

Nov. 20, 1956

D. E. THOMAS

2,771,584

FREQUENCY-CONTROLLED TRANSISTOR OSCILLATORS

Filed April 15, 1953

6 Sheets-Sheet 1

FIG. 1

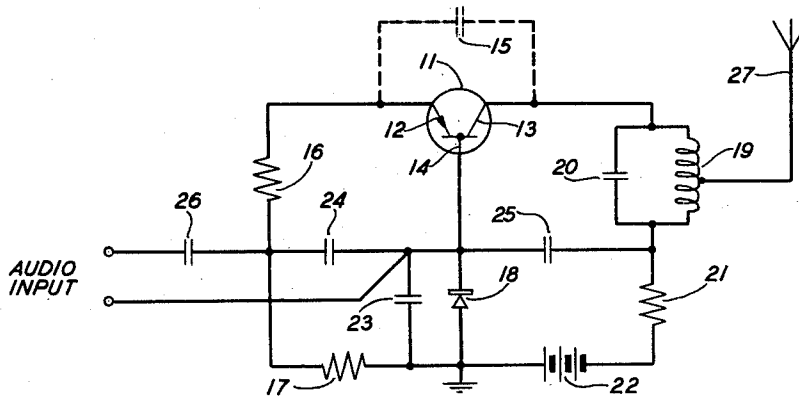


FIG. 1A

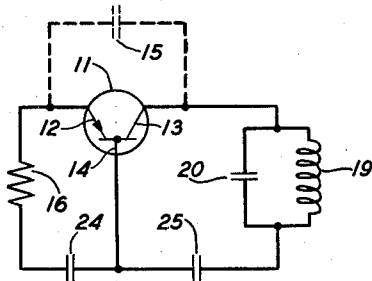


FIG. 1B

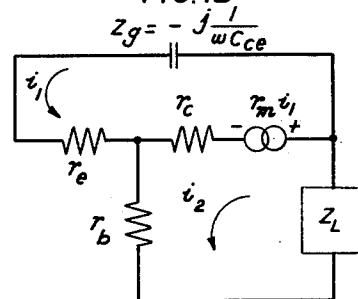
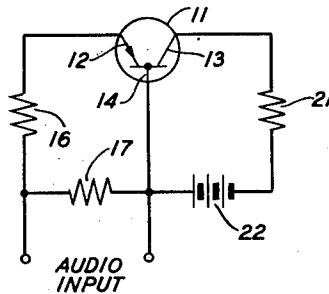


FIG. 1E



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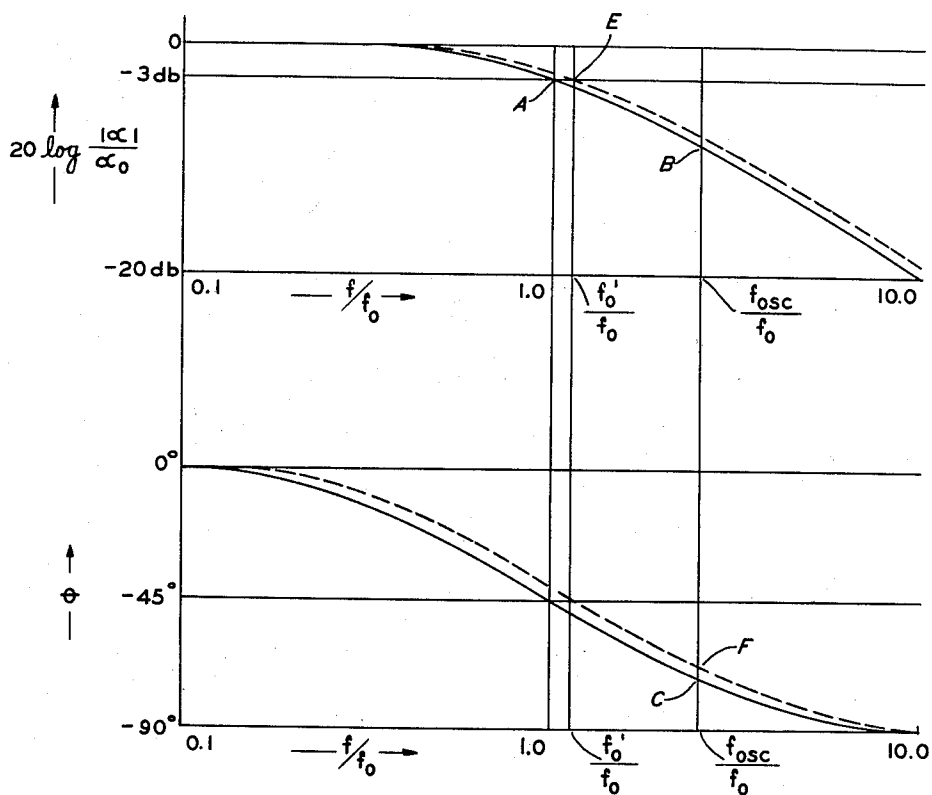
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FIG. 1C



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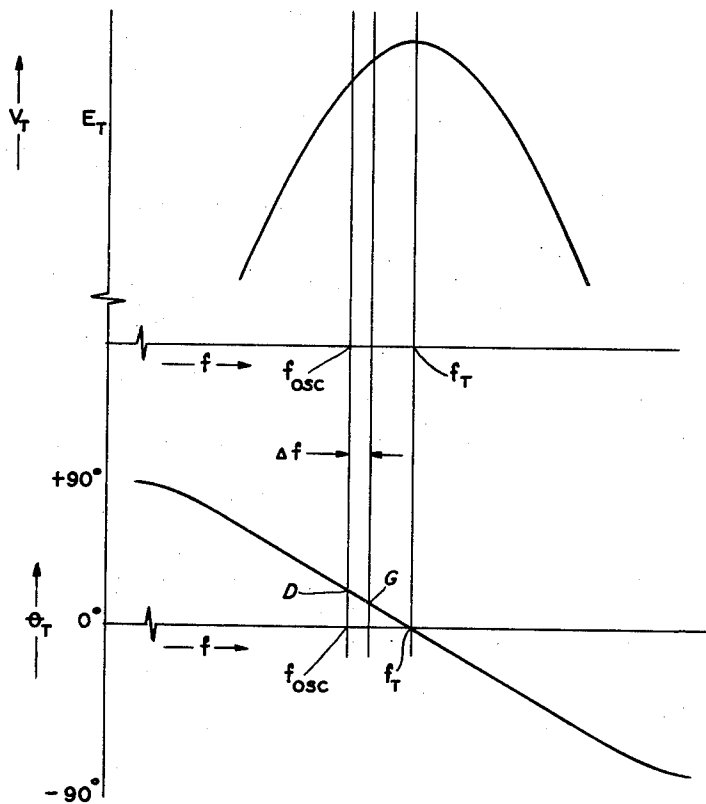
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FIG 1D



