R. K.

LB-906

SYMMETRICAL PROPERTIES OF TRANSISTORS AND THEIR APPLICATION

RADIO CORPORATION OF AMERICA
RCA LABORATORIES DIVISION
INDUSTRY SERVICE LABORATORY

RADIO CORPORATION OF AMERICA

RCA LABORATORIES DIVISION

INDUSTRY SERVICE LABORATORY

LB-906

Symmetrical Properties of Transistors and Their Application

Approved

Stuart Wm Seeley

Symmetrical Properties of Transistors and Their Application

Introduction

Transistors have certain characteristics which are not present in conventional vacuum tubes. Some of these characteristics may be best classified as symmetrical properties. The first kind of symmetry may be found in the complementary characteristics of the n-p-n and p-n-p transistors. Circuits using both kind of transistors in combination provide unique advantages in reduction of components and other circuit simplifications.

A second kind of symmetry is displayed by single units since the transistor can be designed so that the emitter and collector may be interchanged. This symmetry permits a current flow of either direction controlled alike by the base current. This fundamental property is useful in switching circuits for clamping, phase and frequency comparison, modulation, deflection circuits, etc.

These symmetrical properties of transistors make possible a large variety of novel circuits, which can be used to advantage in radio, radar, television, and control equipments. The use of p-n-p and n-p-n transistors in circuits with complementary symmetry permits direct coupling, single-ended push-pull operation and efficient pulse amplification with a minimum number of components. Similar effects can be found in n-type and p-type point-contact transistors or in n and p channel unipolar transistors, etc. Similarly the single-unit symmetrical effect may be used in point contact transistors, unipolar transistors or fieldistors. Where a symmetrical unit is not available, two asymmetrical units with their emitters and collectors cross connected can be used to investigate the behavior of symmetrical units in circuits.

Complementary Symmetry

The junction transistor differs from the electron tube in that there are two basic types, n-p-n and p-n-p. One is the symmetrical counterpart of the other, as a hypothetical positron tube would form the counterpart of the conventional electron tube. The term complementary symmetry may be used to describe this property.

A typical static characteristic curve of either type of transistor is shown in Fig. 1. The top signs apply to an n-p-n transistor, while the bottom signs correspond to its p-n-p counterpart. The abscissa is the potential drop between the emitter and the collector (V_c), and the ordinate is the collector current (I_c) for a family of base currents (I_b). A more elaborate presentation would be provided by eliminating the alternate signs and showing the characteristics of the p-n-p unit in the third quadrant of the coordinate system. Either way, the odd-function symmetry of the two units is apparent.

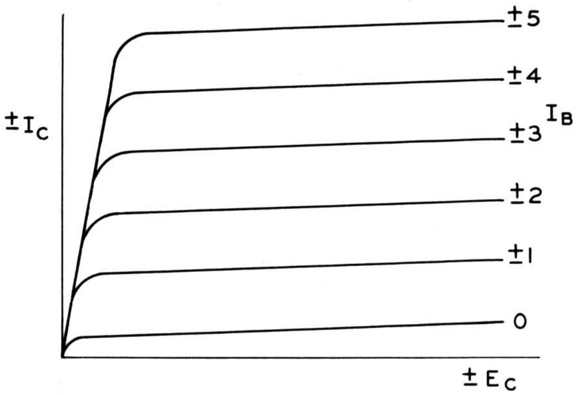


Fig. 1 - The characteristics of n-p-n or p-n-p transistors.

