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MODULATED TRANSISTOR OSCILLATORS AND THEIR APPLICATIONS

RADIO CORPORATION OF AMERICA
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Modulated Transistor Oscillators and Their Applications

Approved

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Introduction

The low power drain and small physical size of transistors make them particularly suitable for miniature transmitters intended for short-range applications. Several such experimental applications were described in LB-898, *Progress Report on Transistor Research and Circuit Applications*. This bulletin deals with the working principles and modulation characteristics of both junction and point-contact transistor oscillators in various circuit arrangements. Both amplitude modulation and frequency modulation are considered.

Amplitude modulation of transistor oscillators can be achieved by means of collector modulation, base modulation, or emitter modulation. Factors governing the linearity of different kinds of modulation are discussed. Modulating power is high for collector modulation and low for base modulation. The input impedance to modulation at the base can be made high, of the order of 10^5 ohms.

Frequency variation due to applied amplitude modulation can be minimized by modulating two electrodes of the transistor simultaneously. A reverse process for frequency modulating an oscillator with minimum amplitude variation is also described.

I. Amplitude Modulation

(A) Junction Transistor Oscillator

Fig. 1 shows a typical junction transistor oscillator of the reversed feedback type. It can be modulated either at the base, emitter or the collector. The mechanism of modulation can be understood from the following analysis.

(a) Collector Modulation

When oscillation is sustained, the collector voltage and current can be represented approximately by Fig. 2(a) and (b). At the instant of maximum collector current pulse the voltage at the collector is the difference between the collector supply voltage, V_{CC}, and the voltage drop, I_cR_l, across the load due to the fundamental frequency component of current flowing through the r-f load R_l. If this minimum

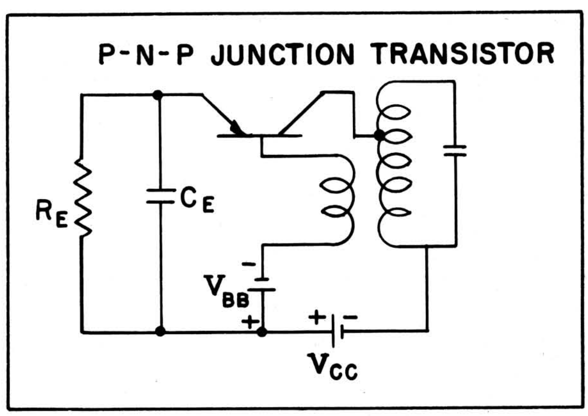

Fig. 1 - Typical p-n-p junction transistor oscillator circuit.

collector voltage, v_{cem}, lies in Region A of

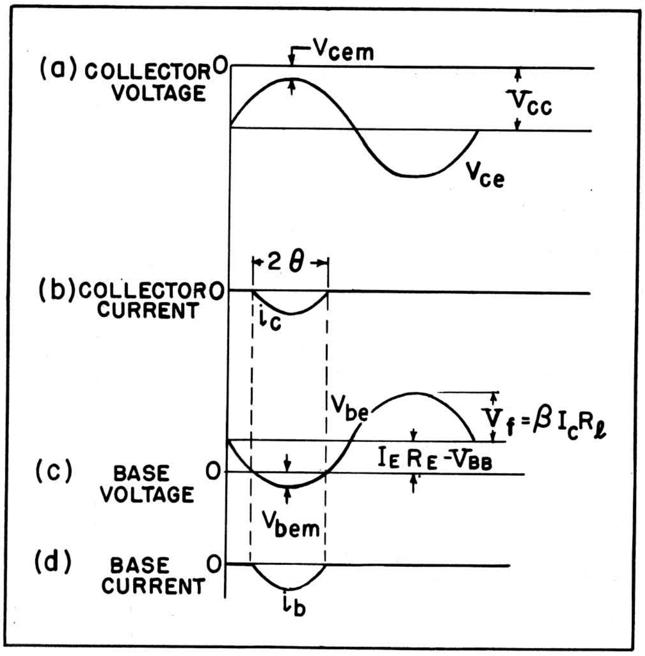

Fig. 2 - Current and voltage relations at the collector and at the base of typical junction transistor oscillator.

the collector output characteristic as shown at point "a" in Fig. 3, it is approximately equal to zero. Then the r-f voltage varies linearly with modulation, the r-f voltage also varies linearly with modulation.