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FIG. 2

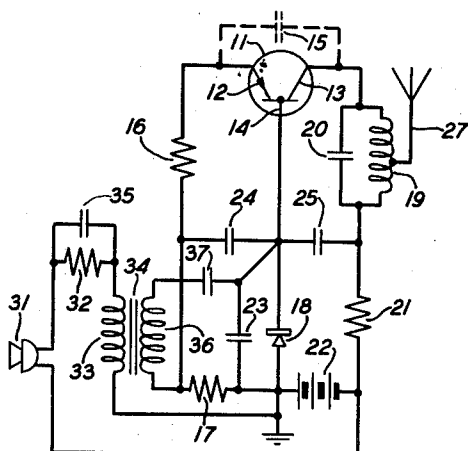


FIG. 3

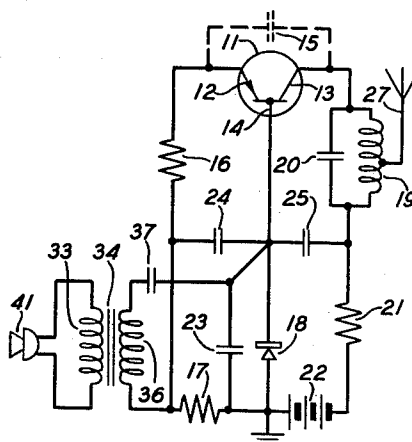


FIG. 4

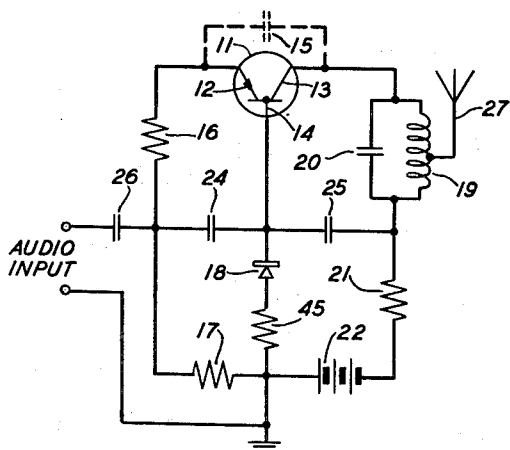
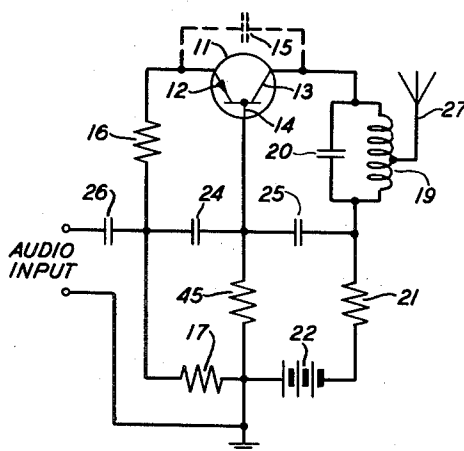


FIG. 5



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FIG. 6

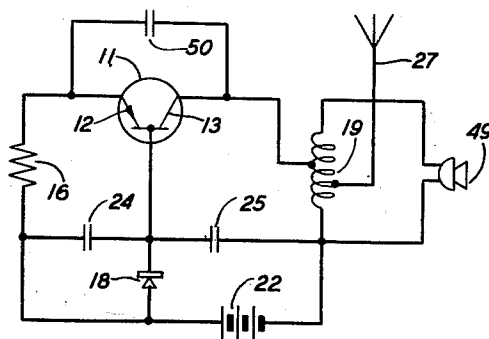
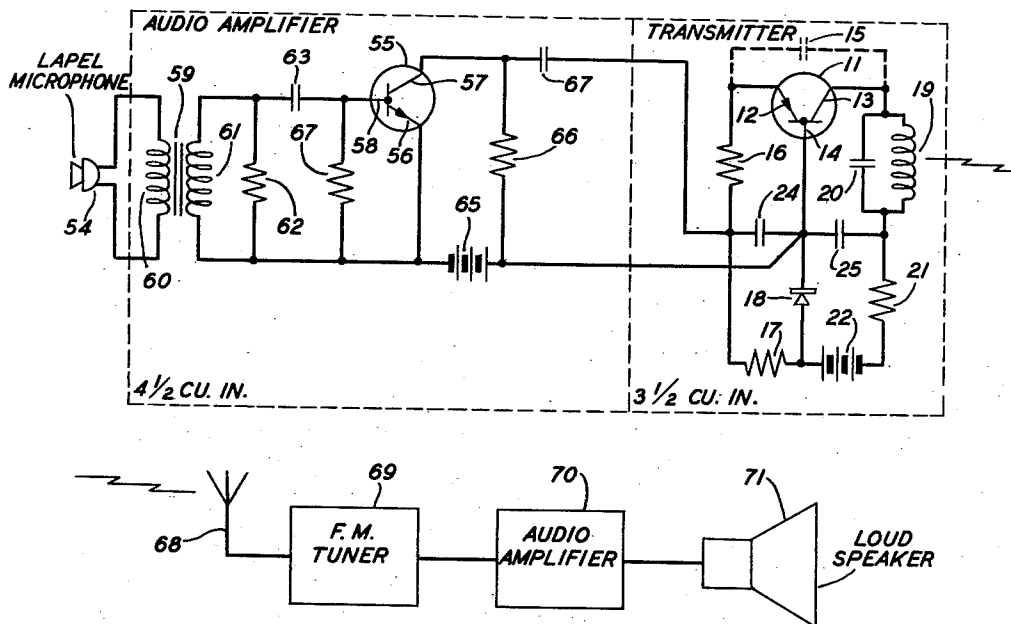


FIG. 7



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FIG. 8

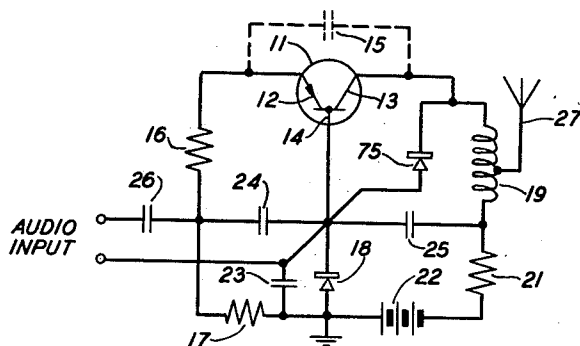


FIG. 9

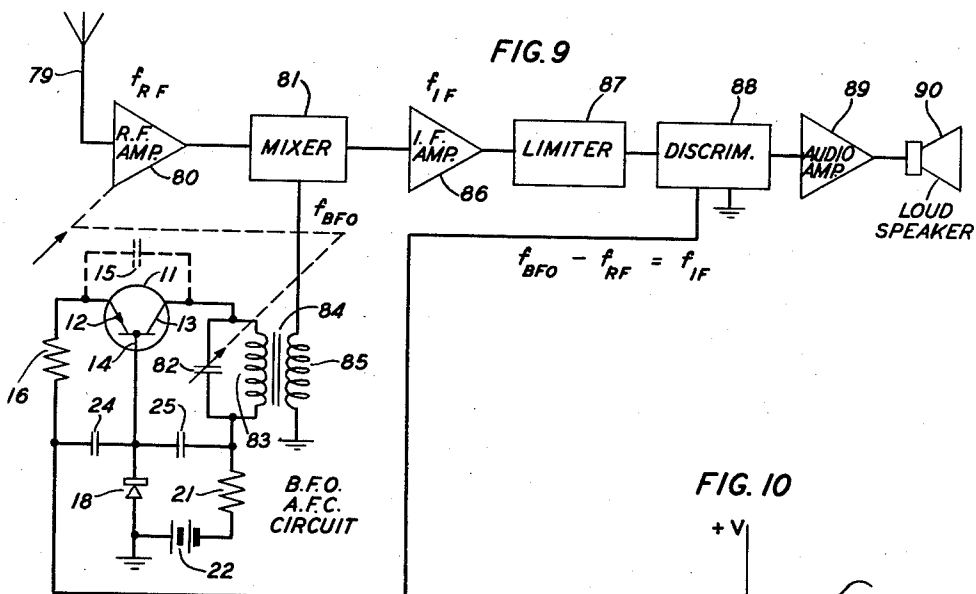
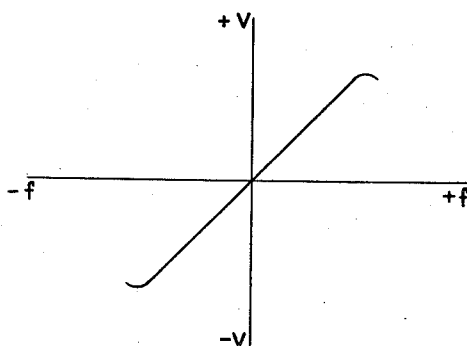


FIG. 10



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FREQUENCY-CONTROLLED TRANSISTOR OSCILLATORS

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Application April 15, 1953, Serial No. 348,901

19 Claims. (Cl. 332-29)

This invention relates generally to transistor oscillators and more particularly, although in its broader aspects not exclusively, to those transistor oscillators which operate at frequencies above the normally used frequency range of transistor current gain.