This property can be used in a number of ways. As the base current is changed in the same direction in both units, the emitter-collector current flow will increase in one and decrease in the other. A pair of these units fed from the same signal will therefore provide a single-ended push-pull output. Fig. 2 shows such a single-ended push-pull circuit which operates without a transformer or phase inverter. The constants are based on an experimental setup using an RCA developmental p-n-p type TA-153 transistor and its n-p-n counterpart, experimental type TA-154 transistor.[1]

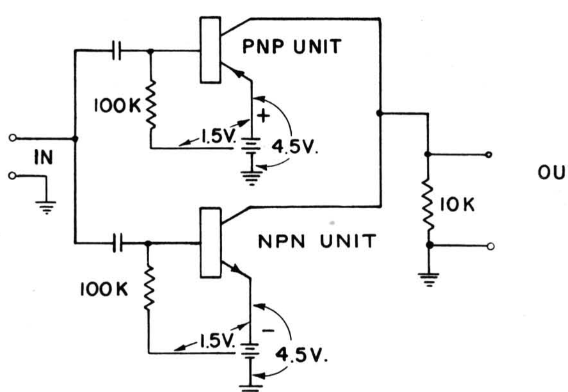


Fig. 2 - Push-pull transistor amplifier using complementary symmetry principle.

[1]LB-903, *A Germanium n-p-n Junction Transistor by the Alloy Process.*

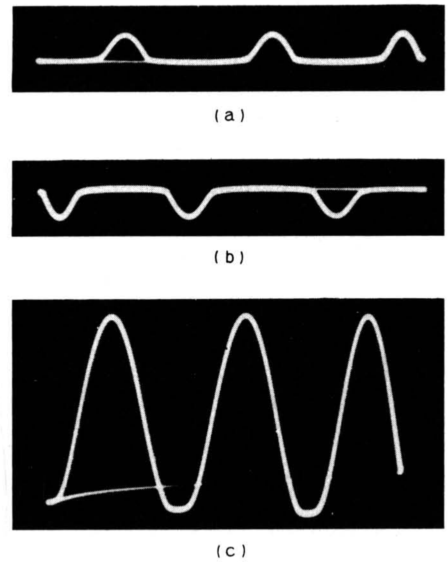


Fig. 3 - Output of the push-pull amplifier shown in Fig. 2.

The power supply in this circuit is connected between the common element of each transistor and ground. As the base current is increased (it is made more negative for the p-n-p unit or more positive for the n-p-n unit) the resistance between the emitter and the collector is reduced and the potential of the output circuit approaches that of the respective power supplies. Thus if the input swings positive the resistance of the n-p-n unit is reduced and the top of the load becomes negative since at the same time the emitter-collector resistance of the p-n-p unit is increased. Similarly a negative input swing reduces the resistance of the p-n-p unit and increases the resistance of the n-p-n unit thus making the potential of the load impedance positive. The amplifier as shown operated Class A and provided a gain of 46 db. The waveforms in Fig. 3 show the output of the individual units with one unit removed and with both units inserted (c). With both units inserted, the applied voltage is 9v instead of 4.5v. Since one unit acts as the load for the other, the external load impedance may be removed and a high voltage gain can be obtained for a number of special applications.

Fig. 4 shows the circuit of an audio amplifier using two RCA type TA-153 transistors and an experimental n-p-n transistor which provides 100 milliwatts of audio output directly into a 500-ohm voice-coil speaker. The complete experimental amplifier with two 22½-volt heari id batteries is shown in Fig. 5. A similar plifier using RCA experimental n-p-n and p-n-p power transistors with emitter output provided a 0.65-watt audio output from a 9-volt supply. Since no d.c. flows through the load, the voice coil is balanced; similarly there is no de-centering if the circuit is used for vertical magnetic kinescope deflection.

