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BASIC AMPLIFIERS (1)

1. INTRODUCTION.

1.1 In the paper "Semiconductor Devices 1" we saw that a small variation in current between the base and emitter of a bipolar transistor causes a large variation in the emitter to collector current.

Although amplifier circuits vary considerably in design, according to their application, three basic requirements are generally common. These are:-

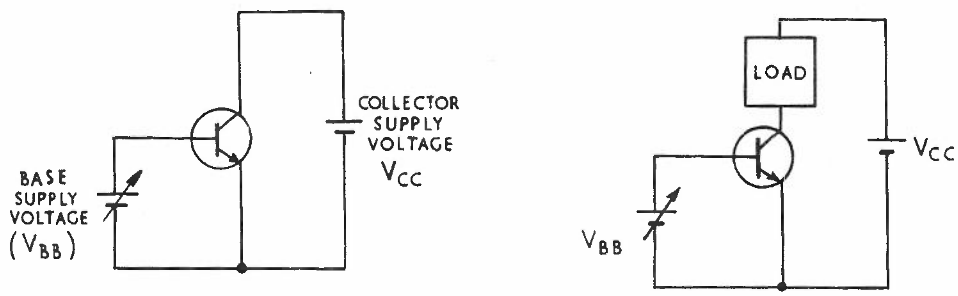
- The output signal is required to be identical to the input signal in all respects, other than amplitude.
- The amplifier's input circuit must be designed to "match" the external equipment for optimum operating conditions, and to limit unwanted signals such as noise.
- The amplifier's output circuit must be designed to "match" the external equipment for optimum operating conditions and minimum distortion.

1.2 This paper describes basic single stage and two-stage audio frequency amplifiers using bipolar and field effect transistors (FETs). For simplicity, the basic principles of the amplifiers are explained using bipolar transistors, and the principles are then applied to amplifiers using FETs. Generally the circuits described use NPN transistors, but PNP transistors can be used in the same circuits provided the power supply potentials are reversed.

2. TRANSISTOR LOAD.

2.1 GENERAL. Bipolar transistors are suitable for use in amplifier circuits because small current changes in the base-emitter circuit produce large current changes in the collector circuit. This action takes place in Fig. 1a, but the circuit contains no circuit element which could make use of the collector current changes. Also, there are no collector voltage changes which could be used as an output signal, because the voltage across the transistor remains steady at the value of the supply voltage, irrespective of the value of the base current.

As a result, the circuit shown in Fig. 1a cannot be used as an amplifier without the addition of another circuit element termed the "load". The load is connected into the collector circuit as shown in Fig. 1b.



(a) Transistor Without a Load. (b) Basic Amplifier.

FIG. 1. BASIC TRANSISTOR AMPLIFIER.

2.2 RESISTOR LOAD. The most common form of load is a resistor connected in series with the collector circuit (Fig. 2). The addition of the load resistor (RL) has the following effects on the circuit:

- The supply potential at any instant is divided across the transistor and load resistor.

- Changes in base current produce changes in collector current with consequent variations in potential drop across the load resistor RL and the transistor.

An increase in base current increases the collector current and has the effect of decreasing the resistance between the emitter and collector. Consequently, the voltage drop across the transistor decreases as the collector current increases.

A decrease in base current decreases the collector current and has the effect of increasing the transistor resistance. Consequently, the voltage drop across the transistor increases as the collector current decreases.

- The variations in voltage drop across the transistor are applied to the output terminals as an amplified voltage output.

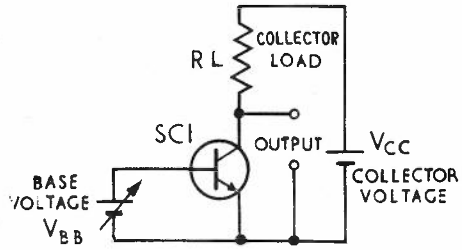


FIG. 2. BASIC AMPLIFIER WITH RESISTOR LOAD.

2.3 The effects of the load resistor are demonstrated with the aid of two examples in Table 1. The circuit in these examples uses a 5000 ohm load resistor and an 8 volt collector supply. Note that the increase in collector current increases the voltage drop across the load resistor, decreases the voltage drop across the transistor, and decreases the resistance of the transistor. The voltage changes which occur in the circuit are taken from across the transistor and applied to the output. This, therefore, becomes the voltage output of the amplifier.