A principal object of the invention is to control the frequency of a radio frequency transistor oscillator with an applied signal in as simple a manner as possible.

A related object is to reduce the size and weight of frequency-controlled transistor oscillators without adversely affecting the performance characteristics thereof.

Another object is to frequency modulate a single-transistor radio frequency oscillator without using any additional transistors or other active elements.

Still another object is to maintain constant frequency in a radio frequency transistor oscillator under the control of an error signal without using any additional transistors or other active elements.

In general, a transistor is a current-amplifying device which takes the form of a body of semiconductive material having three separate electrode connections thereto called the emitter, the collector, and the base. When, in one manner of operation, a signal is applied between the emitter and base electrodes, an amplified replica thereof appears in a load circuit connected between the collector and the base. The ratio of the shift in short-circuit collector current which results from an incremental change in emitter current to that change in emitter current is known as the current amplification factor, α , of the transistor. The factor α , it has been found, is generally substantially constant in magnitude at low signal frequencies but falls off with frequency at a fairly regular rate once a frequency known as the α cut-off frequency has been exceeded. A change in phase accompanies this change in the magnitude of α .

For signal amplification purposes, reduction in the magnitude of α tends to reduce the usefulness of most transistors at those frequencies which are well above their α cut-off frequencies. This reduction in the magnitude of α is not, however, as serious in the use of such transistors as oscillators, and many radio frequency oscillators of the feedback type are known which oscillate well above the α cut-off frequencies of their respective transistors.

In accordance with the present invention, the oscillation frequency of a feedback transistor oscillator is controlled by controlling the α cut-off frequency of the transistor. The phase of the current amplification factor α , particularly at frequencies above cut-off, is varied as α cut-off frequency is varied, thus varying the phase shift around the feedback loop at those frequencies and causing the frequency of self-oscillation to be varied. Particularly in transistors of the point-contact type (described, for example, in the article "Some circuit aspects of the transistor" by R. M. Ryder and R. J. Kircher, appearing at page 367 of the July 1949, issue of the Bell System Technical Journal), α cut-off frequency varies with changes in D.-C. operating parameters, being most sensi-

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tive to changes in collector voltage and changes in emitter current. If one of these D.-C. operating parameters is changed under the control of an applied signal of some kind, whether it be an audio frequency signal or merely slowly varying D.-C., the frequency of self-oscillation of such an oscillator is caused to change under the control of the applied signal.

A number of embodiments of the invention take the form of single-transistor frequency modulated radio frequency oscillators. In each, a single three-electrode transistor is made to generate self-oscillations at a frequency above its α cut-off frequency by a suitable feedback circuit, and the α cut-off frequency of the transistor is varied under the control of a modulating signal. As the α cut-off frequency is changed under the control of the modulating signal, a change in the phase of the transistor α occurs which causes the oscillator to change its oscillation frequency by an amount corresponding to the change in signal amplitude.

Another embodiment of the invention is in the form of a single-transistor radio frequency oscillator which contains its own automatic frequency control mechanism. As in the frequency modulated oscillator embodiments, the transistor is provided with a suitable feedback path to cause it to become self-oscillatory at a frequency considerably in excess of the transistor α cut-off frequency. The α cut-off frequency of the transistor is varied under the control of a slowly varying D.-C. signal which may, for example, be derived as an error signal from a departure of the operating frequency of the oscillator from a predetermined standard. As the D.-C. error signal varies, the α cut-off frequency of the transistor is changed in the proper direction to restore the oscillation frequency of the device to the standard value.

A more thorough understanding of the invention may be obtained from a study of the following detailed description of several specific embodiments. In the drawings:

Fig. 1 is a schematic diagram of a single-transistor V. H. F. FM transmitter embodying the present invention;

Fig. 1A is a representation of the circuit shown in Fig. 1 as it appears at radio frequencies;

Fig. 1B is an equivalent circuit of the radio frequency circuit shown in Fig. 1A;

Fig. 1C consists of curves showing the variation of the magnitude and phase of transistor α with frequency;

Fig. 1D consists of curves showing the variation of voltage and phase with frequency in the tank circuit of the FM transmitter illustrated in Fig. 1;

Fig. 1E is a representation of the circuit shown in Fig. 1 as it appears at audio and lower frequencies;

Figs. 2 through 5 are schematic diagrams showing variations of the single-transistor FM transmitter illustrated in Fig. 1;

Fig. 6 is a schematic diagram of a single-transistor FM transmitter resembling that illustrated in Fig. 1 but operating on a somewhat different principle;

Fig. 7 is a combination schematic and block diagram of a complete portable public address system using the FM transmitter shown in Fig. 1;

Fig. 8 is a schematic diagram of still another variation of the transmitter shown in Fig. 1;

Fig. 9 is a combination schematic and block diagram of an FM receiver embodying the invention using a beat frequency oscillator having its own automatic frequency control; and

Fig. 10 is a curve showing the output voltage versus frequency error characteristic of a discriminator used in the FM receiver set forth in Fig. 9.

In Fig. 1, the transistor 11 possesses an emitter elec-

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trode 12, a collector electrode 13, and a base electrode 14. In the conventional symbol shown, the emitter is indicated by the arrow, and the direction of positive emitter flow is indicated by the direction of the arrow. Since its emitter current normally flows into the body from the emitter, a point-contact transistor having a body of n-type semiconductive material (described in the above-mentioned article by Ryder and Kircher) is represented by a symbol in which the emitter arrow points toward the base. On the other hand, since its emitter current normally flows away from the body into the emitter electrode, one having a body of p-type semiconductive material is represented by a symbol in which the emitter arrow points away from the base. For convenience in this and succeeding figures, the conventional transistor symbol used has the emitter arrow pointing toward the base and all battery and rectifier polarities are chosen for the indicated direction of emitter current flow. The illustrated embodiments of the invention are not, however, limited to transistors having any particular type of body conductivity. For positive emitter current flow in the opposite direction, battery and rectifier polarities are reversed from those shown in the drawings.

