A SINGLE-TRANSISTOR, L-BAND TELEMETERING TRANSMITTER

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The exceptional high-frequency capabilities of the new RCA overlay transistors, together with the variable-reactance characteristics of the collector-to-base p-n junction in these transistors, have made possible the development of a novel, efficient microwave power source called the transistor oscillator-multiplier. In this type of power source, a single overlay transistor is used as the active component for both an rf oscillator and an output frequency multiplier to develop microwave signals at frequencies well beyond those considered in the normal range of transistor capability. This paper describes a developmental transistor oscillator-multiplier type of microwave power source, RCA Dev. No. S-131, intended for use as an L-band telemetering transmitter. Fig. I shows a photograph of the basic S-131 unit and a variant of this unit, the S-131VI.

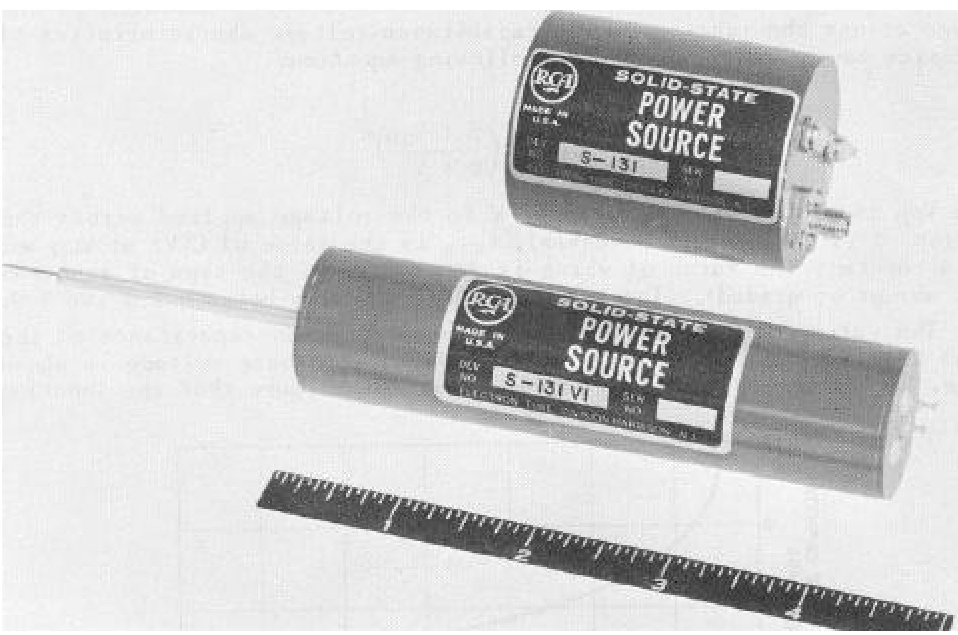

Fig.1- The S-131 L-Band Power Source, a transistor oscillator-multiplier intended for use as a telemetering transmitter.

The S-131 L-band power source is a compact, lightweight device capab I e of delivering more than 250 milliwatts of output power at an efficiency of 12 per cent when operated at a center frequency of 1680 megacycles. The power source can be easily adapted for either frequency or pulse modulation, and its center frequency can be readily changed over a 2-per-cent tuning range by a single screw adjustment. These characteristics, together with the inherent reliability and simplicity of the solid-state circuit, make possible the use of the S-131 as a highly dependable L-band telemetering transmitter capable of excellent performance in a wide range of applications.

PRINCIPLES OF OPERATION

The operation of the transistor oscillator-multiplier (TOM) is essentially the same as that of an rf power source which consists of a transistor oscillator in cascade with a separate varactor-diode frequency multiplier, except that in the TOM a single transistor provides both the amplification for the oscillator and the nonlinear reactance (voltage-variable reactance) for the multiplier. In the S-131 L-band unit, these dual functions are provided by the RCA-2N3553 overlay transistor. This transistor can simultaneously fulfill the active-component requirements of both the oscillator and the multiplier because of the voltage-variable characteristics of its collector-to-base junction capacitance. This capacitance varies with the voltage across the junction in much the same way as that of a varactor diode so that, in effect, a varactor diode is built into the transistor.