If the minimum difference voltage does not lie in Region A but lies in Region B of the collector characteristic, say point "b", any increase of V_{CC} does not increase the collector current but only serves to increase v_{cem}. For this duration of the modulation cycle, the r-f voltage does not change. The result is that the modulation is no longer linear. Therefore, in order to have linear collector modulation, it

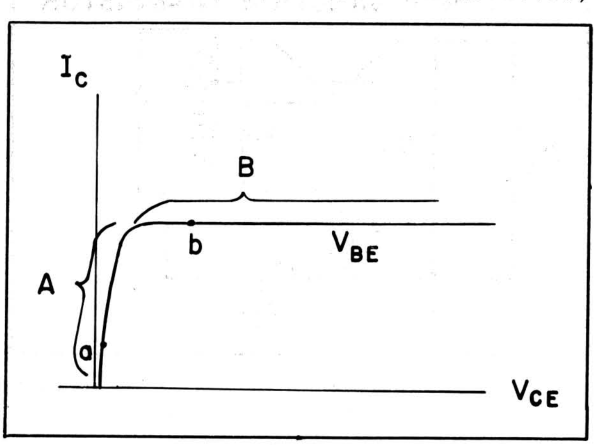

Fig. 3 - Collector output characteristic of a junction transistor.

is necessary to keep V_{CC} low or I_cR_l high.

Fig. 4 shows a set of collector modulation characteristics. Note that when high R_l is used, modulation is linear, whereas when low R_l is used output flattens at high amplitudes.

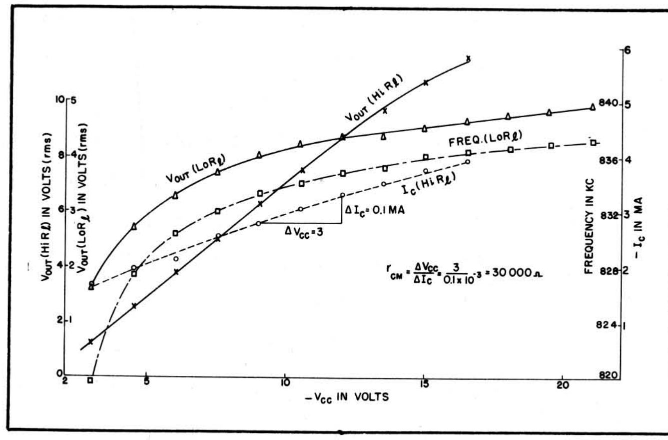

Fig. 4 - Collector modulation characteristics of a junction transistor oscillator.

(b) Base Modulation

In base modulation, the d-c base voltage, V_{BB}, is changed to cause a change in output current I_c. If the base-to-emitter impedance, r_{be}, the flow angle, 2θ, and the collector-to-base current amplification, A_{cb}, can be maintained constant as base voltage is varied, the modulation is linear. This can be seen from Fig. 2(c) and (d). If the base-to-emitter impedance is constant, the base current pulse will be of the same shape as the voltage pulse lying below the line of cutoff. By Fourier analysis it can be shown that the base r-f current is related to this pulse as a function of the flow angle.[1] The base r-f current is amplified, producing an r-f voltage across the load R_l which is fed back to the base. Thus, if the current amplification, the load, and the r-f base-to-emitter impedance remain unchanged, the flow angle will not change for whatever values of currents, or the bias $I_ER_E - V_{BB}$ which the feedback voltage βI_cR_l must overcome in order to cause current flow. However, if the bias is changed by changing V_{BB} the currents I_E and I_C must proportionately increase in order to maintain the same flow angle. Thus, it is established that the output current varies linearly with the applied base voltage pro-

[1] W. L. Everitt, COMMUNICATION ENGINEERING, McGraw-Hill Co., 1938, pp. 565-572.

vided the collector-to-base current amplification and base-to-emitter impedance are constant.

In order to obtain satisfactory linear modulation, the transistor should be operated in such a way as to keep the base-to-emitter impedance, the current amplification and the r-f load as constant as possible. As R_l is somewhat dependent on r_{be}, to which it couples, only r_{be} and A_{cb} need be considered.

A_{cb} is relatively constant when the collector current is sufficiently high or v_{cem} lies in Region B of the collector output characteristic. If $I_c R_l$ is increased or the collector supply voltage is decreased to a point where v_{cem} lies in Region A, A_{cb} can no longer be considered constant. The effect is shown in the set of base modulation characteristics in Fig. 5. Note that when R_l is used, the characteristics flattens in contrast to the linear characteristic obtained with low R_l.