The transistor 11 in Fig. 1 has an interelectrode parasitic capacitance 15 between its emitter and collector electrodes and has its emitter electrode connected to one side of a resistance 16. Resistance 16 is very large in comparison with the internal emitter resistance of transistor 11 and has its other side connected to ground through a resistance 17. The base electrode of transistor 11 is connected to ground through a varistor 18, while the collector is connected to one side of a tank circuit made up of an inductance 19 connected in parallel with a capacitance 20. The other side of the tank circuit is connected through a load resistance 21 to the negative terminal of a source of direct biasing potential, conventionally represented by battery 22. The positive terminal of source 22 is grounded. Varistor 18, which is poled for easy current flow in the direction toward the base electrode of transistor 11, is bypassed at audio frequencies by a condenser 23, and a pair of radio frequency bypass condensers 24 and 25 are connected, respectively, from the junction between resistances 16 and 17 to the base of transistor 11 and from the base of transistor 11 to the junction between the tank circuit and resistance 21. One of a pair of audio input terminals is connected through a coupling condenser 26 to the junction between resistances 16 and 17, while the other is connected directly to the base electrode of the transistor 11. If desired, an antenna 26 may be connected as shown to an intermediate point on inductance 19.

The circuit which has been described is a single-transistor FM transmitter in which the transistor, which is preferably of the point-contact type, functions as a radio frequency oscillator, an audio frequency amplifier, and a frequency modulator. Broadly, its operation can be described in the following manner: the transistor 11 generates self-oscillations at a predetermined radio frequency, an audio signal applied at the audio input terminals causes the oscillation frequency to shift under its control in a substantially linear manner, and the frequency modulated output wave is radiated from coil 19 or antenna 27. Direct voltage source 22 is poled to bias the collector electrode transistor 11 in the reverse direction and varistor 18 and resistance 17 cooperate to bias the emitter electrode in the forward direction. This particular single-battery biasing arrangement forms the basis for applicant's prior application Serial No. 246,984, filed September 17, 1951 (U. S. Patent 2,757,243, issued July 31, 1956). Varistor 18 is a voltage-sensitive resistance device of the rectifier type (e. g., a crystal or copper oxide rectifier) and serves, with resistance 17, to supply the required biasing potential to the emitter.

A more detailed explanation of the operation of the circuit shown in Fig. 1 is possible with the aid of Figs. 1A

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through 1E. Fig. 1A shows the circuit as it appears at radio frequencies. Condensers 24 and 25 serve as radio frequency shorts and thus eliminate the biasing circuits and load resistance 21 from consideration, while resistance 16 has the effect of opening the emitter-base circuit of the transistor 11 at radio frequencies and eliminating feedback through the base circuit in order to prevent both reduction of the circuit cut-off frequency below the transistor α cut-off frequency and relaxation oscillations.

Together with parasitic capacitance 15, the tank circuit in Fig. 1A forms a feedback circuit for transistor 11, causing it to generate self-oscillations at a frequency considerably in excess of the transistor α cut-off frequency. With resistance 16 omitted from consideration, the equivalent circuit of the resulting oscillator is shown in Fig. 1B. There, transistor 11 is represented by its equivalent T-network comprising its internal emitter resistance r_e , collector resistance r_c , and base resistance r_b and the equivalent generator $r_m i$. In the latter expression, r_m is the so-called mutual resistance of the transistor, and i is the emitter current. Parasitic emitter collector capacitance 15 is represented in Fig. 1B as Z_g and the impedance of the tank circuit is represented as Z_L .

The feedback loop gain of the equivalent circuit shown in Fig. 1B is approximately

$$\mu\beta \doteq \frac{\alpha}{1 + \frac{Z_g}{Z_L'}} \quad (1)$$

where Z_L' consists of Z_L and r_c in parallel. As has already been pointed out, the current amplification of transistors is generally substantially constant in magnitude at low frequencies but falls off with frequency at a fairly regular rate once a frequency known as the α cut-off frequency has been exceeded. A change in phase accompanies this change in the absolute magnitude of α . As a close approximation, this frequency response of α can be represented by the expression

$$\alpha = \frac{\alpha_0}{1 + j\left(\frac{f}{f_0}\right)} \quad (2)$$

where α_0 is the low frequency value of α , f is frequency, and f_0 is the frequency at which the magnitude of α is down 3 db from its low frequency value (i. e., the α cut-off frequency).

Substitution of (2) into (1) gives the expression

$$\mu\beta \doteq \frac{\alpha_0}{1 + j\left(\frac{f}{f_0}\right)} \cdot \frac{1}{1 + \frac{Z_g}{Z_L'}} = \frac{|\alpha|/\theta}{1 + \frac{Z_g}{Z_L'}} \quad (3)$$

where θ is the phase of α .

In a feedback oscillator of the type shown in equivalent form in Fig. 1B, oscillation takes place at the frequency at which the absolute value of $\mu\beta$ is unity and the phase of $\mu\beta$ is zero. In Fig. 1B, the absolute value of α is less than unity at the frequencies at which oscillation takes place. In order to make the magnitude of $\mu\beta$ equal to or greater than unity, it is necessary that the absolute magnitude of the denominator of Expression 3 also be less than unity. The quantity

$$\frac{Z_g}{Z_L'}$$

must therefore have a negative real component and, since Z_g is substantially a pure capacitive reactance, this can be true only if Z_L' has a positive reactive component. Therefore, the oscillator will generate self-oscillations at a frequency somewhat less than the resonant frequency of the tank circuit. This is confirmed by the fact that the oscillator in the circuit shown in Fig. 1 does oscillate at a frequency approximately 0.9 of the tank frequency.

The operation of the oscillator in Fig. 1 may be pic-

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tured from the point of view of phase shift around the feedback loop with the aid of the curves in Figs. 1C and 1D. In Fig. 1C, the upper solid curve represents the variation of transistor α with frequency, and the quantity

$$20 \log \frac{|\alpha|}{\alpha_0}$$

is plotted against

$$\frac{f}{f_0}$$

Over the flat portion of the curve, α maintains its low frequency value α_0 . If f is increased, the magnitude of α begins to decline at a rate of substantially 6 db per octave. At the α cut-off frequency, f_0 (indicated by point A in Fig. 1C), the magnitude of α is down 3 db from its low frequency value. The lower solid curve in Fig. 1C illustrates the variation of α phase with frequency, with phase being plotted against

$$\frac{f}{f_0}$$

Here, it is shown that the phase of α varies from substantially zero degrees at low frequencies to substantially -90 degrees at extremely high frequencies, passing through -45 degrees at the α cut-off frequency, f_0 .

Fig. 1D illustrates the amplitude and phase relationships existing in the tank circuit, the lower curve representing the variation of tank circuit phase, θ_T , with frequency and the upper curve representing the variation of tank circuit voltage, V_T , with frequency. Tank circuit phase crosses over from substantially $+90$ degrees to substantially -90 degrees in the vicinity of the resonant frequency of the tank circuit, f_r , having a phase of zero degrees at the resonant frequency itself. The tank circuit voltage, which is shown for comparison, reaches a maximum at the tank circuit resonant frequency.

As has already been pointed out, the oscillator in the embodiment of the invention illustrated in Fig. 1 (shown separately in Fig. 1A) generates self-oscillations at the frequency, f_{osc} , at which the total phase shift around the feedback loop is zero. The three principal factors contributing to this phase shift are the phase of the transistor current amplification factor α , the phase of the parasitic emitter-collector capacitance 15, and the phase of the tank circuit. Proper proportioning of the tank circuit elements 19 and 20 can, for example, yield a steady state oscillation frequency, f_{osc} , which is of the order of twice the α cut-off frequency f_0 . As shown in Fig. 1C, the magnitude of α is well below its low frequency value at that frequency (indicated by point B) and the phase of α is approximately -70 degrees (indicated by the point C). The phase around the remainder of the feedback loop, i. e., through the tank circuit and parasitic capacitance 15, must therefore be substantially $+70$ degrees for self-supporting oscillations to result. Of these, parasitic capacitance 15 is found to contribute about 50 degrees and the tank circuit the remaining 20. The tank circuit thus operates below resonance but on a substantially linear portion of its phase versus frequency characteristic, as shown at point D in Fig. 1D.