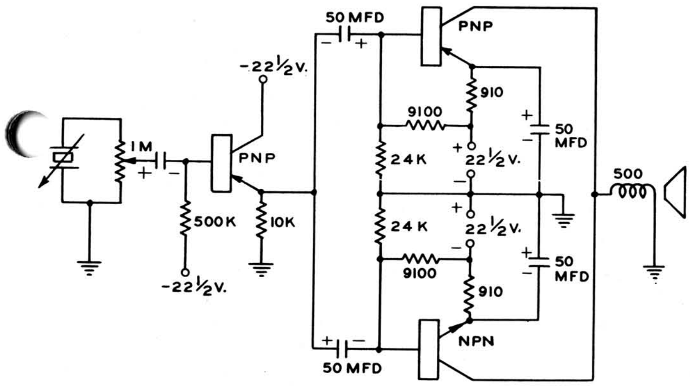
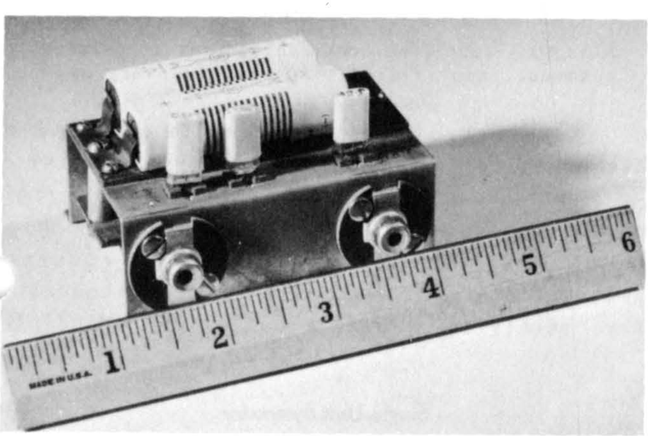


Fig. 4 - Class A push-pull audio amplifier driven by a single transistor.

In certain cases it is desirable to use a power supply with as low a voltage as possible, and to realize a large portion of this voltage r the swing across the load. This may be accomplished by splitting the load and applying the potential swing available across each half of the load. By this means the peak-to-peak voltage swing approaches twice the potential of the power supply. The split load as shown in Fig. 6 may represent two primary windings of a transformer, two halves of a deflection yoke or a split voice coil.

Another application of the use of p-n-p and n-p-n transistors in combination is shown



ig. 5 - 100 milliwatt Class A push-pull transistor amplifier (Fig. 4).

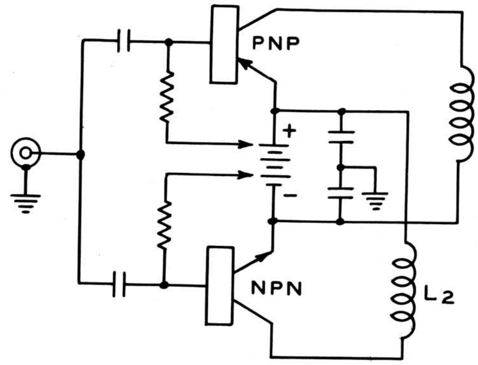


Fig. 6 - Push-pull amplifier with split load.

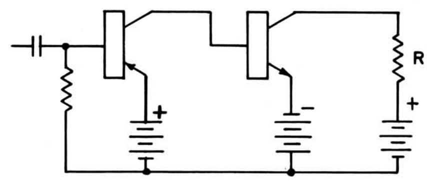


Fig. 7 - Direct-coupled transistor amplifier, using the complementary principle.

in Fig. 7, in which the two complementary units form a direct-coupled amplifier. The circuit shows only two stages but the chain can be extended by additional cascaded stages using the same power supply. Again the power supply is between the common electrode and ground. Although the circuit provides a slightly lower voltage or current gain than α_{cb} (see Appendix) and a considerably lower gain than would be obtainable with matching circuits, it provides a simple d-c amplifier with a minimum number of components. Voltage gains in the order of 25 per stage were obtained.

The complementary symmetry of transistors finds an interesting application when it is applied to the cascading of push-pull amplifier stages. This principle is applied in the two-stage direct-coupled Class B amplifier shown in Fig. 8. This circuit draws negligible current until a signal is applied. Unlike conventional Class B amplifiers, however, it does not require either an input or output transformer. As may be observed from its circuit diagram, it does not contain any parts other than the transistors themselves when operating from a high input resistive source directly into a 16-ohm loud-speaker voice coil. The low output impedance and the stable operation is made possible by the overall feedback which extends to d.c. The amplifier provides a zero center d-c output.