Varactor Characteristics of Collector-to-Base-Junction

A varactor (variable-reactance) diode is a semiconductor junction in which the junction capacitance varies nonlinearly as a function of the voltage across the junction. The capacitance-voltage characteristics of the device may be expressed by the following equation:

$$C(V) = C_{min} \left(\frac{\phi + V_{BD}}{\phi + V} \right)^{\frac{1}{n}}$$

where V_{BD} is the breakdown voltage, V is the voltage applied across the junction, ϕ is the contact potential, C_{min} is the value of C(V) at V_{BD} and n is a constant, the value of which is determined by the type of junction (e.g. abrupt or graded). The value of n is typically between 2.0 and 3.0.

The variation in the collector-to-base junction capacitance of the 2N3553 transistor as a function of the collector-to-base voltage is shown in Fig. 2. It is apparent from the curve in this figure that the junction

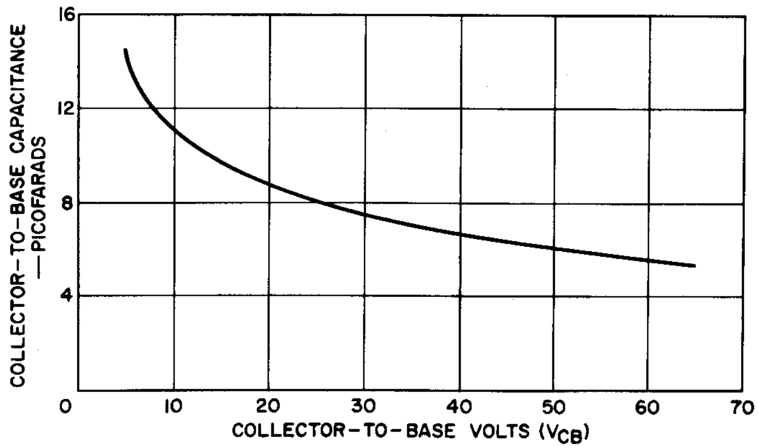

Fig.2 -Collector-to-base junction capacitance of the RG4-210553 overlay transistor as a function of the voltage applied across the junction.

capacitance is also nonlinearly dependent upon the junction voltage. It was further determined that for an n of 2.5, a value well within the typical range for a varactor diode, this curve is essentially defined by Eq.(D. Thus, the collector-to-base junction of the 2N3553 transistor exhibits the same characteristics as those of a varactor diode and may be considered as such in the design of a transistor-oscillator-multiplier.

The Oscillator Circuit

Fig. 3 shows a schematic of the S-131 circuit. The dotted line encloses the oscillator portion of the circuit; the remainder of the circuit together with the collector-to-base junction capacitance of the 2N3553 transistor forms the multiplier. As shown in the figure, a conventional grounded-base configuration was employed for the transistor oscillator. The grounded-base arrangement assures that the collector-to-base (varactor) terminals are the oscillator output terminals and thus the multiplier input terminals.

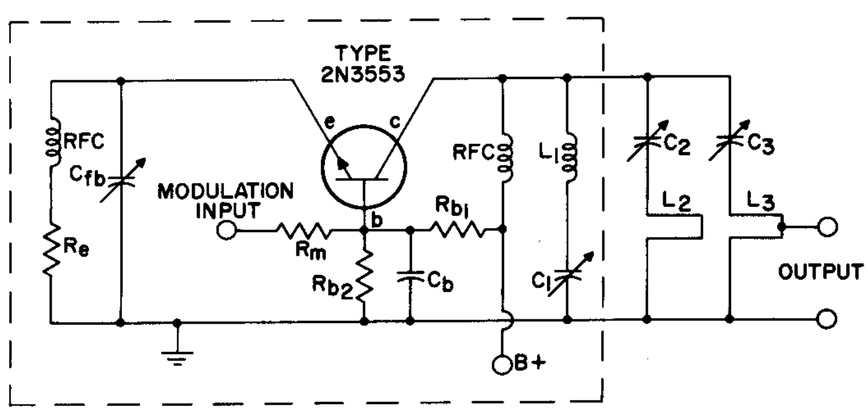

Fig. 3 - Schematic of the S-131 L-band TOM power source.