As explained thus far, the circuit of Fig. 1 represents a stable radio frequency transistor oscillator which operates well above the α cut-off frequency of the single three-electrode transistor. In accordance with the principles of the present invention, this oscillation frequency is varied by changing the transistor α cut-off frequency under the control of an applied signal. In the embodiment of the invention shown in Fig. 1, that signal is an audio frequency modulating signal.

The α cut-off frequency of a transistor, particularly

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one of the point-contact type, varies with the D.-C. operating parameters of the transistor, being most sensitive to changes in collector voltage and emitter current. Cut-off frequency increases with collector potential and decreases with emitter current. Therefore, if either the collector voltage or the emitter current of the transistor in Fig. 1 is varied at an audio rate, the transistor α cut-off frequency is varied at the same rate and the radio frequency wave generated by the transistor is frequency modulated under the control of the incoming signal.

At audio and lower frequencies, the circuit in Fig. 1 appears as shown in Fig. 1E. Radio frequency bypass condensers 24 and 25 appear as open circuits at such frequencies and the tank circuit appears as a substantial short-circuit. As a result, the circuit appears in the form of an audio amplifier. The audio signal appearing across resistance 17 is amplified by transistor 11 and appears in enlarged form across load resistance 21. In this manner, the collector potential swings in accordance with the audio signal and, as explained above, the transistor α cut-off frequency changes under the control of the applied audio signal.

The manner in which the oscillation frequency is controlled by shifts in α cut-off frequency is illustrated graphically in Figs. 1C and 1D. For purposes of discussion, it is assumed that the instantaneous amplitude of the applied audio signal is shifted from zero to a substantial negative value. This results in an increase in the transistor α cut-off frequency. In effect, the curve in Fig. 1C representing the variation of the absolute value of α with frequency is shifted to the right and now appears in the position indicated by the dashed line curve. The frequency of α cut-off, where α is down 3 db from its low frequency value, is correspondingly greater and is indicated as f'_0 in Fig. 1C. In the upper curve of Fig. 1C, the new α cut-off frequency is indicated by point E.

The shift to the right of the curve representing the magnitude of α is accompanied by a corresponding shift to the right of the curve representing the variation of the phase of α with frequency, as shown by the dashed line curve in the lower half of Fig. 1C. At the oscillation frequency, the phase of α is changed to a new value (e. g., from -70 degrees to -65 degrees) as indicated at point F. In order for the total phase shift around the feedback loop to continue to be zero, the phase shift through the remaining elements of the loop must change by a corresponding amount. This is accompanied by the shift in the oscillation frequency indicated as Δf in the lower portion of Fig. 1D. In the numerical example which has been chosen, as the phase of α changes to -65 degrees, the oscillation frequency shifts to change the phase across parasitic capacitance 15 to substantially $+48$ degrees and the phase across the tank circuit to substantially $+17$ degrees. The new operating point for the tank circuit is shown at point G in the lower curve of Fig. 1D. The oscillator of the circuit shown in Fig. 1 then generates oscillations at the new frequency until the transistor α cut-off frequency is changed again to some new value. As is evident from the upper portion of Fig. 1D, the amplitude modulation accompanying this frequency modulation is negligible.

In the manner which has been described, the α cut-off frequency of transistor 11 in Fig. 1 is varied substantially linearly, for small signal inputs, under the control of the instantaneous amplitude of the incoming audio frequency modulating signal. The resulting changes in α cut-off frequency are accompanied by changes in α phase, causing the oscillator portion of the circuit to seek a new frequency of self-oscillation. The carrier frequency generated by the oscillator is thus frequency modulated in a linear manner under the control of the instantaneous amplitude of the modulating signal.

The following specific values for the circuit elements

in the embodiment of the invention set forth in Fig. 1 are given by way of example:

Transistor 11.....	Type 1832 (point-contact).
Resistance 16.....	3000 ohms.
Resistance 17.....	2000 ohms.
Capacitance 20.....	9 micromicrofarads.
Resistance 21.....	5000 ohms.
Battery 22.....	22.5 volts.
Capacitance 23.....	4 microfarads.
Capacitance 24.....	0.001 microfarad.
Capacitance 25.....	0.001 microfarad.
Capacitance 26.....	4 microfarads.

Using the above set of values, the tank circuit coil 19 is chosen to give a resonant frequency of approximately 118 megacycles. The α cut-off frequency of the transistor should be at least 40 megacycles and the oscillation frequency in the absence of a modulating signal is approximately 105 megacycles.

The single-transistor V. H. F. FM transmitter shown in Fig. 1 is rugged and reliable and has the additional advantages of simplicity, small size, and light weight. The transistor itself is an extremely small device, and none of the other circuit elements are large enough to add any appreciable bulk to the system. The particular biasing arrangement employed permits the use of a single biasing battery which contributes further to the small size of the complete transmitter. Antenna 27 may or may not be used, depending upon the wishes and requirements of the operator. Without antenna 27, coil 19 has been found to radiate enough energy to be received at distances of several hundred feet. If it is desired to extend this range, antenna 27 may be used.

It should be noted that biasing resistance 17 and load resistance 21 can, if desired, be shunted with audio frequency bypass coils in order to save battery power. This is not normally done, however, since the saving in battery power is generally more than outweighed by the extra space which such coils would require.

With some transistors, it has been found that load resistance 21 can be eliminated from the circuit of Fig. 1 and performance will still be satisfactory. With such transistors, the variation of emitter current produced by variations in the modulating signal is itself sufficient to control the transistor α cut-off frequency in the desired manner, and the additional control realized by varying collector voltage is not necessary.

Figs. 2 and 3 show embodiments of the invention which are substantially the same as the single-transistor FM transmitter illustrated in Fig. 1, the principal difference being that those in Figs. 2 and 3 illustrate in more detail how an audio frequency modulating signal wave is to be applied. In Fig. 2, a carbon microphone 31 is provided as an audio signal input device. One side of microphone 31 is connected through a load resistance 32 to one side of the primary winding 33 of an audio input transformer 34. The other side of winding 33 is grounded and resistance 32 is bypassed at audio frequencies by a condenser 35. The other side of microphone 31 is connected to the negative terminal of direct voltage source 22. One side of the secondary winding 36 of transformer 34 is connected to the junction between resistances 16 and 17, while the other is connected through a coupling capacitance 37 to the base electrode of transistor 11.

Fig. 3 differs from Fig. 2 in that a crystal microphone 41 is used for an audio input device. Microphone 41 is connected directly across the primary winding 33 of transformer 34 and the secondary winding 36 is connected in the same manner as in Fig. 2. If appropriate, a phonograph pick-up can be used in Fig. 3 in place of crystal microphone 41.

In the FM transmitter shown in Fig. 4, the oscillation frequency swing for a given audio input may be increased by increasing the gain of transistor 11 at audio frequencies. Additional bias resistance is provided for transistor

11 by inserting resistance 45 in series with varistor 18. Audio frequency bypass condenser 23 is removed, and the resulting positive feedback through the resistance in the base circuit increases the audio frequency transistor gain. Furthermore, for some transistors, varistor 18 may be omitted when resistance 45 has been added to give increased audio gain. Such an arrangement is illustrated in Fig. 5. However, in both Figs. 4 and 5, the second audio input terminal is grounded rather than connected to the base electrode of transistor 11 as in Fig. 1.