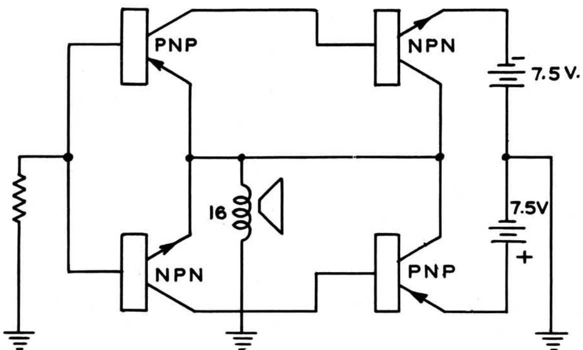


Fig. 8 - Schematic of a Class B push-pull transistor amplifier with complementary symmetry.

The amplifier was built in one form with the four transistors mounted in a small plastic case with a four-prong base, as shown in Fig. 9. The four connections correspond to the input, output and the two battery terminals. A maximum r-m-s power output of one-half watt was obtained on a short time basis, using TA-153 p-n-p transistors and experimental n-p-n transistors. Since for speech or music the average power is 10 db lower than the maximum requirement, and since the amplifier has an overall efficiency (power output/total power input for both the driver and the output stage) of 50 per cent at practically all levels, the unit can be used at the maximum rating as an audio amplifier. The power gain of the amplifier was approximately 28 db. Because of the feedback the voltage gain was slightly less than unity. The total distortion at the 0.5-watt level was approximately 2 per cent.

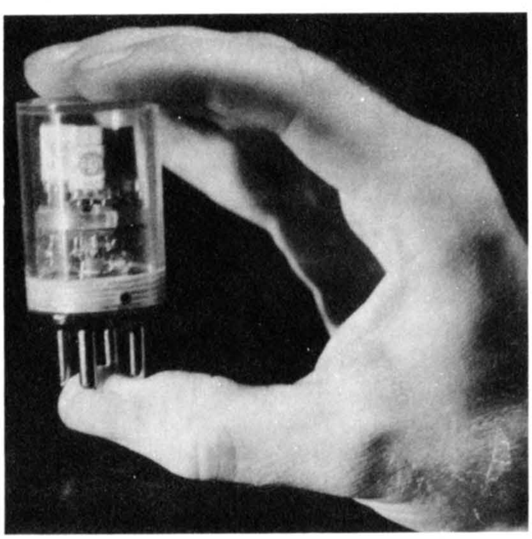


Fig. 9 - A half-watt Class B push-pull transistor amplifier.

The operation of a push-pull amplifie using complementary symmetry may be considere in the light of the family of collector curves and the manner in which the load impedance determines such output characteristics as the maximum power output and the distortion. In all the circuits the power supply is in series between the common electrode and ground. Thus the origin of the output voltage shifts in the positive current domain to the left and in the negative current domain to the right, as shown in Fig. 10. The shifts correspond to the voltage applied between the common electrode and groun The load line now may be drawn through th origin with the slope corresponding to the load resistance. From the load intersections with the collector current curves, the power output and the distortion may be estimated readily. For Class A operation the collector curves should be shifted vertically to make the zero signal currents coincide, and the currents of the two transistors should be added.

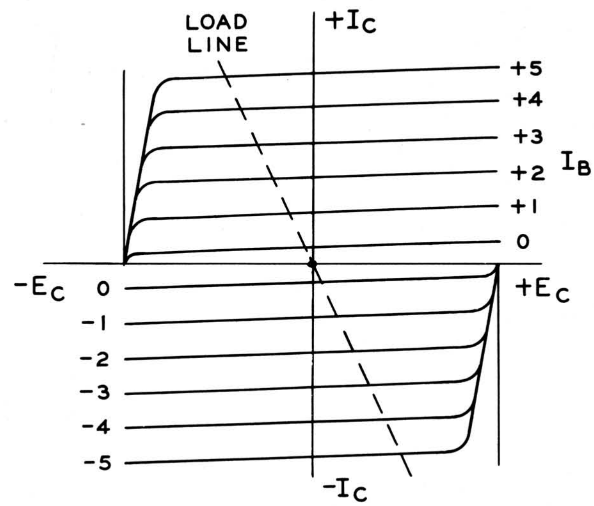


Fig. 10 - Load line construction for transistor push-pull amplifiers using complementary symmetry.

