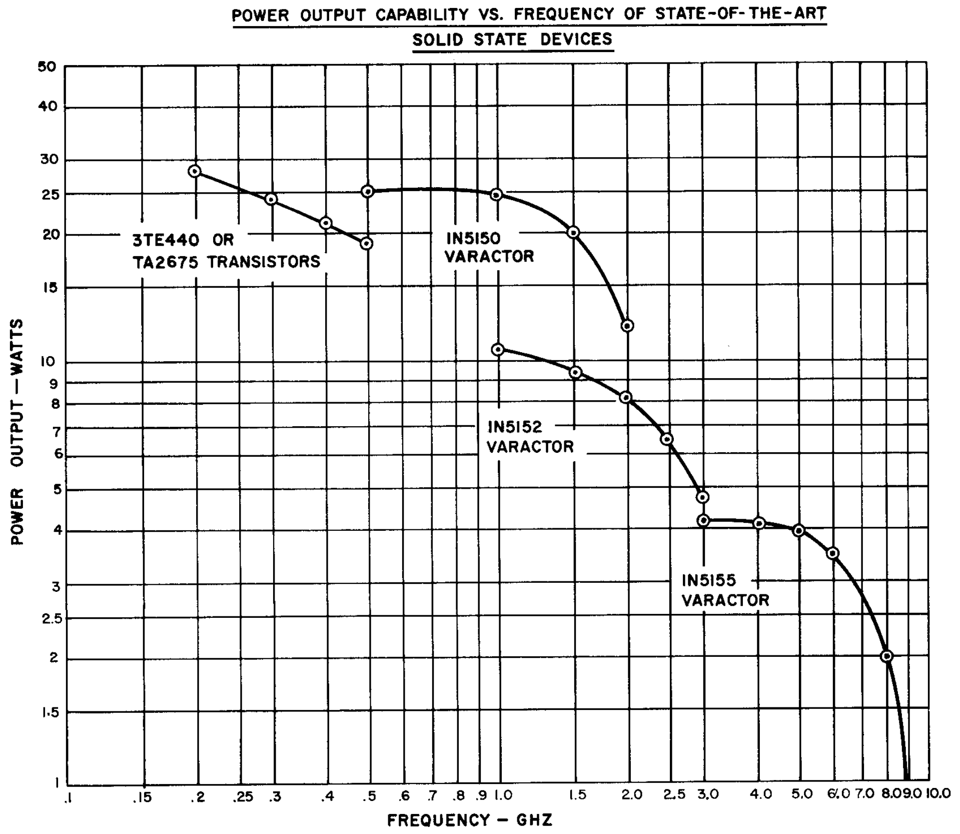


Figure 2

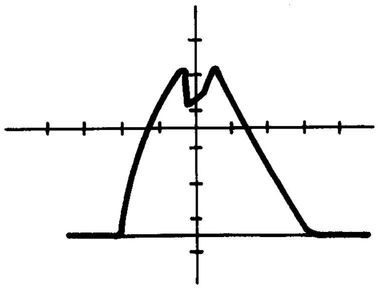


Fig. 3-Swept Frequency Response of Typical Parametric Breakup

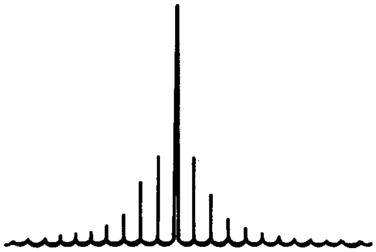
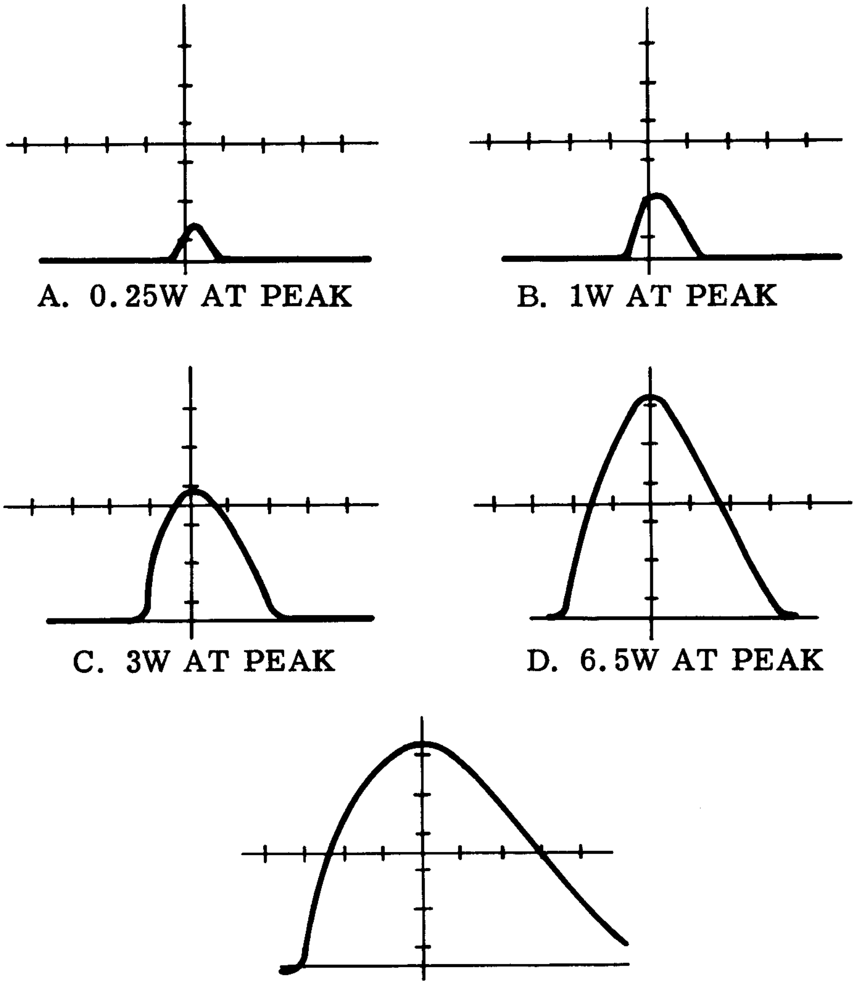