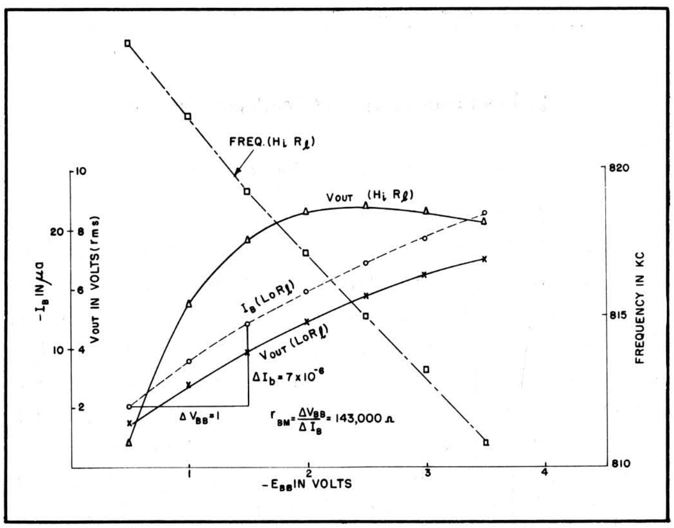

Fig. 5 - Base modulation characteristics of a junction transistor oscillator.

The base-to-emitter impedance for small signal consists of the base resistance r_b and an equivalent impedance equal to the product of emitter resistance r_e and some function of current amplification.[2] Usually r_b is relatively constant, but r_e decreases with increase in emitter current.[3] If the equivalent product impedance is made smaller than r_b, then r_{be} will not change very much. A large emitter current may be used to make r_e, hence the product, small. An impedance in series with the base will make the effective r_b high. An impedance in series with r_e will make the effective r_e less changeable with emitter current. One or more of these means may be incorporated in the design of such oscillators for achieving modulation linearity.

(c) Emitter Modulation

The mechanism of emitter modulation is similar to that of base modulation. The factors governing the modulation linearity in the case of base modulation apply equally well to emitter modulation. A set of emitter modulation characteristics is shown in Fig. 6.

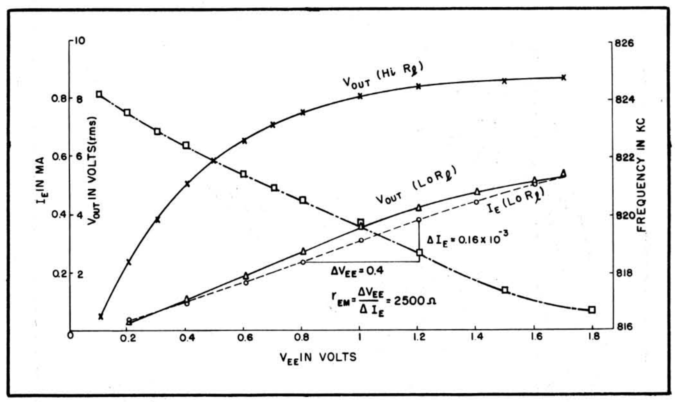

Fig. 6 - Emitter modulation characteristics of a junction transistor oscillator.

(B) Point-Contact Transistor Oscillators

Point-contact transistor oscillators are ordinarily designed to operate by virtue of their negative resistance characteristics.[4] One type of point-contact transistor oscillator is shown in Fig. 7.

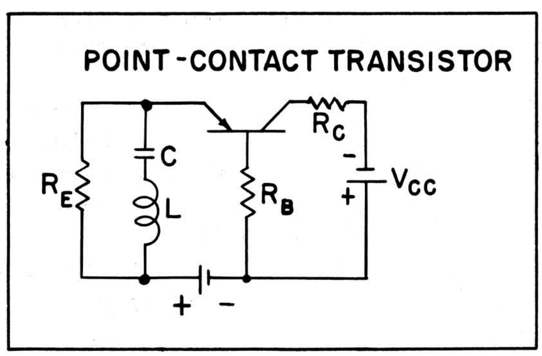

Fig. 7 - Typical point-contact transistor oscillator circuit.

[2] R. L. Wallace and W. J. Pietenpol, "Properties and Applications of n-p-n Transistors", *Proc. IRE*, July, 1951.