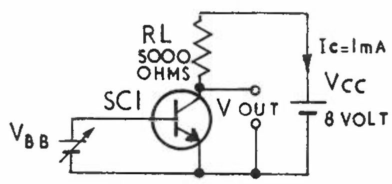
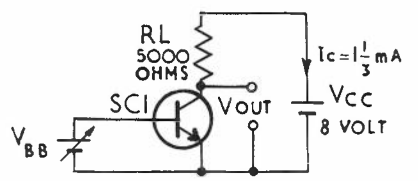
EXAMPLE A. Collector current = 1mA		EXAMPLE B. Collector current = $1\frac{1}{3}$mA	
			
Voltage across RL	$= I_c \times RL$ $= \frac{1}{1000} \times 5000$ $= 5$ volt	Voltage across RL	$= I_c \times RL$ $= \frac{4}{3000} \times 5000$ $= 6\frac{2}{3}$
Voltage across SC1 (V_{SC1})	$= V_{CC} - V_{RL}$ $= 8 - 5$ volt $= 3$ volt	Voltage across SC1 (V_{SC1})	$= V_{CC} - V_{RL}$ $= 8 - 6\frac{2}{3}$ $= 1\frac{1}{3}$ volt
Resistance of SC1	$= \frac{V_{SC1}}{I_c}$ $= \frac{3}{1} \times 1000$ $= 3000$ Ohm.	Resistance of SC1	$= \frac{V_{SC1}}{I_c}$ $= \frac{1\frac{1}{3} \times 1000}{1\frac{1}{3}}$ $= 1000$ Ohm.

TABLE 1.

Similarly, it can be shown that a decrease in collector current produces:

- A decrease in P.D. across the load resistor RL.
- An increase in the P.D. across the transistor.
- An increase in the transistor resistance.

3. BIAS.

3.1 REASONS FOR BIAS. Bias is the name given to the fixed DC voltage connected between the base and emitter of a transistor. Bias causes a steady current in the base-emitter circuit when no signal is applied to the transistor. Bias is provided for two reasons, these are:

- To allow current to flow through the base-emitter junction. We saw in the paper "Semiconductor Devices 1" that there is a minimum forward voltage which must be applied to a PN junction before any significant base current is produced. In a silicon junction this voltage is about 0.6 volt and bias greater than this is required to make the transistor conduct.

- To avoid distortion of the amplified signal waveshape due to the rectifying action of the base-emitter junction. Amplifiers which do not introduce distortion are called 'linear amplifiers'.

3.2 DISTORTION INTRODUCED BY INSUFFICIENT BIAS. In the circuit shown in Fig. 3 assume that a bias voltage equal to the minimum forward voltage of the base-emitter junction (say 0.6 volt) is connected to the transistor. Assume also, that a signal voltage varying between 0.2 volt positive and 0.2 volt negative is applied to the input. The positive half cycle of signal (+0.2 volt) adds to the +0.6 volt bias and increases the collector current accordingly. However, the negative half cycle of signal (-0.2 volt) opposes the +0.6 volt bias to produce a resultant of +0.4 volt between the base and emitter. This is below the minimum voltage required to produce base current, therefore no collector current flows during the negative half cycle of signal. As a result of this, the collector current is rectified, and since it is not a faithful reproduction of the input signal, it is said to be distorted.

We saw in para. 2.3 that collector current variations cause voltage variations at the output terminals. Therefore, any distortion in the waveshape of the collector current also produces distortion in the output voltage waveshape.

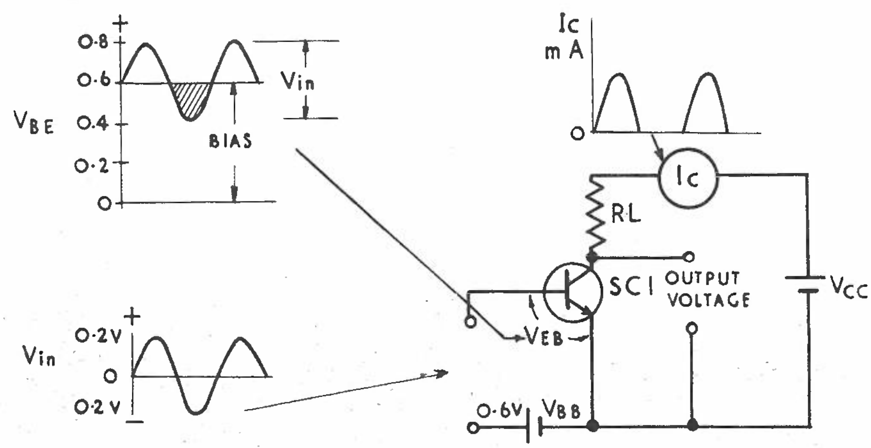


FIG. 3. AC SIGNAL APPLIED TO NPN TRANSISTOR WITH MINIMUM BIAS.

3.3 CORRECT BIAS. To prevent the signal voltage reducing the base potential to a value at which the collector current is cut off, the bias voltage must be greater than the minimum forward voltage of the base-emitter junction. The correct value of bias voltage is derived by adding the transistor cut off voltage, the peak opposing signal voltage, and a small additional voltage which allows for minor supply and signal variations. The bias voltage of the amplifier in Fig. 4 is calculated as follows:

Bias voltage = Cut off voltage + peak signal + safety margin

= 0.6 Volt + 0.2 Volt + 0.1 Volt

= 0.9 Volt

3.4 The effects of correct bias on an amplifier can be seen by examining the input signal and the collector current of the amplifier in Fig. 4 which shows that

- The input voltage (Vin) varies about the DC bias potential of +0.9 Volt; from +1.1 Volt on the positive half cycle to +0.7 Volt on the negative half cycle. Since the base voltage does not fall below +0.6 Volt, base current is not cut off and the collector current is never reduced to zero.