A number of circuits can be devised to take advantage of the complementary symmetry of n-p-n and p-n-p transistors to provide certain unique properties such as very low or high output impedances, low impedance frequenc compensation, etc. The circuits described abo serve merely as illustrations of the principle.

Single-Unit Symmetry

Transistors display another symmetric property involving a single unit. This cha.

acteristic may be best described by a simple experiment, using the test setup shown in Fig. 11. A collector voltage with either polarity can be applied through a double-pole double-throw switch and similarly the potential applied to the base can be varied continuously with either polarity.

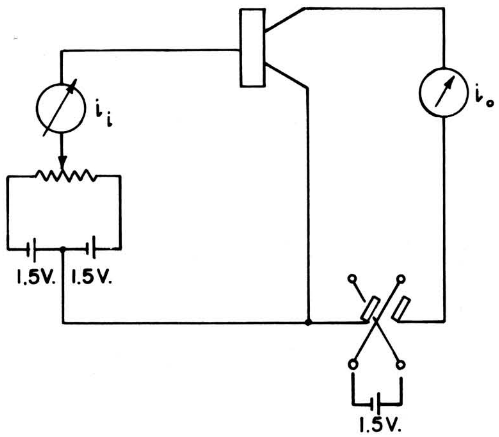


Fig. 11 - Test setup to check transistor symmetry.

The results of such a test are shown in Fig. 12. The current flowing in the base circuit is shown on the abscissa and the emitter-collector current is shown as the ordinate. There is no comparable action in vacuum tubes since this would require an anode emitting electrons and a thermionic cathode accepting them. With transistors, however, units with a high degree of symmetry can be constructed. This is particularly true for the alloying process of transistor making.

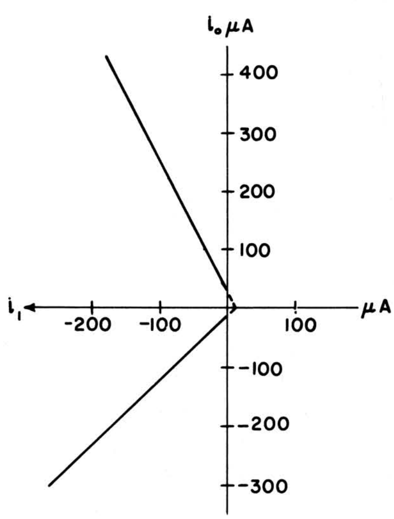
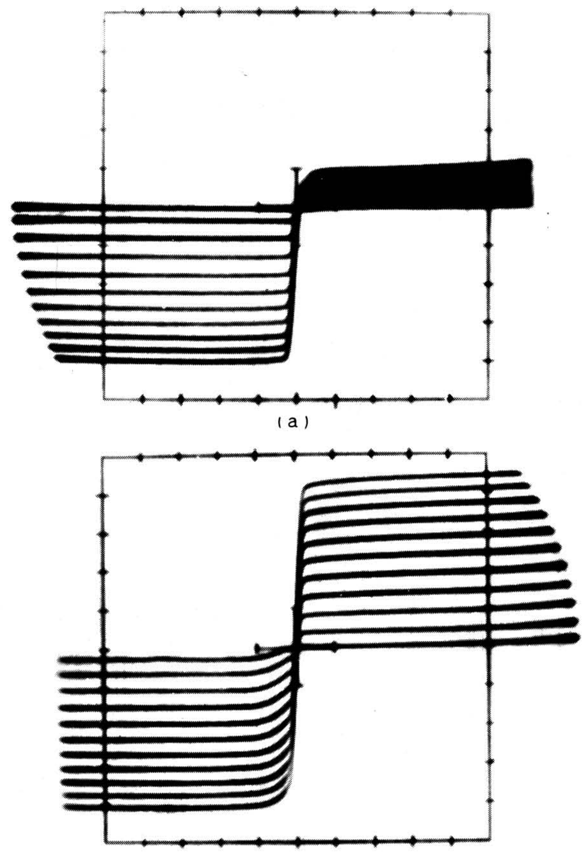