An equivalent circuit of the oscillator is shown in Fig. 4. The diagram on the left shows that the oscillator feedback loop is formed by the impedances Z_2 and Z_3; in the diagram on the right, it is shown that Z_2 represents the collector-to-emitter capacitance C_{ce} and that Z^3 represents the variable capacitor C_{fb}, shown in Fig. 2. These capacitances form a voltage divider which permits the amount of feedback voltage to be controlled by the adjustment of capacitor C_{fb}. The oscillator output impedance, Z_1, includes the lumped components L_1 and C_1 in parallel with the

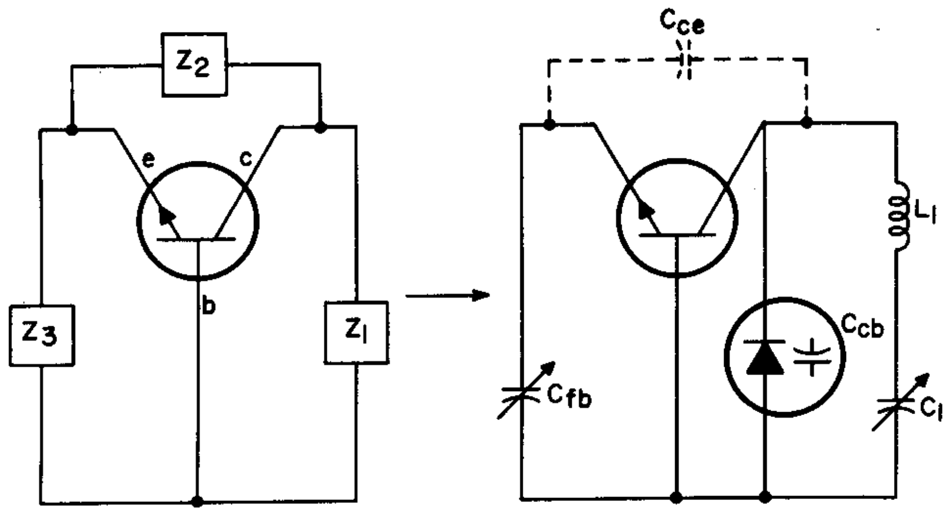

Fig. 4 - AC equivalent circuits of the oscillator section of the TOM.

collector-to-base (varactor) capacitance, C_{cb}, of the transistor. This combination formstheoutput resonant circuit which essentially establishes the fundamental frequency of the oscillator. The variable capacitor CI is used to adjust the fundamental oscillator frequency and thereby to control the output frequency of the TOM.

The operating point of the oscillator is established by the dcbiasing resistors R_{b1}, R_{b2}, and R_e, shown in Fig. 3. The optimum values for these resistors were determined empirically. Operating at a frequency of 420 megacycles, the oscillator has an efficiency of about 35 to 40 per cent and provides 0.75 watt of output power.

The Multiplier Circuit

The equivalent circuit of the over-all TOM is shown in Fig. 5. In this circuit, the transistor is shown as a power source which operates at the fundamental oscillator frequency, f_1. Each of the impedances Z_2 and Z_4, the idler and output resonant circuits of the multiplier, respectively, consists of a shorted section of microstrip transmission line in series with a variable capacitor. The oscillator and multiplier sections are joined together by the capacitance of the collector-to-base junction of the transistor. Because of the voltage-variable capacitance characteristics of this junction, this capacitance, C_{cb}, is represented by a varactor diode.