- The collector current remains steady at 150mA with no signal applied. The positive signal peak increases the collector current to 220mA and the negative peak reduces it to 80mA. The current variations follow the input waveshape at all times. Since the collector current waveshape is a faithful reproduction of the input signal, the voltage waveshape produced across the output terminals is undistorted, and is the amplified output voltage of the stage.

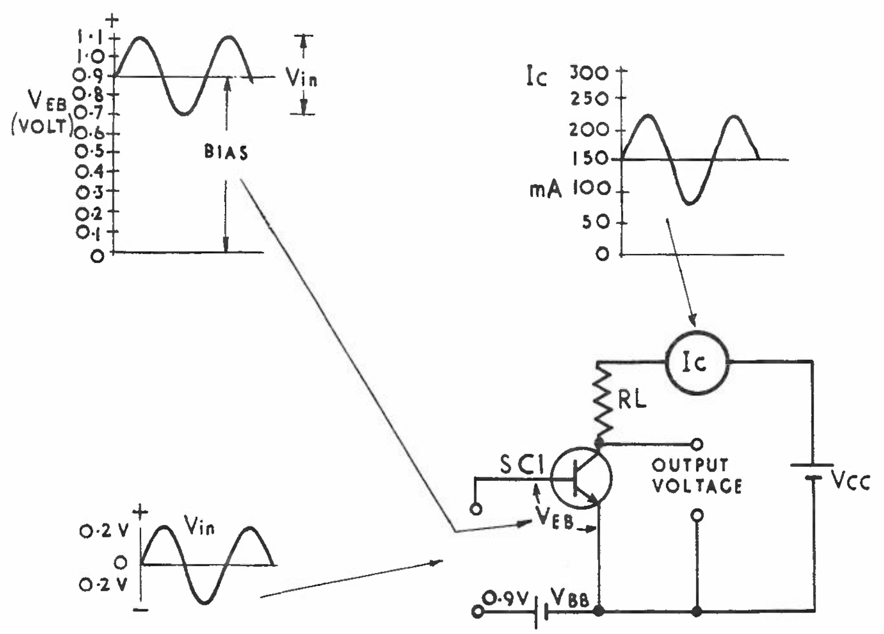


FIG. 4. NPN TRANSISTOR WITH CORRECT BIAS.

3.5 It should be noted that when no input signal is applied to the amplifier there is a significant collector current flow due to the bias voltage (150mA in Fig. 4). This current dissipates power in the resistance of the transistor and its load. It is, therefore, an advantage to keep the bias potential at the lowest value which avoids distortion. This is of particular importance in portable equipment operating from batteries.

Germanium transistors require a smaller minimum forward voltage (0.2Volt) between the base and emitter than silicon transistors and generally require a lower bias voltage.

3.6 BIAS CIRCUIT FACTORS. In the circuits considered so far, the bias voltage has been obtained from a separate battery. Since both the collector and the base have the same polarity with respect to the emitter, it is usually more convenient to derive the bias potential from the same source as the collector voltage. There are, however, two factors which are important in bias circuits of this type. These are:

(a) THERMAL RUNAWAY. There are two separate currents which flow through the reverse biassed base-collector junction of a transistor. One is the collector current produced by the normal transistor action of the base-emitter current, and the other is a smaller leakage current (Ico). In some circuit connections this leakage current returns to the power supply through the base-emitter junction and thus causes a small increase in the total base-emitter current. The leakage current, in conjunction with temperature changes, can cause thermal runaway in transistor circuits. Thermal runaway is a self generating condition which can destroy a transistor. It occurs as follows:

- The leakage current increases due to an increase in the temperature of the transistor.
- The leakage current adds to the base current, thus increasing the total base current.
- The base current change is amplified and causes a larger collector current change.
- The increased collector current further raises the temperature of the transistor.
- The increased temperature causes more leakage current.
- The cycle is repeated until the transistor is damaged.

Bias circuits, therefore, are carefully designed to avoid this destructive condition. Because the leakage current is much smaller in silicon transistors, the danger of thermal runaway is much less in circuits using them, than in circuits using germanium transistors.

(b) PRODUCTION TOLERANCES: There are always differences in the gain and other characteristics of transistors of the same nominal type. Collectively, these differences are called 'Production Spread', and bias circuits are designed for stable operation with any transistor within the limits of the type used. This permits transistors to be changed when necessary without making the circuit unstable.

3.7 BIAS CIRCUITS. There are several methods of deriving bias from the collector supply voltage in a transistor circuit. The most common methods used in audio amplifier circuits are:-

- Series bias.
- Voltage divided bias.
- Collector bias.
- Combination bias.

3.8 SERIES BIAS. The amplifier in Fig. 5 derives its bias voltage from the supply voltage Vcc via resistor R1. The current flowing through the voltage divider, formed by R1 and the resistance of the base-emitter junction, develops the required bias voltage across the junction. This is called series or fixed bias, and has the disadvantage that the circuit is unstable because no precautions are included to prevent the following effects:-

- Leakage current altering the bias.
- Thermal runaway.