Fig. 12 - Collector current symmetry in symmetrical transistors.

In Fig. 13 there are two examples showing the variation that can be obtained with the alloying technique with respect to the single-unit symmetry. The curves are of the collector voltage and current family of two units, with Fig. 13a showing the curves of a unit made deliberately non-symmetrical, and Fig. 13b representing a symmetrical unit. In both cases the abscissa represents the collector voltage, the ordinate, the collector current, and the curves depart further from the origin as the base currents are increased. These curves, taken on a transistor curve tracer[2], display an odd-function symmetry.



(a)

(b)

Fig. 13 - Collector current curves for (a) symmetrical and (b) asymmetrical transistors.

Single-unit symmetry has many interesting applications since it provides a fast bi-directional switch. It has been pointed out that a bi-directional switch can provide a sawtooth current with very high efficiency.[3] A single symmetrical transistor can provide

[2] LB-882, *A Transistor Curve Tracer.*

[3] G. C. Sziklai, "Current Oscillator for Television Sweep", *Electronics*, p. 120, Sept. 1946.

this function with a minimum number of circuit components and with an efficiency considerably surpassing tube circuits. The operation of the circuit will be described briefly here; it is described in greater detail, however, in LB-907[4].

The basic deflection circuit is shown in Fig. 14. When the base is biased negatively, the emitter collector circuit is closed, and the current increases linearly in time according to the relation $di/dt = E_b/L$.

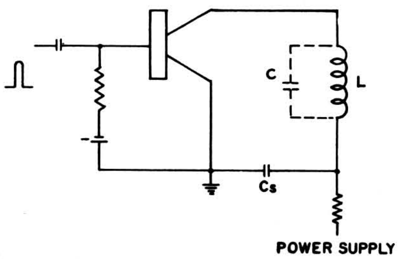


Fig. 14 - Switching circuit for horizontal deflection, using a symmetrical transistor.

When the positive pulse opens the circuit, the energy stored in the inductance is discharged through C in an oscillatory manner according to the relation

$$i = \frac{E_B}{\sqrt{L/C}} \cos \frac{t}{\sqrt{LC}}$$

If the transistor is made to be conductive again at t = LC (in other words, at the half period of the natural frequency of the yoke circuit), the energy is returned to the power supply C_S through the reverse path of the transistor. The current will change again in a linear manner until it drops to zero, when the cycle starts again.

The Symmetrical Clamp Circuit

A conventional diode clamp circuit is shown in Fig. 15. During the clamping interval, push-pull pulses are applied to two diodes connected bi-directionally. The diodes connect the grid and charge the coupling capacitor to a predetermined potential applied to the center-tap of a transformer. After the pulse, the

[4] LB-907, *A Study of Transistor Circuits for Television.*

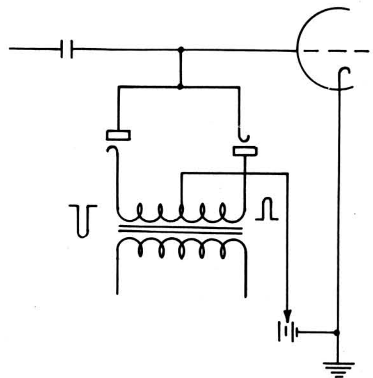


Fig. 15 - A conventional diode clamp circuit.

coupling capacitor retains its charge. The potential thus applied then forms the a-c axis for the signal until the next pulse comes along. The push-pull transformer may be replaced by a triode phase splitter coupled through RC networks. A symmetrical transistor connected as shown in Fig. 16 provides a simple clamp circuit. The circuit requires a single pulse (negative for p-n-p or positive for n-p-n transistors), which essentially shorts the emitter-collector path during the clamping interval.