Fig. 4-Spectrum Analyzer Display of Parametric Breakup



A. 0.25W AT PEAK

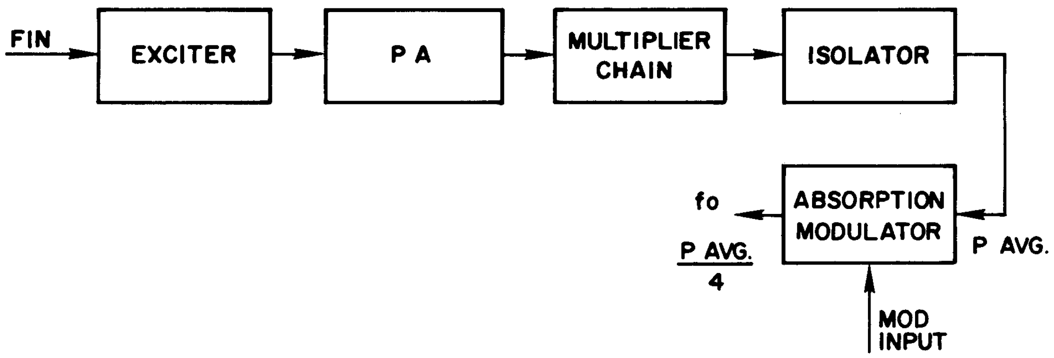
B. 1W AT PEAK

C. 3W AT PEAK

D. 6.5W AT PEAK

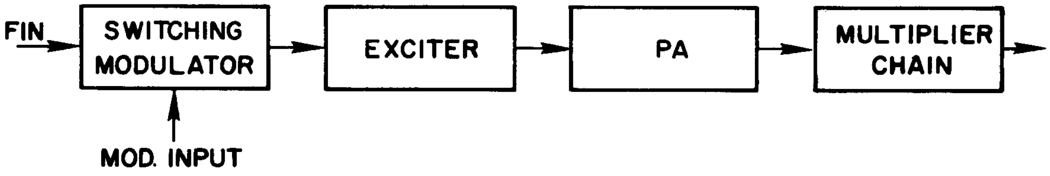
E. 6.5W AT PEAK
(MARKER AT 1 DB POINT = 10 MHZ)