Because of its lack of stability, series bias is seldom used with germanium transistors, but is sometimes used in low gain silicon transistor circuits.

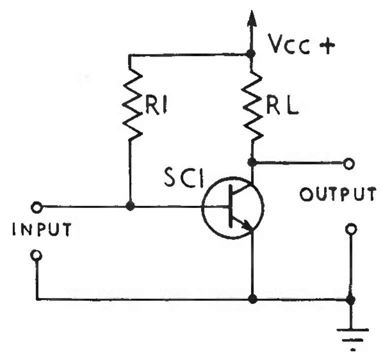


FIG. 5. SERIES BIAS

3.9 VOLTAGE DIVIDER BIAS. A more stable form of bias is obtained from a voltage divider network, as shown in Fig. 6. The current through the divider network, consisting of R1 in series with R2, determines the bias voltage for the transistor. This type of bias is used with both germanium and silicon transistors because the effects of leakage current are reduced. This reduction occurs because some of the leakage current is shunted away from the base-emitter junction by the bias network resistor R2. However, the circuit does not provide any stabilisation against changes in base-emitter voltage produced, for example, by supply voltage variations.

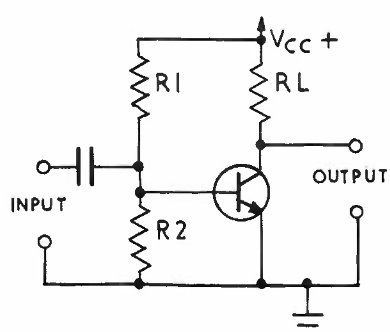


FIG. 6. VOLTAGE DIVIDER BIAS.

3.10 COLLECTOR BIAS. Greater stabilisation is obtained by making the bias voltage dependent upon the collector potential. This is achieved by connecting the bias resistor R1 to the collector, as shown in Fig. 7. The bias voltage is, therefore, determined by the instantaneous voltage of the collector.

Assume there is an increase in the temperature of the transistor. As a result, the leakage current is increased and the following action occurs:

- The increase in leakage current through the base-emitter junction tends to increase the collector current by normal transistor action.
- The increased collector current indicates a decrease in the transistor resistance, which causes a decrease in the collector potential.
- The decreased collector potential reduces the current through the voltage divider network R1 + R2.
- The bias potential developed across R2 is reduced and the collector current is restored to almost its previous value.

A similar action takes place if the temperature decreases or a minor variation in supply voltage occurs.

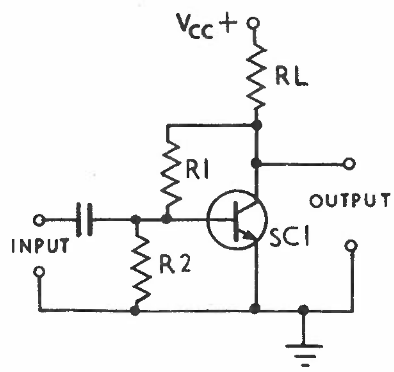


FIG. 7. COLLECTOR BIAS.

3.11 The reduced gain of collector bias circuits is avoided by dividing the bias resistor R1 into two parts and connecting a capacitor (C1) to earth, as shown in Fig. 8.

In this circuit, low frequency collector variations, caused by temperature changes etc., allow time for the capacitor to charge to the new voltage and are stabilised, as explained in para. 3.10. Higher signal frequencies, however, are absorbed by the capacitor C1, which has a large capacitance, and tends to hold an average value of charge. It therefore acts as a buffer and avoids signal voltage changes being transferred from the collector to the base as these voltage changes would reduce the gain of the amplifier.

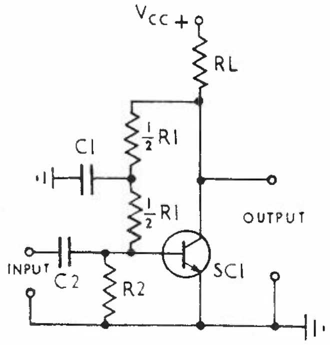


FIG. 8. COLLECTOR BIAS WITH SPLIT BIAS RESISTOR.

3.12 COMBINATION BIAS. The most effective method of stabilising the bias voltage is to connect a resistor R_E in the emitter circuit, as shown in Fig. 9a. The voltage produced across this resistor is dependent on the value of the collector current, the return path of which is via the emitter. Since the emitter current is always in the same direction (being merely increased or decreased by the base.signal current) the polarity of the voltage drop across the emitter resistor is fixed. In an NPN circuit the end of the resistor connected to the emitter is always positive with respect to the end furthest from the emitter, which is negative (these potentials are reversed in PNP circuits).