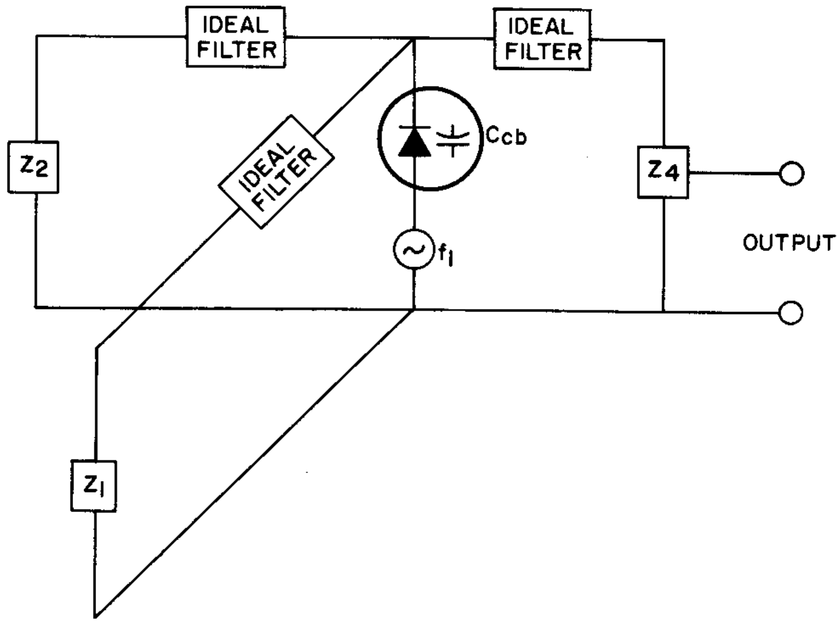

Fig.5 -Equivalent circuit of the TOM.

It is well known that the nonlinear, voltage-variable capacitance characteristics of a semiconductor junction (varactor diode) provide the basis for an efficient frequency-multiplier process.[1] The principles of operation of a varactor-diode frequency multiplier have been described in detail by Penfield and Rafuse[2]. These principles are equally applicable to the multiplier circuit in the S-131. Briefly, this multiplier allows all the fundamental, 420-megacycle current developed by the oscillator to flow through the varactor junction of the transistor so that the nonlinear capacitance of the junction (C_{cb} Fig. 5) can generate harmonics of the fundamental frequency. For efficient operation, the quadruplet requires an idler, which is a circuit that is resonant to twice the fundamental oscillator frequency, $2f_1$. In the equivalent circuit shown in Fig. 5, this idler circuit is represented by the varactor and the impedance Z_2.

The idler allows all the second-harmonic ($2f_1$) current to be circulated through the varactor; this action, in turn, produces the second harmonic of the circulating current, $4f_1$, which increases the total available output power from the quadruplet. The output impedance of the multiplier, Z_4, should be resonant with the varactor at the harmonic desired as the output.

DESIGN APPROACH

In the design of the S-131 L-band power source, the oscillator and multiplier sections were considered as two distinct circuits Joined together by the collector-to-base unction of the 2N3553 overlay transistor. Important considerations included the use of this variable-reactance junction as both the load impedance for the oscillator and the source for the multiplier, and the selection of the optimum type of impedance for the idler and output circuits of the multiplier.

In most conventional oscillators, the power developed is usually delivered to an external load impedance. In a TOM, however, the main element of the oscillator load impedance is the varactor junction, which I'S also the source for the multiplier.