Fig. 5-Swept Frequency Response of Transmitter at Various Drive Levels



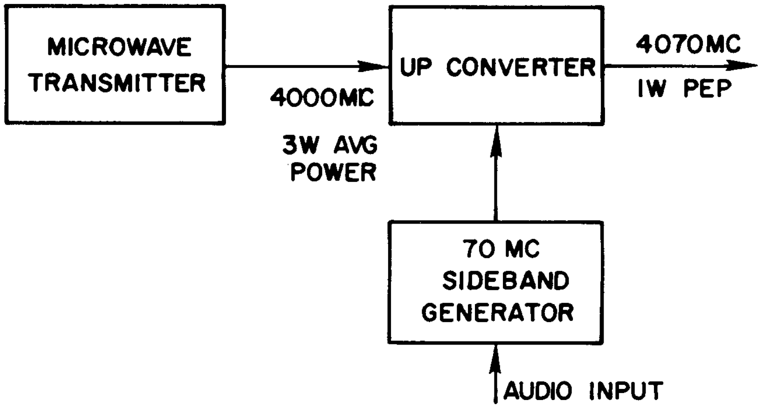
LINEAR AM MICROWAVE TRANSMITTER

Figure 6



NON-LINEAR AM MICROWAVE TRANSMITTER

Figure 7



SINGLE SIDEBAND MICROWAVE TRANSMITTER

Figure 8

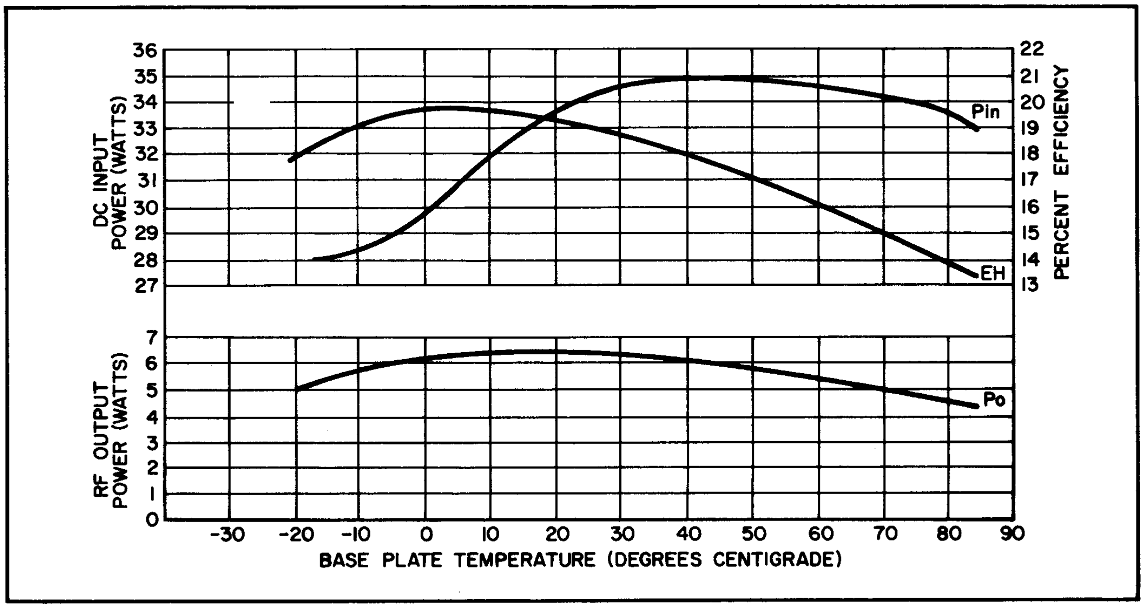