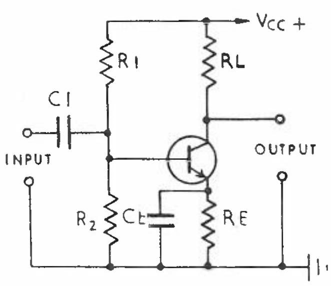
The resultant potential difference between the base and the emitter is the difference between the voltage drop across R2 and the voltage drop across R_E in Fig. 9b, that is:-

$$\text{Bias voltage } V_{EB} = V_{R2} - V_{RE}$$

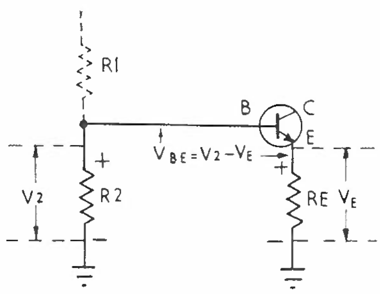
An increase in collector current, produced by an increase in transistor junction temperature, causes an increased voltage drop across the emitter stabilising resistor R_E. The base voltage is accordingly reduced and the collector current reduced to almost its former value before the temperature increase. The bias voltage has therefore been stabilised against thermal runaway. The effects of supply voltage variations are minimised in a similar way.

This method of deriving bias from two opposing voltages is generally called "combination bias".

Signal voltages dropped across the stabilising resistor R_E by the varying collector current tend to reduce the gain of the amplifier. This is prevented by connecting a large value capacitor C_E across the stabilising resistor to bypass signal frequency voltages across the emitter resistor.



(a) Basic Circuit



(b) Development of Bias Voltage

FIG. 9. VOLTAGE DIVIDER BIAS WITH EMITTER STABILISING RESISTOR.

4. BASIC CIRCUIT CONFIGURATIONS.

4.1 GENERAL. The amplifier circuits considered so far have the same circuit configuration. That is, the signal to be amplified is connected between the base and emitter of the transistor, and the amplified signal is taken from the collector and emitter (Fig. 10a). The emitter is, therefore, common to both the input and the output circuits. For this reason, these amplifiers are described as being connected in the common emitter configuration.

There are three main circuit configurations in general use, these are:

- Common emitter (collector follower) circuits.
- Common collector (emitter follower) circuits.
- Common base (grounded base) circuits.

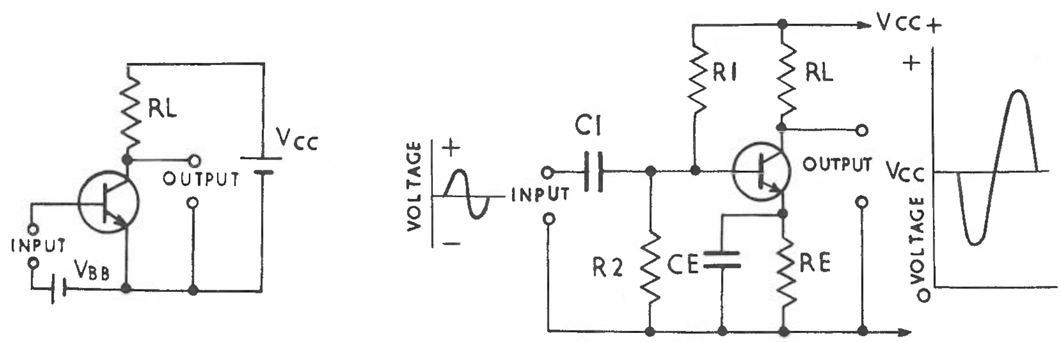
The circuit configuration affects the gain, stability, and the resistance offered by the transistor to external circuits. Each configuration has its own characteristics which determine the circumstances in which it is used.

4.2 COMMON EMITTER CONFIGURATION (CE). This is the most widely used configuration for transistor amplifiers. Fig. 10 shows a basic common emitter circuit in which the input signal is applied between the base and the emitter. The output signal is taken from across the collector and emitter thus making the emitter common to input and output circuits.

In a common emitter circuit, small changes in base current and voltage produce large changes in collector current and voltage. This means that a high current and voltage gain is obtained in this configuration. Because current and voltage gains are obtained the power gain is high.

PHASE INVERSION IN THE COMMON EMITTER CONFIGURATION. An increased positive potential applied to the base of an NPN transistor causes an increased collector current. We saw in para. 2.3 that it also causes the transistor resistance to be reduced. Because of this there is a greater voltage drop across the load resistor and a smaller voltage drop across the transistor. As a result of the redistribution of potentials, the collector potential becomes less positive when the base becomes more positive (Fig. 10b).

Similarly, when the base becomes less positive, the transistor resistance increases and the collector potential becomes more positive. The transistor collector potential change is therefore opposite or inverted compared to the input voltage, thus the output signal is said to be phase inverted in a common emitter amplifier.

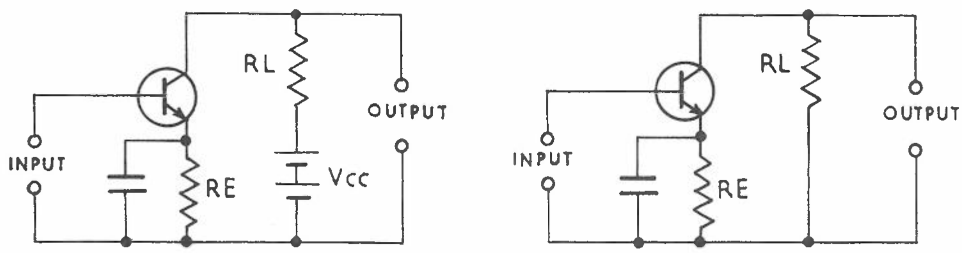


(a) Basic Circuit (b) Practical circuit

FIG. 10. COMMON EMITTER AMPLIFIER.