In the multiplier section of the TM, the idler impedance and the output impedance (shown as Z_2 and Z_4 on the TDM equivalent-circuit schematic given in Fig. 5) are required to be resonant with the varactor-junction capacitance of the transistor at the second and fourth harmonics, respectively, of the fundamental oscillator frequency. For an oscillator frequency of 420 megacycles, the resonant frequency of the idler circuit should be 840 megacycles, and that of the output circuit should be 1680 megacycles. At these frequencies, it is extremely difficult to construct a coil type of inductor having the high unloaded Q required. Moreover, the limitations imposed on the size and weight of the TOM precluded the use of waveguides or coaxial lines for the resonant circuits. For these reasons, a shorted length of microstrip transmission line in series with a variable capacitor was used for the idler and output resonant circuits. The lengths of microstrip required for these circuits can be determined from either Smith Chart impedance plots or the impedance equations for transmission lines. The calculations are relatively simple and straightforward, although the loading effect of the collector-to-base capacitance may present a slight problem because the average value of the dynamic capacitance can only be approximated.

PERFORMANCE

In a typical TOM (RCA S-131) the output frequency is nominally 1680 megacycles with a power output of 250 milliwatts and an efficiency of 12 per cent. Because the collector-to-base capacitance is a part of the oscillator tuned circuit and its values are a function of voltage, the output frequency can be tuned electronically by varying the supply voltage. Fig. 6 is a plot of power output, efficiency, and frequency as functions of the dc supply voltage. It can be seen from the curves that the modulation sensitivity of the collector is approximately 2.5 megacycles per volt. The frequency change with voltage dictates the use of a regulated supply if frequency stability is desired. The performance with a voltage regulator as a part of the unit is illustrated in Fig. 7. The regulator is simply constructed, using a transistor with a zener diode as the reference. The addition ofthis regulator reduces the over-all efficiency to approximately 8 per cent.

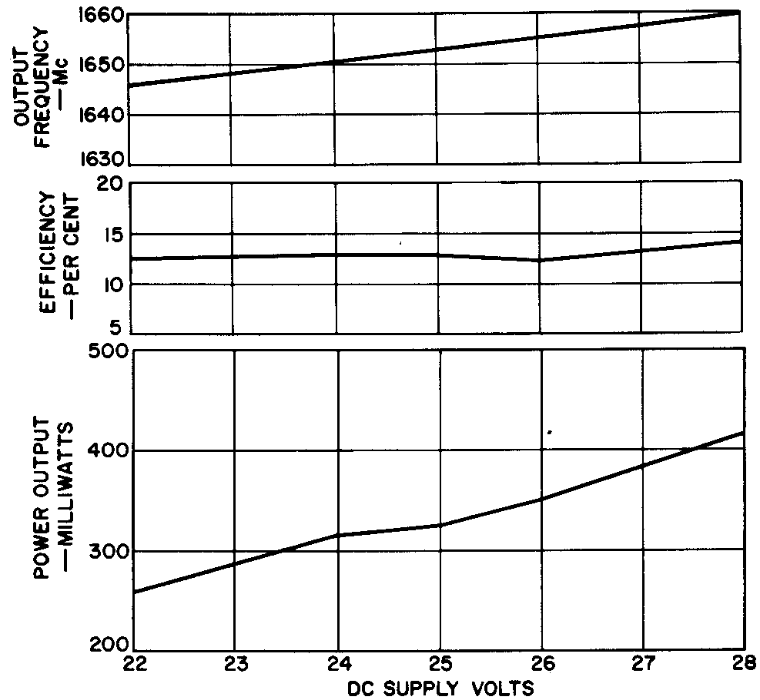

Fig.6- Power output, frequency, an efficiency of the TOM as a function of the supply voltage without regulation.