Fig. 6 illustrates a single-transistor FM transmitter which resembles that shown in Fig. 1 in many respects but which operates on a somewhat different principle. In Fig. 6, a condenser microphone 49 is connected directly across tank coil 19 and tank condenser 20 is omitted. Because of the relatively low collector resistance of point-contact transistors, the condenser microphone 49 cannot be used directly across the transistor collector-base circuit but must be stepped up to a higher impedance level. This is accomplished by connecting tank coil 19 as a radio frequency auto-transformer, with the collector electrode of transistor 11 connected to an intermediate point on coil 19 rather than to the end. A condenser 50 may, if needed, be connected between the emitter and collector electrodes of transistor 11 to supplement the parasitic capacitance between those electrodes. Other differences between the circuit shown in Fig. 6 and that shown in Fig. 1 are that in Fig. 6, both load resistance 21 and biasing resistance 17 are omitted, load resistance 21 being no longer necessary and the function of biasing resistance 17 being performed by biasing varistor 18 alone. Varistor 18 is unbypassed in Fig. 6 in order to increase the audio frequency gain of transistor 11.

The operation of the circuit illustrated in Fig. 6 differs from that of the embodiment of the invention illustrated in Fig. 1 in a number of respects, the principal one being that the oscillator is modulated directly by the condenser microphone 49 rather than by variation in transistor α cut-off frequency. The phase of the tank circuit comprising coil 19 and condenser microphone 49 is varied by the variations in capacitance in microphone 49 and the oscillation frequency is thus controlled directly.

Fig. 7 shows a complete public address system using an FM transmitter embodying the present invention. The FM transmitter is substantially the same as that shown in Fig. 1, with the exception that antenna 27 is eliminated because the radiation from tank coil 19 is generally sufficient and the audio frequency bypass condenser 23 for varistor 18 has been eliminated. A crystal microphone 54, designed for lapel mounting, supplies the voice frequency modulating signal to the transmitter. Because of the low sound levels at a lapel-mounted microphone, some additional audio amplification is provided by means of a grounded emitter n-p-n (see, e. g., the article "Some Circuit Properties and Applications of n-p-n Transistors," by R. L. Wallace, Jr., and W. J. Pietenpol, appearing at page 530 of the July 1951 issue of the Bell System Technical Journal) transistor amplifier. The n-p-n transistor 55, having an emitter electrode 56, a collector electrode 57, and a base electrode 58, is shown with the emitter arrow pointing away from the base since, as has already been explained, the emitter arrow indicates the direction of positive emitter current flow. In an n-p-n type junction transistor, this flow is normally from the body into the emitter electrode, and for that reason the particular symbol shown is used.

The output from crystal microphone 54 is supplied to the base electrode of transistor 55 through an audio transformer 59. The primary winding 60 of transformer 59 is connected directly across microphone 54 and the secondary winding 61 is connected across a resistance 62. An audio frequency coupling condenser 63 is connected between one side of winding 61 and the base electrode of transistor 55. The other side of winding 61 is con-

connected directly to the emitter electrode of transistor 55, and a resistance 64 is connected between the base and emitter electrodes of transistor 55. The emitter of transistor 55 is also connected to the negative terminal of a source of direct biasing voltage 65 and a load resistance 66 is connected between the collector electrode and the positive terminal of voltage source 65. An audio frequency coupling condenser 67 is connected between the collector electrode of transistor 55 and the junction between resistances 16 and 17 of the transmitter, while the positive terminal of direct voltage source 65 is connected directly to the base electrode of transistor 11.

The following specific values for the circuit elements in the grounded emitter amplifier which has been described are given by way of example:

Transistor 55	Type 1833 (n-p-n junction).
Transformer 59	16:1 turns ratio.
Resistance 62	300 ohms.
Capacitance 63	4 microfarads.
Resistance 64	1 megohm.
Battery 65	22.5 volts.
Resistance 66	12,000 ohms.
Capacitance 67	4 microfarads.

The grounded emitter n-p-n transistor amplifier which is illustrated in Fig. 7 has been mounted, with its battery and microphone matching transformer, in a 4½ cubic inch plastic box and its output has been connected by a short cable to the illustrated FM transmitter. The latter has been housed, complete with battery, in a 3½ cubic inch plastic box. Thus packaged, the transistor and audio amplifier can both be carried in the clothing of a speaker, with the lapel microphone the only visible component of the transmitting system.

The frequency modulated signal is radiated from the tank coil 19 of the transmitter and can be received by apparatus at a distance from the speaker's platform and projected through one or more loudspeakers to an audience. Such an arrangement is shown in Fig. 7, where a receiving antenna 68 is shown coupled to a standard commercial FM receiver 69. The output of the FM receiver 69 is fed into an audio amplifier 90 and from there to the loudspeaker 71. The resulting system is capable of amplifying the voice of the speaker and projecting it to an audience through one or more loudspeakers without encumbering or limiting the freedom of motion of the speaker by microphone cables in any way.

A variation of the embodiment of the invention depicted in Fig. 1 appears in schematic form in Fig. 8. The circuitry is substantially the same except that tank condenser 20 has been removed in Fig. 8 and a junction diode 75 is connected from the collector electrode of transistor 11 to the base electrode. The direction of easy current flow of the junction diode 75 is from the base to the collector of transistor 11.

In the FM transmitter illustrated in Fig. 8, the frequency swing for low audio inputs is greater than in the one shown in Fig. 1, thereby making unnecessary the addition of an audio amplifier between the lapel-mounted microphone and the transmitter input in an arrangement of the type shown in Fig. 7. The junction diode 75, whose junction capacity is a function of impressed voltage, is used as the tank circuit capacitance in Fig. 8 and is placed so as to be biased in the reverse direction in order to keep its impedance high. Since one side of diode 75 is returned to the transistor base electrode, the bias across the diode is changed as the collector swings with the audio signal. The diode capacitance is thereby varied at the audio rate and contributes to the frequency swing of the transmitter. The frequency increments due to diode capacity changes and those due to α cut-off frequency variation caused by collector voltage changes are of the same sign and reinforce each other.

In the modulator embodiments of the invention which have been described, the emphasis has been on the sub-

stantially linear variation of the oscillation frequency as the transistor α cut-off frequency is varied under the control of a small modulating signal. From another aspect, however, the present invention takes the form of an arrangement for using an error signal of some kind (e. g., slowly varying direct current) to maintain a substantially constant oscillation frequency. An example is shown in Fig. 9, which is a combination block and schematic diagram of an FM receiver using a transistor beat frequency oscillator embodying the invention. Through automatic frequency control action, any departure of the beat frequency oscillator from its assigned frequency is detected, and a D.-C. error signal is applied to it to restore it to the assigned frequency and prevent unwanted distortion of the output signal.

In the FM receiver illustrated in Fig. 9, an incoming radio frequency signal is picked up by a receiving antenna 79 and applied to a tuned R. F. amplifier 80. The output of amplifier 80 is, in turn, applied to a mixer 81. Also applied to mixer 81 is the output of a beat frequency oscillator which, in its essentials, is substantially the same as the single-transistor FM transmitter of Fig. 1. In Fig. 9, this beat frequency oscillator comprises transistor 11, parasitic capacitance 15, isolating resistance 16, biasing varistor 18, load resistance 21, D.-C. source 22, and radio frequency bypass condensers 24 and 25. Tank capacitance 20 is replaced by a tuning condenser 82, however, and tank coil 19 is replaced by the primary winding 83 of an output transformer 84. The secondary winding 85 of transformer 84 is connected across the beat frequency oscillator input terminals of mixer 81.