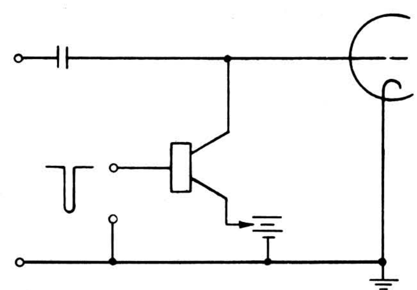


Fig. 16 - A transistor clamp circuit.

Modulator and Detector Circuits

A symmetrical transistor can be arranged to provide a simple balanced modulator. The signal to be modulated is applied between the emitter and the collector in series with a load circuit, and the modulating signal is applied to the base with respect to either of the other two electrodes. The modulating signal can also be applied between the base and the center of the load circuit. Bias voltages can be applied in series with either of the two signals. When the absolute value of either of the signals is zero, the output is also reduced to zero.

The symmetrical transistor also provides a simple phase detector using the connection shown in Fig. 17. When the signal sources A and B are in phase, the transistor conducts only during the negative cycle and the voltage drop across the load will be negative as shown in curve *a*. When the source A lags source B by 90 degrees the output wave will be as shown in curve *b* and the d-c output is zero. Between 0 and 90 degrees the ratio of the positive and negative excursions and d-c output will change gradually. The same condition holds with the opposite polarity between 90 and 180 degrees. When the two sources are 180 degrees out of phase, the collector is positive. When the base is biased negatively, the output wave will be as shown in curve *c* and the d-c output is positive. At 270 degrees the waveform shown in *d* is obtained. The d-c output or the amplitude ratio of the positive and negative wave may be calibrated directly.

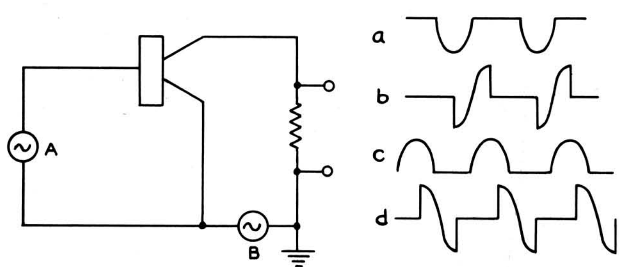


Fig. 17 - Phase detector using a symmetrical transistor.

This type of a phase detector can also be used for detecting the time relationship of a sawtooth and a pulse and thus provide automatic phase control in television synchronizing circuits.[4]

The phase detecting principle may also be used in FM reception. A simple FM detector using a symmetrical transistor is shown in Fig. 18. The demodulated signal output of the FM source appears across the base-emitter path of the p-n-p transistor. During the positive portion of the wave applied to the base the emitter-collector path of the p-n-p transistor is effectively open and therefore no current flows through the output resistor. During each negative swing, however, the emitter-collector path is conductive. (The opposite relationships apply to n-p-n transistors.) The magnitude and direction of the current flow during the conductive periods is determined by the signal developed across the secondary of the transformer. The voltage across the secondary is 90 degrees out of phase with the voltage across the primary when the applied frequency is equal to the resonant frequency. For this condition the d-c voltage drop across the load resistor is zero, as shown in Fig. 17. As the applied frequency is changed, the secondary voltage lags the primary voltage by an angle less than 90 degrees if the frequency is increased, or by an angle more than 90 degrees if the frequency is decreased. As the phase relationship is changed the voltage developed across the load resistor varies in accordance with the frequency modulation.