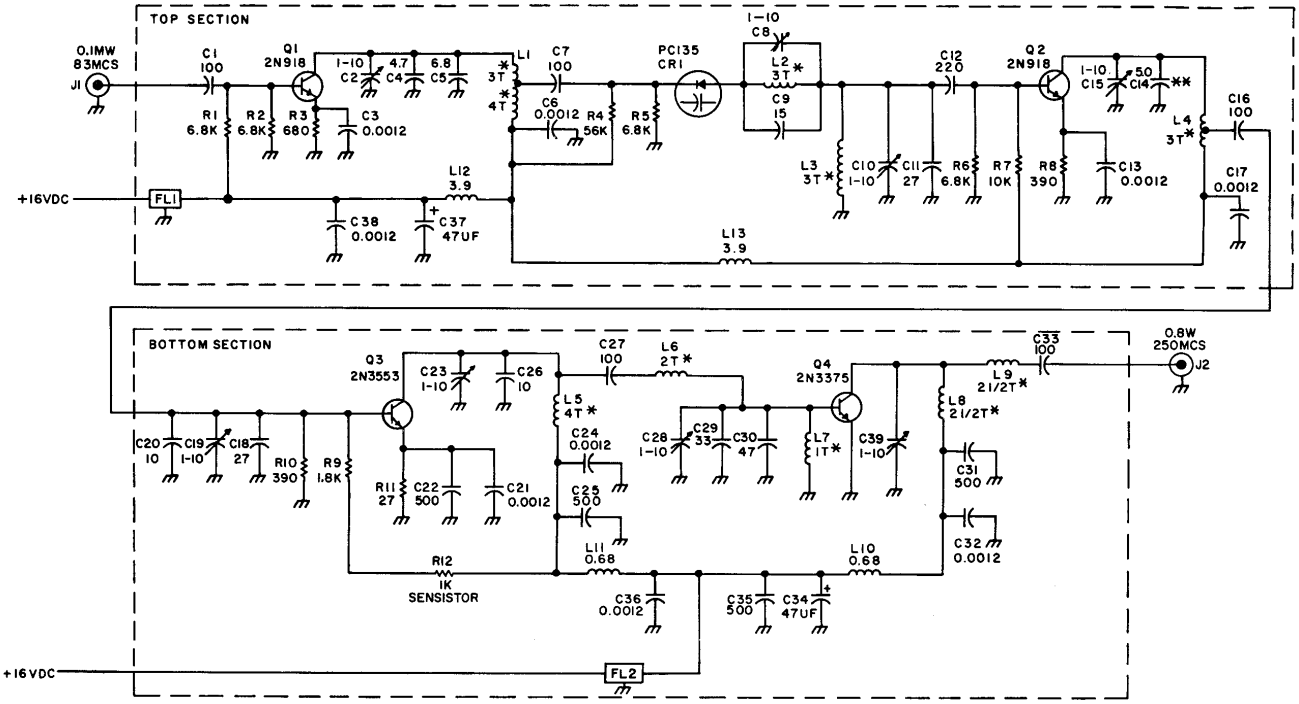


Fig. 9-L-Band Transmitter Temperature Characteristics



NOTES:

1. UNLESS OTHERWISE NOTED: ALL CAPACITORS ARE IN UUF; ALL INDUCTORS IN UH; ALL RESISTORS IN OHMS.
2. * NO.22 WIRE WOUND ON 3/16 INCH FORM.
3. ** TYPE N450 TEMPERATURE COMPENSATING.