The oscillation frequency of the transistor beat frequency oscillator in Fig. 9 is directly controlled by tuning condenser 82, which is ganged with the tuning control for R. F. amplifier 80. The outputs of R. F. amplifier 80 and the beat frequency oscillator are combined in mixer 81 to produce what is supposed to be a constant intermediate frequency output. This output is fed through an I. F. amplifier 86 and a limiter 87 to a discriminator 88 which supplies an audio frequency signal from one set of output terminals and a D.-C. error signal from another. The D.-C. error signal produced in this manner is representative of any departure of the signal put out by mixer 81 from the assigned intermediate frequency of the receiver. The audio frequency output of discriminator 88 is applied through an audio amplifier 89 to a loudspeaker 90, while the D.-C. error signal is fed back to the junction between resistance 16 and condenser 24 in the beat frequency oscillator.

The automatic frequency control feature of the receiver in Fig. 9 comes into action if, for any reason, the intermediate frequency appearing at the output from the mixer 81 departs from the assigned value. Since the intermediate frequency (f_{IF}) is the difference between the frequency of the beat frequency oscillator (f_{BFO}) and the received radio signal frequency (f_{RF}), and the frequency of broadcast FM signals is stabilized to a far higher degree than the beat frequency of any FM receiver is likely to be, for all practical purposes any such departure can originate only as drift in the beat frequency oscillator of the receiver. Such drift is usually caused by the effect of temperature changes on circuit elements of the beat frequency oscillator.

In Fig. 9 any drift in the oscillation frequency of the transistor beat frequency oscillator appears at the input of discriminator 88 as a departure of the intermediate frequency (f_{IF}) from its assigned value. In general, discriminator 88 has a voltage versus frequency characteristic like that shown in Fig. 10, and a positive frequency error yields a positive direct output voltage while a negative frequency error produces a negative direct output voltage. The resulting error voltage is fed to the emitter of transistor 11, thereby changing the emitter current and the collector voltage. If the error is posi-

tive, the emitter current increases and the collector voltage decreases. The decreased collector voltage causes the α cut-off frequency of the transistor 11 to decrease and the frequency of the beat frequency oscillator to decrease. The decrease in oscillator frequency decreases the frequency at the I. F. level and tends to restore the intermediate frequency to the desired nominal value. The effect of a negative increment in intermediate frequency is just the opposite, producing a decrease in emitter current, an increase in collector voltage, an increase in transistor α cut-off frequency, and an increase in the frequency of the beat frequency oscillator.

The beat frequency oscillator in the FM receiver illustrated in Fig. 9 is thus self-correcting and needs no additional apparatus for automatic frequency control purposes. It has the advantages of the single-transistor FM transmitter described in connection with Fig. 1 and is susceptible of application wherever a radio frequency transistor oscillator with automatic frequency control is needed. The other elements of the FM receiver illustrated in Fig. 9 may comprise a standard vacuum tube receiver or may, for example, form an all-transistor FM receiver.

It is to be understood that the above-described arrangements are illustrative of the application of the principles of the invention. Numerous other arrangements may be devised by those skilled in the art without departing from the spirit and scope of the invention.

What is claimed is:

1. In combination, a transistor, means to produce self-oscillations by said transistor, and means to vary the α cut-off frequency of said transistor under the control of an input signal, whereby the oscillation frequency of said transistor is varied under the control of the input signal.

2. In combination, a transistor having an emitter electrode, a collector electrode, and a base electrode, means to produce self-oscillations by said transistor at a frequency above the α cut-off frequency of said transistor, and means to vary the α cut-off frequency of said transistor under the control of an input signal, whereby the oscillation frequency of said transistor is varied under the control of the input signal.

3. A combination in accordance with claim 2 in which said means to vary the α cut-off frequency of said transistor includes means to vary the collector voltage of said transistor under the control of the input signal.

4. A combination in accordance with claim 2 in which said means to vary the α cut-off frequency of said transistor includes means to vary the emitter current of said transistor under the control of the input signal.

5. In combination, a transistor, means to produce self-oscillations by said transistor, and means to supply an input signal to said transistor and vary the α cut-off frequency of said transistor under the control of the input signal, whereby the oscillation frequency of said transistor is varied under the control of the input signal.

6. In combination, a transistor having input and output connections, means including a feedback path between said input and output connections to produce self-oscillations by said transistor, and means to vary the α cut-off frequency of said transistor under the control of an input signal, whereby the oscillation frequency of said transistor is varied under the control of the input signal.

7. In combination, a transistor having input and output connections, means comprising a feedback path including a tank circuit and a capacitance between said input and output connections to produce self-oscillations by said transistor at a frequency above the α cut-off frequency of said transistor, means to supply an input signal to said input connections and vary the α cut-off frequency of said transistor under the control of the input signal, whereby the oscillation frequency of said transistor is varied under the control of the input signal.

8. In combination, a transistor having input and output connections, means including a feedback path be-

tween said input and output connections to produce self-oscillations by said transistor at a frequency above the α cut-off frequency of said transistor, said feedback path including a capacitance between said input and output connections and a tank circuit in the form of a parallel inductance and capacitance, means to supply an input signal to said input connections and vary the α cut-off frequency of said transistor under the control of the input signal, whereby the oscillation frequency of said transistor is varied substantially linearly under the control of the input signal.

9. In combination, a transistor having input and output connections, means including a feedback path between said input and output connections to produce self-oscillations by said transistor at a frequency above the α cut-off frequency of said transistor, said feedback path including a capacitance between said input and output connections and a tank circuit in the form of a parallel inductance and capacitance and said oscillation frequency being below the resonant frequency of said tank circuit on a substantially linear portion of the phase versus frequency characteristic thereof, and means to supply an input signal to said input connections and vary the α cut-off frequency of said transistor under the control of the input signal, whereby the oscillation frequency of said transistor is varied substantially linearly under the control of the input signal.

10. A combination in accordance with claim 9 in which said feedback capacitance between said input and output connections is the parasitic interelectrode capacitance between said input and output connections.

11. A combination in accordance with claim 9 in which said means to vary the α cut-off frequency of said transistor includes means to vary the collector voltage of said transistor under the control of the input signal.

12. A combination in accordance with claim 9 in which said means to vary the α cut-off frequency of said transistor includes means to vary the emitter current of said transistor under the control of the input signal.

13. In combination, a transistor having an emitter electrode, a collector electrode, and a base electrode, means to supply operating bias voltages to said transistor electrodes, means including a feedback path between said emitter and collector electrodes to produce self-oscillations by said transistor at a frequency above the α cut-off frequency of said transistor, said feedback path including a capacitance between said emitter and collector electrodes and a tank circuit in the form of an inductance and a capacitance connected in parallel between said collector and base electrodes and said oscillation frequency being below the resonant frequency of said tank circuit on a substantially linear portion of the phase versus frequency characteristic thereof, means to supply an input signal to said transistor between said emitter and base electrodes, and means to vary the α cut-off frequency of said transistor under the control of the input signal, whereby the oscillation frequency of said transistor is varied substantially linearly under the control of the instantaneous amplitude of the input signal.