INPUT RESISTANCE. The input resistance of a transistor is determined by the current through the PN junction across the input. The non-linear resistance effects of the PN junction were shown in section 2 of the paper "Semiconductor Devices 1". Because of this non-linear resistance, the input resistance of a transistor is high for amplifiers with low base current and low for amplifiers with a high base current.

OUTPUT RESISTANCE. In the common emitter amplifier shown in Fig. 11a the power source has negligible resistance to voice frequency (VF) signals. Therefore, when considering VF signals the power supply is neglected and the circuit can be redrawn as shown in Fig. 11b. It should be noted that to VF signals the transistor and its load resistor are connected in parallel across the output. Since the transistor resistance is usually much higher than that of the load resistor, the output resistance of a common emitter transistor circuit is approximately the same as the value of the load resistor.



(a) Common Emitter Circuit (b) Circuit Omitting the Power Supply

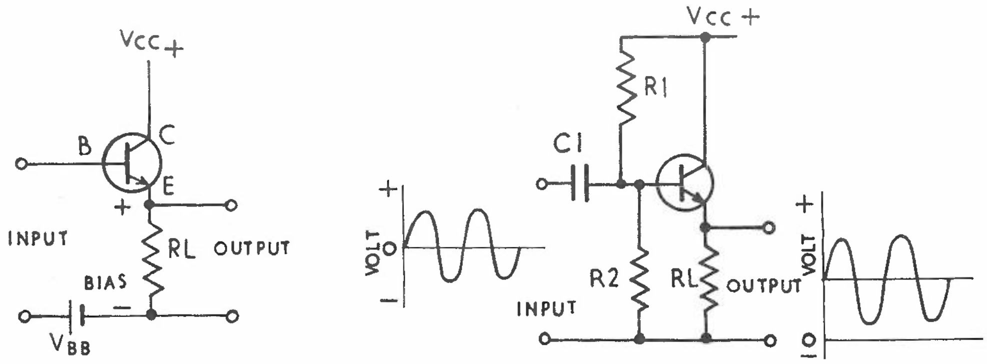
FIG. 11. THE OUTPUT RESISTANCE OF A COMMON EMITTER STAGE.

In common emitter amplifiers the leakage current returns to the supply through the base-emitter junction. For this reason the stability against thermal ruraway is poor unless some precaution, such as bias stabilisation, is included in the amplifier circuit.

4.3 COMMON COLLECTOR CONFIGURATION (CC). The circuit in Fig. 12a shows a basic common collector amplifier. In this circuit the input signal is applied as usual between the emitter and base of the transistor. The transistor load resistor, however, is connected in the emitter circuit. The variations in collector current produce signal variations across the load resistor and the transistor, these variations produce variations of potential at the emitter, which are extended to produce the output voltage of the stage.

Since the load resistor is connected in the emitter circuit in common collector configurations it has the same effect on bias stability as the emitter resistor explained in para. 3.12. However, the resistor is usually of a higher value than the emitter stabilising resistor in a common emitter circuit, and thus has a greater stabilising effect against bias changes and thermal runaway.

In common collector amplifiers there is no inversion of the input polarity at the output. An increase in positive potential applied to the base circuit causes an increase in emitter current. This in turn produces an increased positive potential at the emitter end of the load resistor, thus causing the output signal to become more positive (Fig. 12b). Similarly, a decrease in the positive potential applied to the base circuit causes the output signal to become less positive and there is no phase inversion between the input and output voltages.



(a) Basic Circuit

(b) Practical Circuit

FIG. 12. COMMON COLLECTOR AMPLIFIER.

In common collector configuration a positive potential applied to the base increases the collector current. An increase in collector current increases the voltage dropped across the emitter resistor (RL). This voltage tends to make the emitter positive to the base. Thus the effective signal voltage between base and emitter is the difference between the applied signal and the voltage across the emitter resistor, which is also the output voltage. Therefore, the emitter signal voltage can never be' as great as the input signal which causes it. Because the output voltage of the stage is always less than the input voltage there is no voltage gain from this type of circuit. There is, however, a useful current gain and a power gain, but these are less than those possible from common emitter circuits. The common collector configuration is used in circuits which require a high input impedance and a low output impedance.