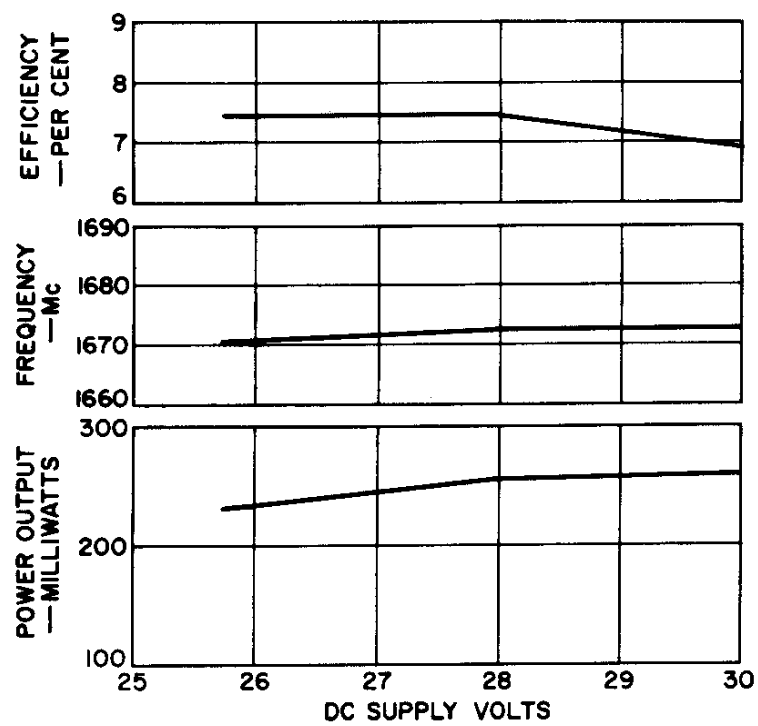

Fig 7 - Power output, frequency, and efficiency of the TOM as a function of the dc supply voltage with a voltage regulator.

The performance of the TOM is also affected by changes in the ambient temperature. Sensitivity of the unit to temperature is demonstrated by the plots of the variation in frequency, efficiency, and power output with temperature shown in Fig. 8 (without voltage regulator). To obtain a minimum variation of power output and frequency over the temperature range, two different types of compensation were required. A positive-temperature coefficient resistor was used in the base-bias circuit in place of R_{b1} (Fig. 3) to maintain a constant bias current which effectively reduced the variation inoutput power. In addition, a negative-temperature-coefficient capacitor was placed in parallel with the variable capacitor from emitter to ground to control the frequency. The performance of a power source which employed these two types of compensation (with voltage regulator) is shown in Fig. 9. The variation in frequency from -50°C to 75°C was only 1 megacycle, while the power output changes a total of approximately 3 db over this range.