Fig. 10-RF Exciter Schematic

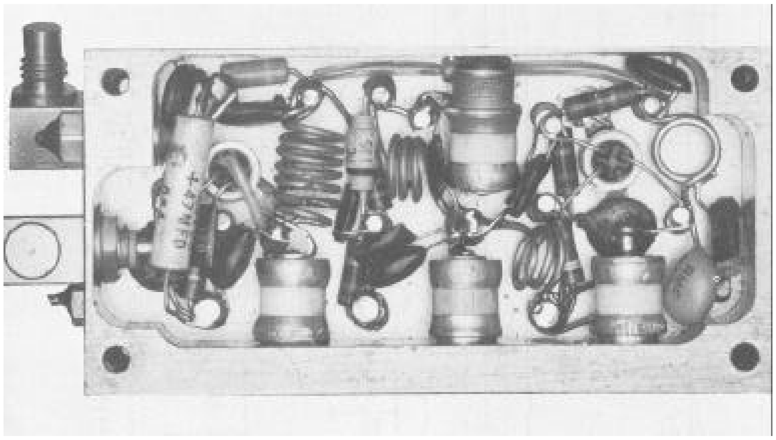


Fig. 11-Low Level Exciter

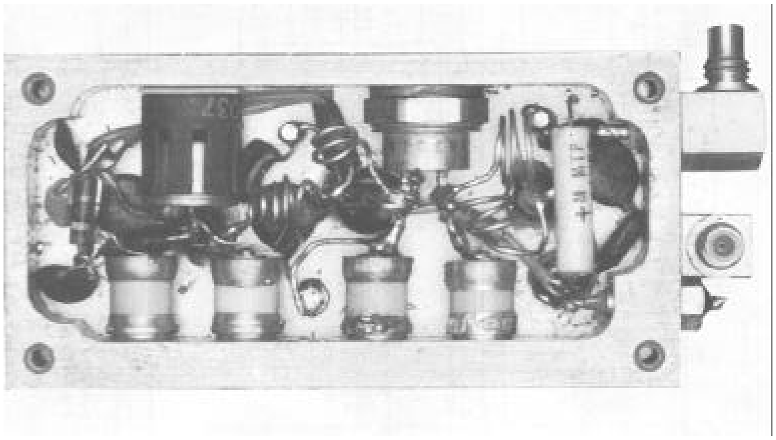


Fig. 12-RF Exciter Module, High Level Section

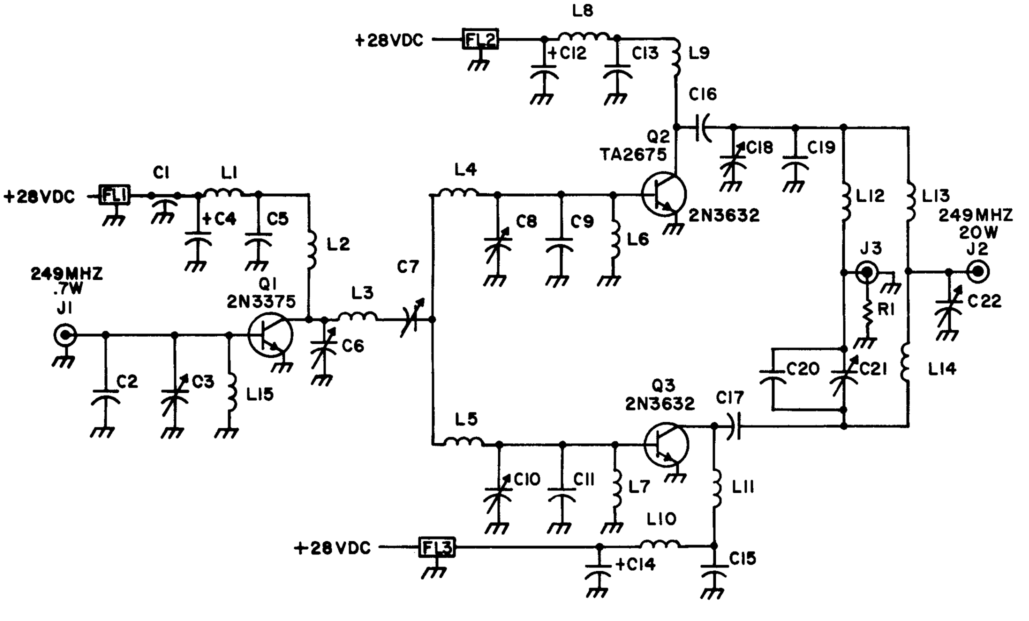