14. In combination, a transistor having an emitter electrode, a collector electrode, and a base electrode, means to supply operating bias voltages to said transistor electrodes, means including a feedback path between said emitter and collector electrodes to produce self-oscillations by said transistor at a frequency above the α cut-off frequency of said transistor, said feedback path including a tank circuit in the form of an inductance and a capacitance connected in parallel between said collector and base electrodes and the interelectrode parasitic capacitance of said transistor between said emitter and collector electrodes and said oscillation frequency being below the resonant frequency of said tank circuit on a substantially linear portion of the phase versus frequency characteristic thereof, means to supply an input signal to said transistor between said emitter and base elec-

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trodes, and means to vary the α cut-off frequency of said transistor under the control of the input signal, whereby the oscillation frequency of said transistor is varied substantially linearly under the control of the input signal.

15. In combination, a transistor having an emitter electrode, a collector electrode, and a base electrode, means to supply operating bias voltages to said transistor electrodes, a feedback path between said emitter and collector electrodes to produce self-oscillations by said transistor at a frequency above the α cut-off frequency of said transistor, said feedback path including a tank circuit in the form of an inductance and a capacitance connected in parallel between said collector and base electrodes and the interelectrode parasitic capacitance of said transistor between said emitter and collector electrodes and said oscillation frequency being below the resonant frequency of said tank circuit on a substantially linear portion of the phase versus frequency characteristic thereof, means to supply an input signal to said transistor between said emitter and base electrodes, and means including a load resistance connected between said collector and base electrodes to control the α cut-off frequency of said transistor by varying the collector voltage of said transistor under the control of the input signal, whereby the oscillation frequency of said transistor is varied substantially linearly under the control of the instantaneous amplitude of the input signal.

16. In combination, a transistor having an emitter electrode, a collector electrode, and a base electrode, means to supply operating bias voltages to said transistor electrodes, means including a feedback path between said emitter and collector electrodes to produce self-oscillations by said transistor at a frequency above the α cut-off frequency of said transistor, said feedback path including a tank circuit in the form of an inductance and a capacitance connected in parallel between said collector and base electrodes and a capacitance between said emitter and collector electrodes and said oscillation frequency being below the resonant frequency of said tank circuit on a substantially linear portion of the phase versus frequency characteristic thereof, a resistance large in comparison with the internal emitter resistance of said transistor connected between said emitter and base electrodes to isolate said emitter electrode from said base electrode and prevent said transistor from generating relaxation oscillations, means to supply an input signal to said transistor between said emitter and base electrodes, and means to vary the α cut-off frequency of said transistor under the control of the input signal, whereby the oscillation frequency of said transistor is varied substantially linearly under the control of the input signal.

17. In combination, a transistor having an emitter electrode, a collector electrode, and a base electrode, means to bias said collector electrode in the reverse direction, means to bias said emitter electrode in the forward direction, a tank circuit in the form of a parallel inductance and capacitance resonant at a frequency above the α cut-off frequency of said transistor, said tank circuit having first and second terminals and having said first terminal connected to said collector electrode, an isolating resistance large in comparison with the internal emitter resistance of said transistor, said isolating resistance having third and fourth terminals and having said third terminal connected to said emitter electrode, capacitances presenting substantial short-circuits at frequencies of the order of magnitude of the resonant frequency of said tank circuit connected respectively between said second terminal and said base electrode and between said fourth terminal and said base electrode, said tank circuit and the interelectrode parasitic capacitance of said transistor between said emitter and collector electrodes forming a feedback path producing self-oscillations by said transistor at a frequency below the antiresonant frequency of said tank circuit but on a substantially linear portion of the phase versus frequency characteristic thereof and said

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isolating resistance effectively opening the emitter-base circuit of said transistor to prevent said transistor from generating relaxation oscillations, means to supply an input signal to said transistor between said fourth terminal and said base electrode, and means including a load resistance connected between said second terminal and said base electrode to control the α cut-off frequency of said transistor by varying the collector voltage of said transistor under the control of the input signal, whereby the oscillation frequency of said transistor is varied substantially linearly under the control of the instantaneous amplitude of the input signal.

18. In combination, a transistor having an emitter electrode, a collector electrode, and a base electrode, a tank circuit in the form of a parallel inductance and capacitance resonant at a frequency above the α cut-off frequency of said transistor, said tank circuit having first and second terminals and having said first terminal connected to said second collector electrode, an isolating resistance large in comparison with the internal emitter resistance of said transistor, said isolating resistance having third and fourth terminals and having said third terminal connected to said emitter electrode, capacitances presenting substantial short-circuits at frequencies of the order of magnitude of the resonant frequency of said tank circuit connected respectively between said second terminal and said base electrode and between said fourth terminal and said base electrode, said tank circuit and the interelectrode parasitic capacitance of said transistor between said emitter and collector electrodes forming a feedback path to produce self-oscillations by said transistor at a frequency below the resonant frequency of said tank circuit on a substantially linear portion of the phase versus frequency characteristic thereof and said isolating resistance effectively opening the emitter-base circuit of said transistor to prevent said transistor from generating relaxation oscillations, a source of direct biasing voltage having fifth and sixth terminals, a biasing resistance connected between said base electrode and said fifth terminal, a load resistance connected between said second terminal and said sixth terminal, a resistance connected between said fourth terminal and said fifth terminal, said source of direct biasing voltage being poled to bias said collector electrode in the reverse direction and the voltage drop across said biasing resistance serving to bias said emitter electrode in the forward direction, and means to supply an input signal to said transistor between said fourth terminal and said base electrode, whereby the amplified replica of the input signal appearing across said load resistance varies the α cut-off frequency of said transistor in accordance with variations in the instantaneous amplitude of the input signal by varying the collector voltage of said transistor and the oscillation frequency of said transistor is varied substantially linearly under the control of the resulting variations in the α cut-off frequency of said transistor.

19. In combination, a transistor having an emitter electrode, a collector electrode, and a base electrode, a tank circuit in the form of a parallel inductance and capacitance resonant at a frequency above the α cut-off frequency of said transistor, said tank circuit having first and second terminals and having said first terminal connected to said second collector electrode, an isolating resistance large in comparison with the internal emitter resistance of said transistor, said isolating resistance having third and fourth terminals and having said third terminal connected to said emitter electrode, capacitances presenting substantial short-circuits at frequencies of the order of magnitude of the resonant frequency of said tank circuit connected respectively between said second terminal and said base electrode and between said fourth terminal and said base electrode, said tank circuit and the interelectrode parasitic capacitance of said transistor between said emitter and collector electrodes forming a feedback path to produce self-oscillations by said transistor at a frequency below the resonant frequency

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of said tank circuit on a substantially linear portion of the phase versus frequency characteristic thereof and said isolating resistance effectively opening the emitter-base circuit of said transistor to prevent said transistor from generating relaxation oscillations, a source of direct biasing voltage having fifth and sixth terminals, a biasing resistance connected between said base electrode and said fifth terminal, a load resistance connected between said second terminal and said sixth terminal, a resistance connected between said fourth terminal and said fifth terminal, said source of direct biasing voltage being poled to bias said collector electrode in the reverse direction and the voltage drop across said biasing resistance serving to bias said emitter electrode in the forward direction, and means to supply an input signal to said transistor between said fourth terminal and said fifth terminal, whereby the amplified replica of the input signal appearing across said load resistance varies the α cut-off

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frequency of said transistor in accordance with variations in the instantaneous amplitude of the input signal by varying the collector voltage of the transistor and the oscillation frequency of said transistor is varied substantially linearly under the control of the resulting variations in the α cut-off frequency of said transistor.

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