[3] W. Shockley, M. Sparks, and G. K. Teal, "P-N Junction Transistors", *Phys. Rev.*, July 1, 1951.

[4] LB-865, *Transistor Oscillators*.

The idealized emitter characteristic I_E - V_{EE} of the transistor[5], as shown in Fig. 8, indicates that as the collector supply voltage, V_{CC}, varies, the negative slope portion of the characteristic also varies.

If the collector-to-emitter current amplification factor α_{ce} and collector resistance r_c can be considered constant, the distance between P_1 and P_2 increases linearly with V_{CC}. As the negative slope portion enlarges, the amplitude of oscillation also increases. Linear modulation is thus possible. Under the condition that the operating point V_E changes linearly with V_{CC}. This can be approached because I_E is proportional to V_{CC} and the bias V_E can be made proportional to I_E.

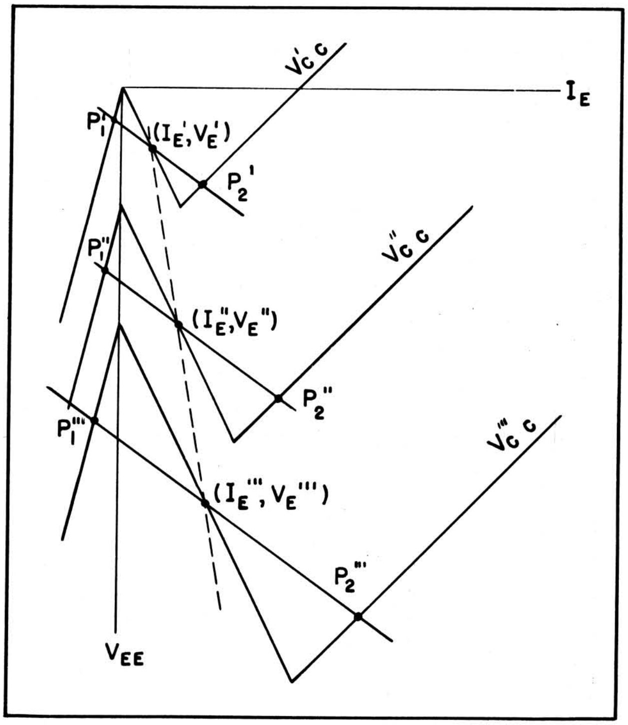

Fig. 8 - Emitter input characteristics of a point-contact transistor oscillator.

If the modulation is applied to the emitter of this oscillation, the operating point on the negative slope changes without appreciable change in the emitter current excursion. However, the ratio of fundamental frequency component current to that of harmonics changes and this change modulates the oscillator.

The effect of base modulation is essentially the same as emitter modulation, because a base voltage change causes changes in emitter current flowing in the resistance R_E. Fig. 9 shows the modulation characteristics of this kind of oscillator.

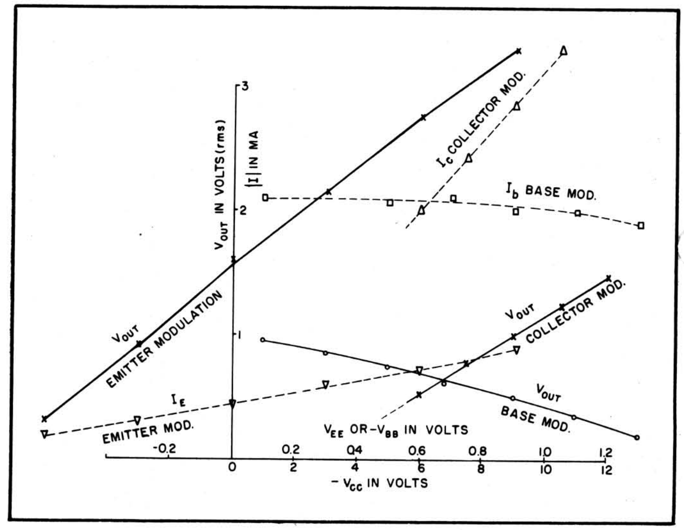

Fig. 9 - Modulation characteristics of a point-contact transistor oscillator.