Fig. 13-Power Amplifier Schematic Diagram

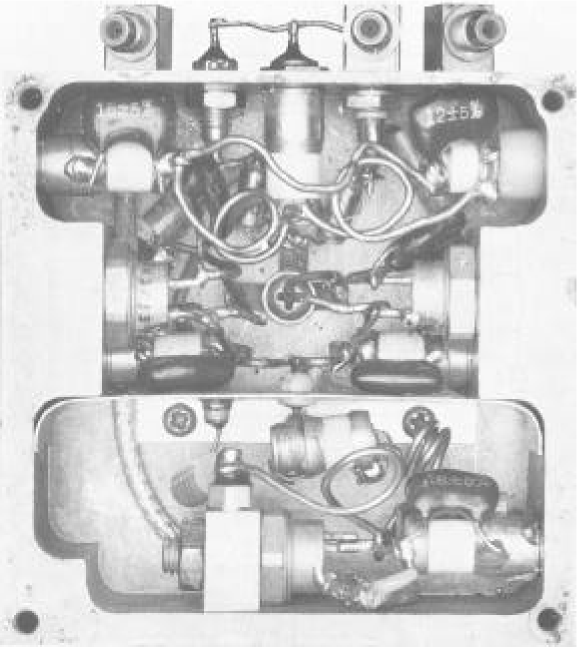


Fig. 14-Power Amplifier Module

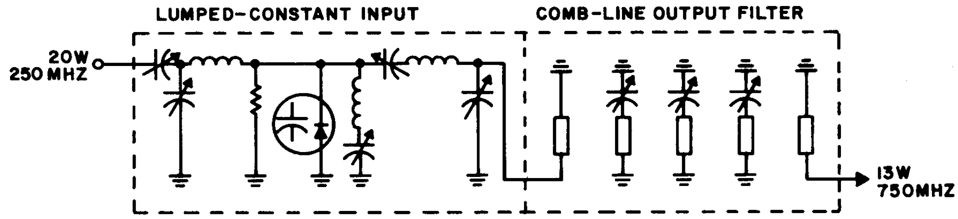


Fig. 15-First Tripler Circuit Diagram

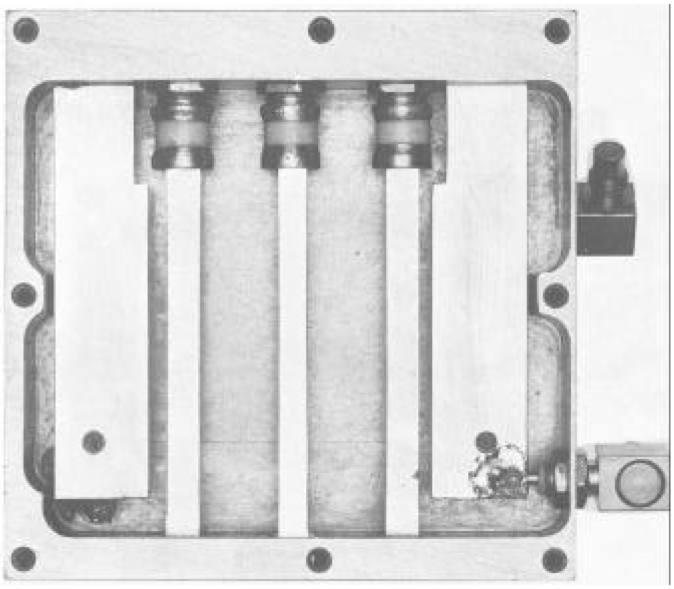