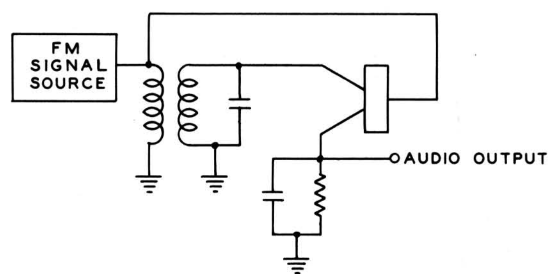


Fig. 18 - A transistor FM detector.

George C. Sziklai

Appendix

The gain of the direct coupled amplifier shown in Fig. 7 may best be computed on the basis of iterative termination. For this condition the load impedance of the stage is equal to the input impedance and the generator impedance is equal to the output impedance. This would be the exact case for one stage of an infinite chain of cascaded amplifiers.

The following derivation uses the terminology suggested in LB-889[5]. The forward voltage amplification (which in the iterative case is the same as the current amplification) is given as:

$$A = -\frac{Z_{21}}{Z_{22}+Z_1} \qquad (1)$$

where Z_{21} is the forward transfer impedance with the output open, Z_{22} is the output impedance with the input open and Z_1 is the input impedance of the next stage. Neglecting the reactive components this relation may be rewritten for the common emitter circuit as:

$$A = -\frac{r_{cb}}{r_{cc}+R_1} \qquad (2)$$

The input conductance 1/R is given by the relation:

$$G_i = g_{bb} - \frac{g_{bc}g_{cb}}{g_{cc}G_1} \qquad (3)$$

or

$$G_1^2 - (g_{bb}-g_{cc})\,G_1+g_{bc}g_{cb}-g_{bb}g_{cc} = 0 \qquad (4)$$

Solving the quadratic

$$G_1 = \frac{g_{bb}-g_{cc}\pm\sqrt{(g_{bb}-g_{cc})^2 - 4(g_{bc}g_{cb}-g_{bb}g_{cc})}}{2} \qquad (5)$$

This can be simplified since $g_{bb} >> g_{cc}$; also the input admittance is much higher than the product of the feedback conductance (g_{bc}) and the forward transadmittance with shorted output (g_{cb}).

The product of g_{bb} and g_{cc} is much smaller than g_{bb} squared. On this basis the second term under the square-root sign is neglected.

$$G_1 \approx g_{bb} \qquad (6)$$

and Eq. (2) may be written as

$$A \approx -\frac{r_{cb}}{r_{cc}+r_{bb}} \qquad (7)$$

For those workers who are more familiar with the data given by Wallace and Pietenpol[6] the following transformations should be useful:

$$r_{cb} = r_e + r_m \qquad (8)$$

$$r_{cc} = r_e + r_c - r_m \qquad (9)$$

$$r_{bb} = r_e + r_b \qquad (10)$$

If r_e which is usually very small is neglected and the above values are substituted in Eq. (7),

$$A \approx -\frac{r_m}{r_c-r_m+r_b} \qquad (11)$$

which is trivially different from

$$\alpha_{cb} \approx \frac{\alpha}{1-\alpha} = \frac{r_c}{r_c-r_m} \qquad (12)$$

In order to illustrate the difference between Eqs. (11) and (12) the gain and the α_{cb} were computed for units No. 1 and No. 4 described by Wallace and Pietenpol.

	Unit No.1	Unit No.4
r_b	240	3070
r_c	13.4×10^6	1.21×10^6
r_{c-m}	0.288×10^6	0.00422×10^6
α	0.9785	0.9965
α_{cb}	45.51	285
Ampl.	45.48	165.5

Since the current and voltage gain are identical in an iteratively coupled stage, the power gain is approximately α_{cb}^2.

[5] LB-889, *Application of Linear Active Four-Terminal Networks to Transistors.*

[6] R. L. Wallace and W. J. Pietenpol, "Some Circuit Properties and Applications of N-P-N Transistors", *B.S.T.J.*, Vol. 30, p. 530, July 1951.