II. Input Impedance and Modulating Power

(A) Junction Transistor Oscillator

(a) Collector Modulation

In the case of collector modulation of junction transistor oscillators, the d-c collector current bears a certain relationship with the r-f current depending on the flow angle and the current amplification. As was pointed out, the minimum collector voltage occurs below the knee of the collector output characteristic where the current amplification is not constant, the flow angle varies with modulation. Fortunately, the ratio of r-f current to d-c current changes very slowly with change in flow angle.[1] Hence the modulation input impedance does not have a serious change with modulation.

It can be shown analytically that the d-c current and the r-f current are of the same order of magnitude. Since the modulation input impedance is equal to the ratio of the change in d-c collector voltage to the change in d-c collector current and the d-c collector voltage is approximately equal to the peak r-f current times the r-f load. The modulation input impedance is also of the same order of magnitude as the r-f load resistance.

[5] LB-875, *Transistor Trigger Circuits.*

(b) Base Modulation

In the oscillator shown in Fig. 1 the external emitter resistance R_E is by-passed by C_E at radio frequency but not at audio frequency. As in the case of a base input audio amplifier, a high resistance in the emitter circuit is highly degenerative to a-f signals and makes the input impedance at the base high. The value of the input impedance is approximately equal to R_E times the low frequency collector-to-base current amplification factor less an amount depending on the r-f feedback of the oscillator. By making R_E high and the feedback small, a high input impedance can be obtained.

(c) Emitter Modulation

The change in emitter current is equal to the change in base current times the emitter-to-base current amplification factor. Thus the modulation input impedance of an emitter modulated oscillator is equal to the corresponding base modulation input impedance divided by the emitter-to-base current amplification factor.

Measured modulation input impedance obtained by taking the slopes of V-I curves from Figs. 4, 5, and 6 are:

$$r_{CM} = 30{,}000 \text{ ohms}$$
$$r_{BM} = 145{,}000 \text{ ohms}$$
$$r_{EM} = 2{,}500 \text{ ohms}$$

Note that the high base modulation input impedance makes it possible for the oscillator to be modulated directly from a high impedance source. Fig. 10 shows the application of this property to the Wireless Phonograph Jack described in LB-898, *Progress Report on Transistor Research and Circuit Applications*. In this unit, the r-f field set up by the oscillator is picked up by a nearby radio. The radio serves as the output device of the phonograph. The basic oscillator circuit is the same as Fig. 1. The bias for the base is obtained from a voltage divider consisting of the 2.2 M and the 220 K resistors. The 68-μμf condenser is in series resonance with 1.2-mh inductance to furnish the r-f bypass for the base. As the crystal pickup is approximately equivalent to a generator in series with a coupling capacitor of the order of 2000 μμf, the frequency response depends somewhat on the setting of the volume control due to the loading of the base input impedance.

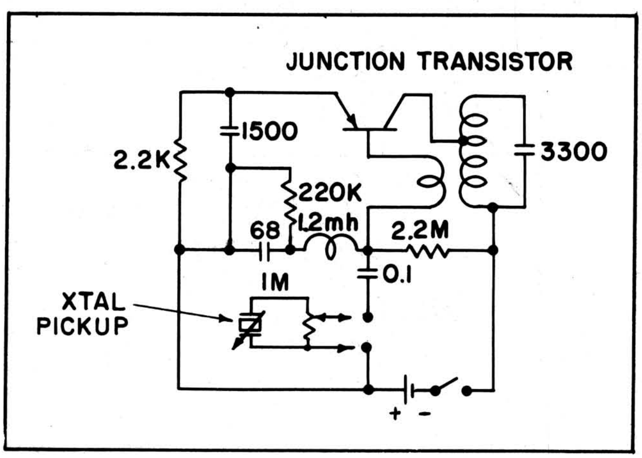

Fig. 10 - Wireless Phonograph Jack.

(B) Collector-Modulated Point-Contact Transistor Oscillators

As shown in LB-875[5], the d-c collector current corresponding to P_1 in Fig. 8 is

$$I_c = \frac{-V_{cc}}{R_b + R_c + r_c}$$

At P_2

$$I_c = \frac{\alpha_{ce} V_{cc}}{\alpha_{ce}(R_b + R_c) - R_b}$$

At the d-c operating point

$$I_c = -\tfrac{1}{2}\left[\frac{1}{R_b + R_c + r_c} + \frac{\alpha_{ce}}{\alpha_{ce}(R_b + R_c) - R_b}\right] V_{CC}$$

The collector modulation resistance is, therefore

$$r_{CM} = \frac{\Delta V_{cc}}{\Delta I_c} = 2\Big/\left[\frac{1}{R_b + R_c + r_c} + \frac{\alpha_{ce}}{\alpha_{ce}(R_b + R_c) - R_b}\right]$$

Note that a higher value of R_b or α_{ce} can increase the modulating resistance.