Fig. 16-First Tripler Module

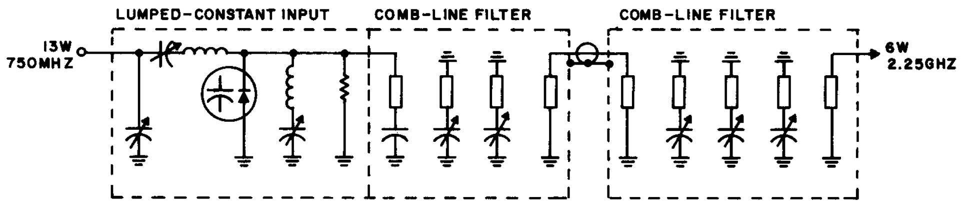


Fig. 17-Second Tripler Circuit Diagram

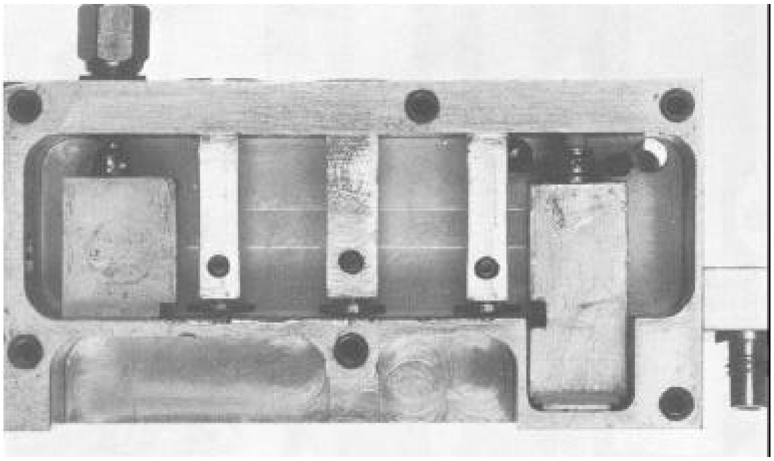


Fig. 18-S-Band Trippler

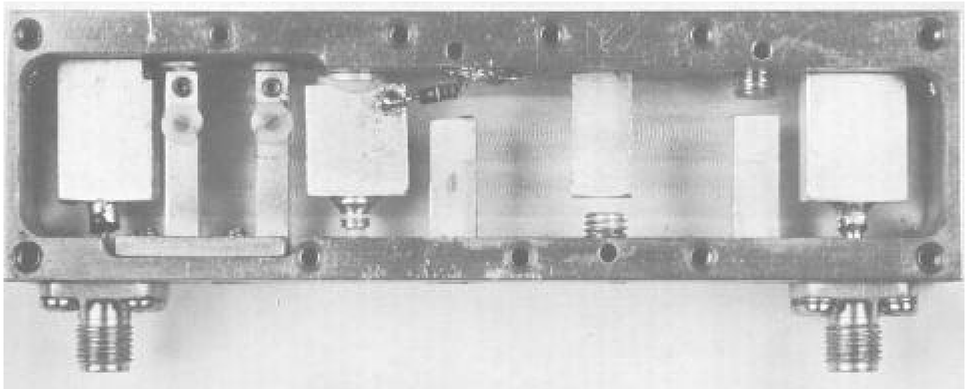


Fig. 19-C-Band Doubler