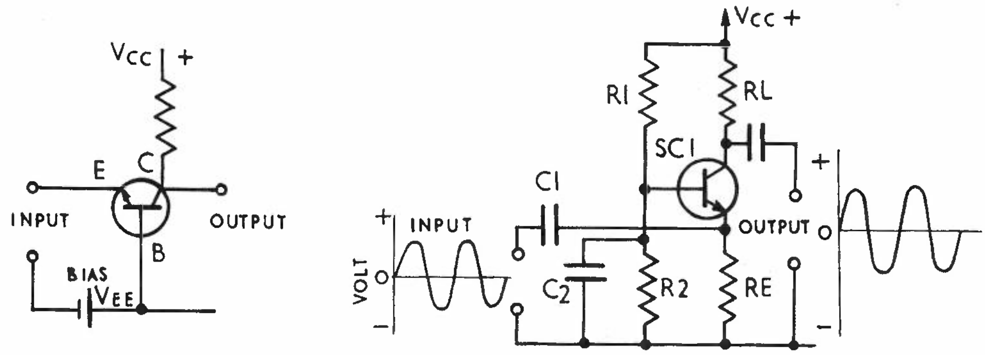
4.4 COMMON BASE CONFIGURATION (CB). Fig. 13 shows this type of configuration which is used mainly at high radio frequencies. In this configuration the input signal is applied between the emitter and the base. The output signal is taken from the collector and base thus making the base the common element.

The input resistance is low: it consists of the base-emitter junction resistance in parallel with the emitter resistor as shown in Fig. 13b. The junction current is usually high in common base circuits, making the junction resistance low due to the non-linear resistance of a PN junction.

The emitter current in this configuration is varied by the input signal. Since the emitter contains both the base and collector currents, the collector current is always less than the emitter current. Thus there is no current gain in common base amplifiers.

The output voltage is the voltage developed across the high resistance of the collector-base junction and high voltage gains are obtained. There is also a power gain obtainable from this circuit.

There is no inversion of the output signal compared to the input signal. An applied signal which makes the emitter more positive with respect to the base decreases the collector current. This causes the collector potential to become more positive. (Fig. 13b) Conversely, a signal that makes the emitter less positive with respect to the base causes the collector to become less positive.



(a) Basic circuit (b) Practical circuit

FIG. 13. COMMON BASE AMPLIFIER

4.5 TYPICAL CIRCUIT CONDITIONS. Table 2 shows the three main configurations and typical characteristics of each type. There are considerable variations of gain and impedance possible, because, in most cases these are largely determined by the external circuitry. It should, therefore, be clearly understood that values given are typical and vary in practice.

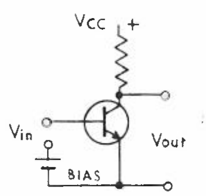
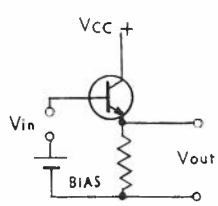
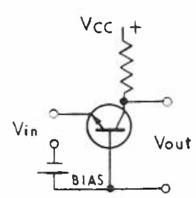
CONFIGURATION	BASIC CIRCUIT	TYPICAL CHARACTERISTICS
Common Emitter		Input Impedance 1.5K Ohm Output Impedance 50K Ohm Current Gain 50 Voltage Gain 50 Power Gain 10.000 Output Voltage Inverted
Common Collector		Input Impedance 500K Ohm Output Impedance 500 Ohm Current Gain 50 Voltage Gain Less than 1 Power Gain 40 Output Voltage Not Inverted
Common Base		Input Impedance 35 Ohm Output Impedance 1 Meg Ohm Current Gain Less than 1 Voltage Gain 400 Power Gain 400 Output Voltage Not Inverted

TABLE 2.

5. COUPLING CIRCUITS.

5.1 GENERAL. Amplifier circuits often need more gain than can be obtained easily from a single transistor amplifier. Also, a more stable circuit can often be obtained by providing two low gain stages of amplification, instead of one high gain stage. For this reason, circuits must be provided to couple or connect transistors to other parts of the amplifier. A perfect coupling circuit should:

- Carry AC signals from one part of a circuit to another without losses at any frequency.

- Prevent the DC potentials of one circuit from altering the DC potentials of a circuit coupled to it. For example, the collector potentials of one transistor must not upset the bias of the stage to which it is coupled.

Four types of coupling circuit in common use are:

- Resistor capacitor coupling.

- Impedance coupling.

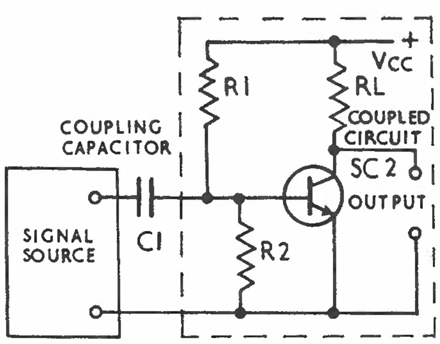
- Transformer coupling.

- Direct coupling.

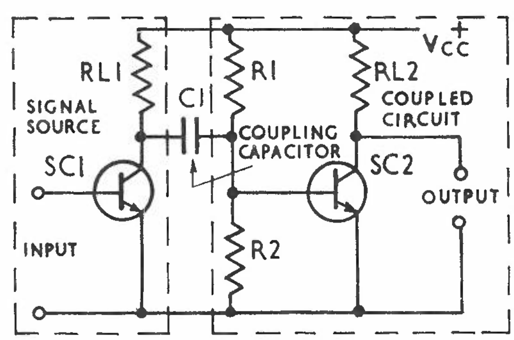
Each method has its advantages which make it suitable for particular circuit requirements. Some of the factors which the circuit designer has to consider when choosing a coupling method are impedance matching, circuit gain, circuit stability, and the cost of the coupling elements used.