Example:

Given a point-contact transistor connected as shown in Fig. 7, for which R_c (external) = 560 ohms, R_b (external) = 910 ohms, r_b (internal) = 300 ohms, r_c (internal) = 20,000 ohms, α_{ce} = 5.6.

Then effective R_b = 910 + 300 = 1210 ohms.
From the last equation, r_{CM} = 3120 ohms.
The measured result obtained by taking the slope of $I_C - V_C$ characteristic of Fig. 8 is 3470 ohms.

Once the input impedance to modulation is known, the modulation power can be derived. Modulating power for 100 per cent modulation is equal to $(\Delta V_M)^2/2r_M$ or $\frac{1}{2}(\Delta I_M)^2 r_M$, where ΔV_M is the crest modulating voltage, ΔI_M is the crest modulating current and r_M is the input resistance to modulation.

To compare base modulation with collector modulation on the same basis, assume the same R_l and same maximum r-f current in the collector at 100 per cent modulation. Since the a-f collector current is of the same order of magnitude as the r-f collector current and the corresponding a-f base current is reduced by a factor equal to the current amplification factor, the higher the current amplification factor, the smaller the base current. In general, the modulating power for base modulation is much less than that for collector modulation. A typical set of values of modulating power with collector supply of 22.5 volts are:

P (Collector modulation) = 8 mw
P (Base modulation) = 15 μw
P (Emitter modulation) = 1 mw

In the case of a collector-modulated point-contact transistor oscillator of the first type just described, the modulating power depends on the maximum swing in collector voltage ΔV_{CC} and is equal to

$$\frac{1}{2}\frac{(\Delta V_{CC})^2}{r_{CM}} = \left(\frac{\Delta V_{CC}}{4}\right)^2 \left[\frac{1}{R_b+R_c+r_c} + \frac{\alpha_{ce}}{\alpha_{ce}(R_b+R_c)-R_b}\right]$$

Assuming ΔV_{CC} = 24 volts in the example given previously, the modulating power is 21 mw.

III. Frequency Stabilization of Amplitude-Modulated Transistor Oscillator

When modulation is applied to any electrode of a transistor oscillator, frequency modulation as well as amplitude modulation is produced. The reason for this is that a voltage change in any electrode causes a change in the effective internal capacitance.

It was found, however, that in a circuit such as that shown in Fig. 1, the effect on frequency due to collector modulation is opposite to that due to base modulation. A set of

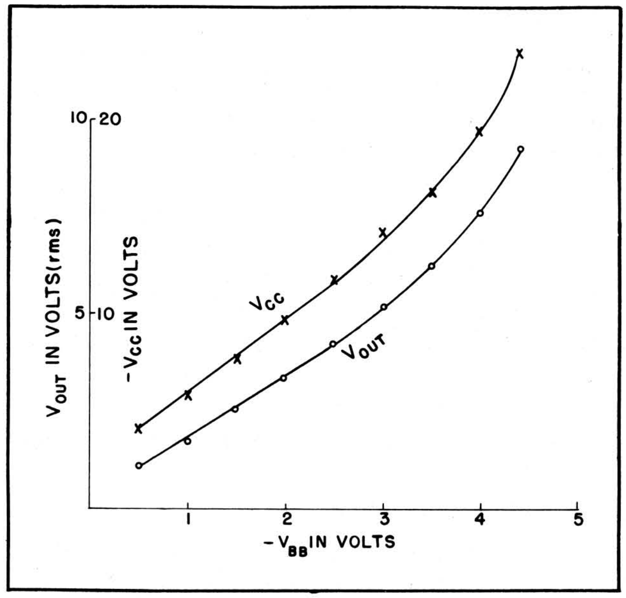

Fig. 11 - Constant frequency characteristics of an amplitude-modulated junction transistor oscillator.

constant frequency characteristics is shown in Fig. 11. Note that the base modulating voltage necessary for maintaining constant frequency is a linear function of V_{CC}. Note also that the modulation characteristic is linear over a wide range of V_{CC}.