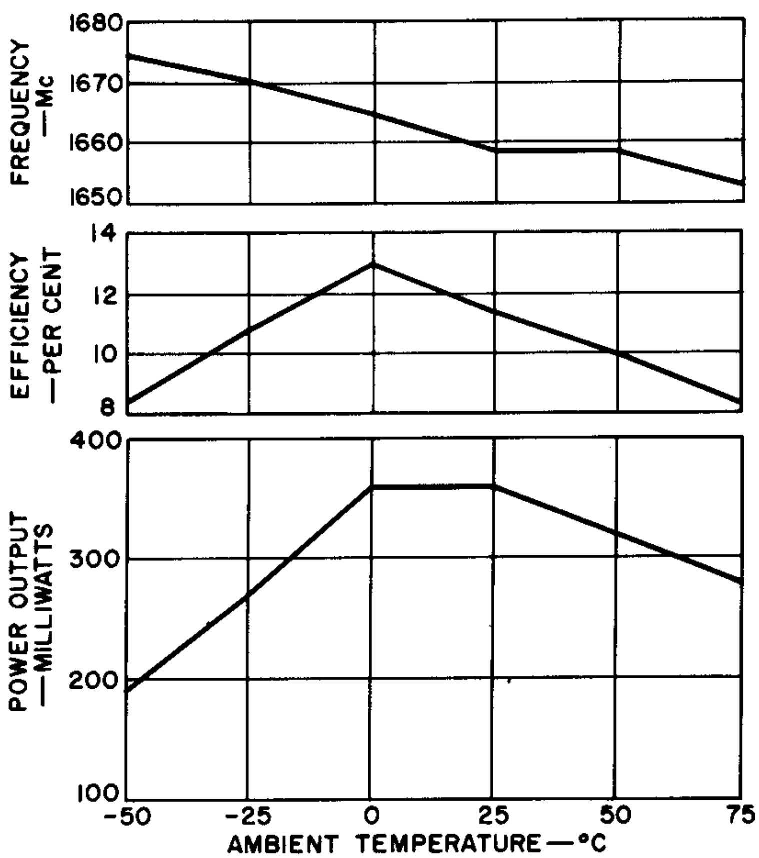

Fig.8 -Power output, frequency, andefficiency of the TOM as afunction of ambient temperature for a unit operatedwithout temperature compensation and from an unregulated dc power supply.

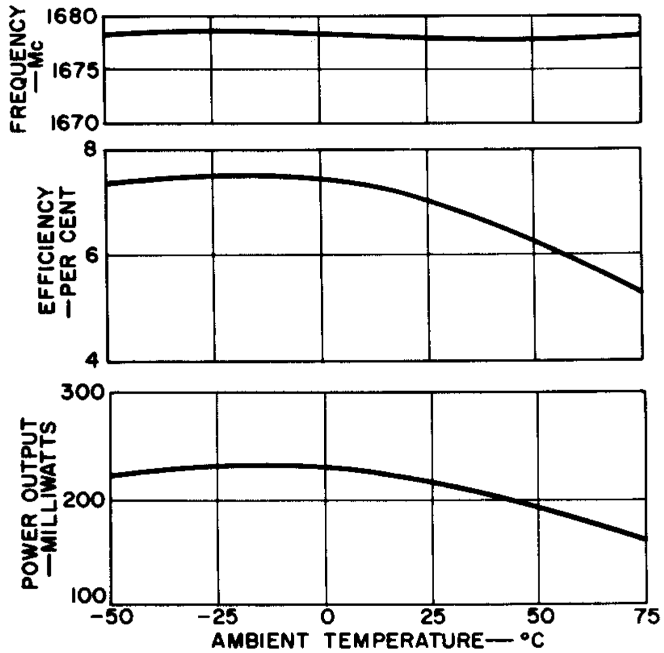

Fig. 9 -Power output, frequency, and efficiency of the TOM as afunction of ambient temperature for a temperature-compensated unit operated with a voltage regulator.

The unit can also be easily adapted for frequency modulation. This modulation is implemented by applying the modulating voltage through a series resistor to the base. The modulation sensitivity of the base depends upon the value of the series resistor. With a modulating frequency of 50 kilocycles, sensitivities of 0.5 to 1 megacycle per volt (rms) are typical.

The oscillator frequency is primarily determined by the combination of L_1 and C_1 (Fig. 3). By adjusting C_1, it is possible to vary the output frequency without tuning any other variable. Fig. 10 shows a curve of power output as a function of frequency for the single-screw tuning.

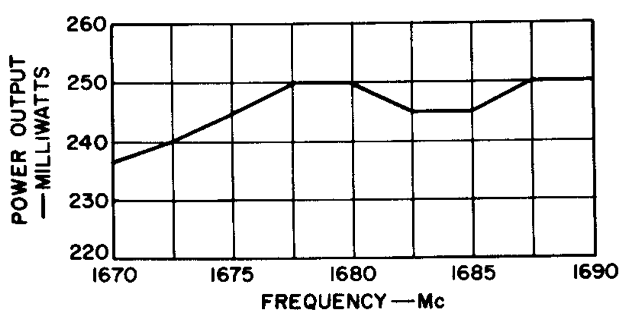

Fig.10 -Power output as a function of frequency using mechanical single-screw tuning.

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BIBLIOGRAPHY

1. Leeson, D. B. and Weinab, S., "Frequency Multiplication with Nonlinear Capacitors - A Circuit Analysis", Proc. IRE.

2. Penfield, P. and Rafuse, R. , "Varactor Applications", MIT Press.