Although the analytic relationship between V_{CC} and V_{BB} for maintaining constant frequency is not a linear one, actual experiment shows a wide range of linearity. Thus, by modulating the base and the collector simultaneously, it

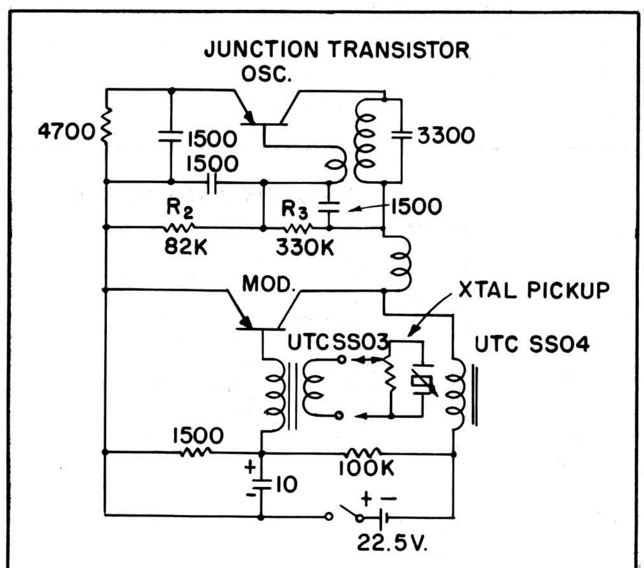

Fig. 12 - Frequency stabilized phonograph oscillator.

is possible to eliminate frequency modulation to a large degree.

This method for eliminating frequency modulation was employed in the Transistor Phonograph Oscillator described in *LB-898*. The circuit diagram is shown in Fig. 12. In this circuit, modulation is directly applied to the collector. R_2 and R_3 serve as a voltage divider to feed a portion of the modulation to the base for maintaining constant frequency.

IV Frequency Modulation

Frequency modulation can be produced by modulating any one of the electrodes of a transistor oscillator. However, frequency modulation is often accompanied by amplitude modulation. In order to achieve satisfactory frequency modulation, attention should be directed to the elimination of amplitude modulation and the linearity of frequency deviation.

(A) Collector Modulation

Referring again to Fig. 2(a), $v_{cem} = V_{CC} - I_C R_l$. When $I_C R_l$ is made much less than V_{CC} so that v_{cem} is operating in the saturation region of the collector output characteristic, then any change in V_{CC} will not change the current and hence the amplitude of oscillation. Fig. 4 shows the flattening of the modulating characteristics at higher values of V_{CC} particularly when low R_l is used. The corresponding frequency deviation is also shown in the same graph.

(B) Base or Emitter Modulation

In base or emitter modulation, operation is dependent upon v_{cem} lying in the saturation region of collector output characteristic. Any change in base or emitter voltage then only changes the frequency. This is shown in Figs. 5 and 6.

(C) Double Modulation

An effective way to eliminate amplitude modulation is to modulate two electrodes at the same time. This is the reverse of the process used in stabilizing frequency (Section III). By proper proportioning of the modulation applied to two different electrodes, it is possible to minimize amplitude modulation and to obtain linear frequency modulation. In addition, the frequency deviation can be increased over that obtainable when modulation is applied to only one electrode. Fig. 13 shows a constant-amplitude frequency modulation characteristic. Note that there is a region where frequency deviation is quite linear.

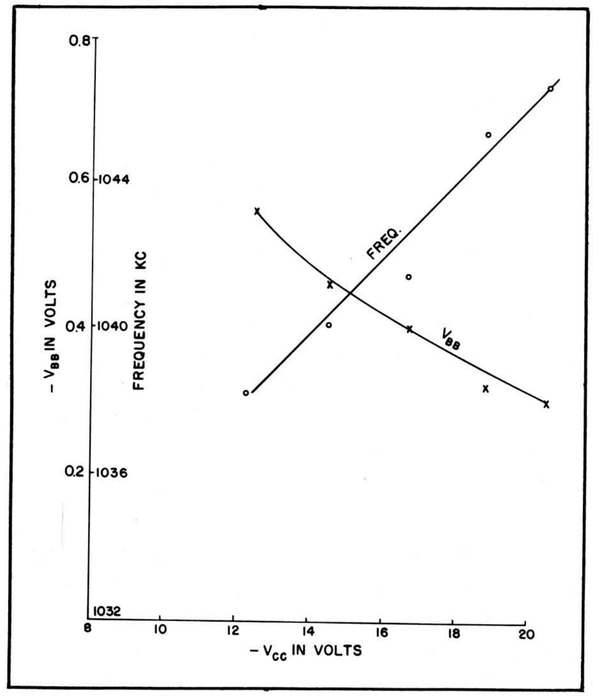

Fig. 13 - Constant amplitude characteristics of a junction transistor oscillator.

A practical application is the Roving Microphone shown in Fig. 14. This is a 90-Mc FM transmitter employing a point-contact transistor. By proper choice of R_2 and R_3, the

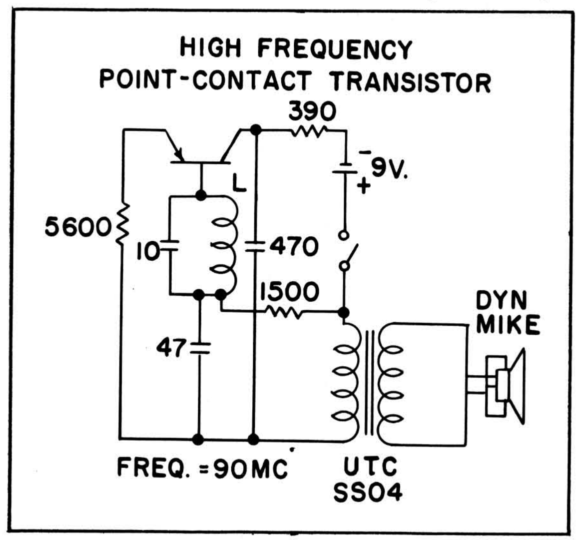

Fig. 14 - Constant amplitude FM point-contact transistor oscillator.

modulation applied to the emitter and that to the collector is in the correct proportion to produce frequency modulation with minimum amplitude modulation.

V. Self Modulation

A transistor oscillator can be made to be self-quenching simply by using a large RC time constant in the emitter circuit. The operation is roughly as follows:[6] If the emitter is initially charged negatively, the transistor is cut off. The charge on the emitter condenser gradually leaks off through the resistance in the emitter circuit reducing the bias until a point is reached where oscillation starts. As the amplitude of oscillation increases, emitter current flows and charges the condenser. This bias builds up and damps out the oscillation, and a cycle is completed.

An application of this mode of oscillation is the 8-note Musical Toy described in *LB-898*. The schematic of this unit is shown in Fig. 15. This toy is used in conjunction with a radio. Depressing a key produces a tone in the radio corresponding to a particular time constant in the quenching circuit. When no key is depressed,

[6]W. A. Edison, "Intermittant Behavior of Oscillators", *BSTJ*, Jan. 1945.

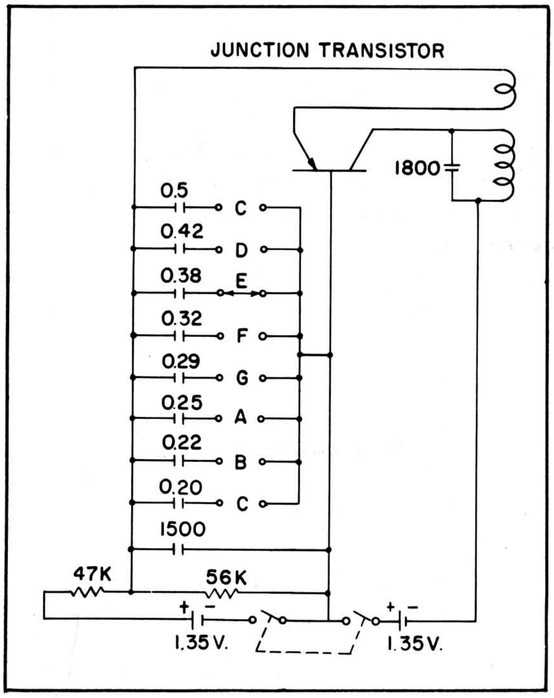

Fig. 15 - Schematic diagram of a self-quenching junction transistor oscillator.

the small condenser, C_o, serves to produce continuous oscillation so as to activate the receiver AGC and to quiet the radio. The current drain of this unit is about 50 µamps. Using two 1.35 volt, 0.3 amp-hr. mercury cells, the life of the battery should exceed 5000 hours.

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