5.2 RESISTOR CAPACITOR COUPLING. One method of coupling, extensively used in amplifier circuits, consists of a capacitor and the input resistance of the transistor in parallel with its bias network, as shown in Fig. 14a.

Two examples of the use of RC coupling are shown in Figs. 14a and b in which the input circuit of transistor SC is coupled by a capacitor to two different sources of signal input. In Fig. 14a the input signal source could be the output of any type of testing equipment, or a microphone, etc. In Fig. 14b the input of SC2 is coupled to the output of another transistor (SC1).



(a) Transistor Coupled to an AC Signal Source.



(b) Transistors Coupled by RC Network Coupling

FIG. 14. RESISTOR CAPACITOR COUPLING.

If the signal source in Fig. 14a is connected without the capacitor C, its output resistance is placed in parallel with the bias resistor R2 and, therefore, decreases the bias voltage applied to the base of the transistor. The capacitor isolates the DC potentials of the two circuits. Similarly, in Fig. 14b the collector voltage of transistor SC1 is more positive than the bias voltage at the base of the transistor SC2. Capacitor C provides the required isolation between DC potentials at the collector of SC1 and the base of SC2.

The AC signal voltage from the signal source in each case forms the input to the coupling network and is divided between the capacitive reactance of C and the input resistance of the transistor.

The value of capacitor C is chosen to ensure that, over the required frequency range, its reactance is low compared to the input resistance of the transistor. In this way the voltage dropped across the capacitor is kept small. This is necessary because any voltage dropped across C is not applied to the following transistor and is, therefore, wasted.

At low frequencies the reactance of C becomes high, thus reducing the voltage applied to the transistor and the gain of the amplifying stage.

At middle and high frequencies the reactance of the capacitor is very low and can be neglected. Over this frequency range the full voltage applied to the coupling circuit is developed across the transistor input.

5.3 PRACTICAL RESISTOR CAPACITOR COUPLED AMPLIFIER. The circuit shown in Fig. 15 uses RC coupling at the input, the output and between stages of the amplifier. AC signals at the input produce a varying signal across resistor R2 which aids or opposes the bias developed by resistors R1 and R2. The varying base current of transistor SC1 causes a change in its collector current. The resultant collector voltage variations are coupled by C1 to the base-emitter junction of transistor SC2. These in turn produce collector current and voltage variations in SC2, which are coupled to the output terminals via C2.

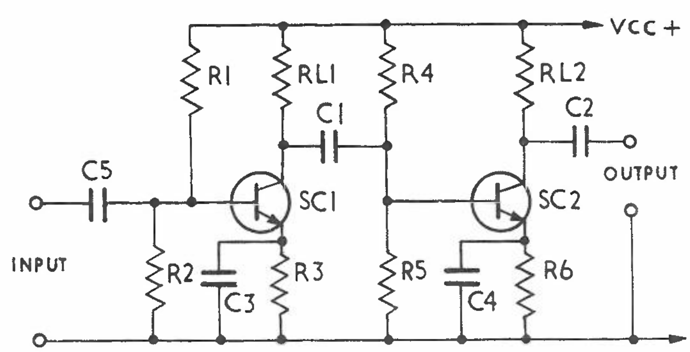


FIG. 15. RC COUPLED AMPLIFIER.

5.4 FREQUENCY RESPONSE. A convenient way to assess the performance of an amplifier over a range of frequencies is to study a frequency response graph of the amplifier. One method of obtaining a frequency response graph is to measure the gain of the amplifier at a number of frequencies over the range to be used. These gains are then plotted on a graph of output level versus frequency. The frequency at which the output power drops to half the power obtained at a middle frequency, usually 1kHz, determines the upper and lower frequency limits at which the amplifier provides a useful gain.

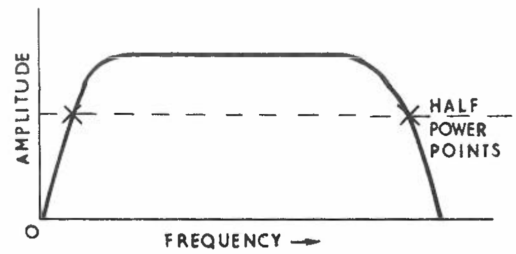


FIG. 16. FREQUENCY RESPONSE OF AN RC COUPLED AMPLIFIER.

A typical frequency response graph of an RC coupled stage is shown in Fig. 16. It shows that the gain is reduced to zero at very low frequencies. This is due to the very high reactance of C at these frequencies. As the input frequency is increased the gain rises until the reactance of C is negligible. Over this middle range of frequencies the gain does not vary with increased frequency. At high frequencies the gain is again reduced due to the shunting effect of stray capacitances.

5.5 The properties of RC coupling are:

- The middle range frequency response is flat. This can be extended into the megahertz range by special circuit arrangements.
- The very low frequency response is poor.
- The frequency response is poor at high frequencies, above the middle range.
- The circuits coupled are isolated from the DC potentials of each other.
- The coupling elements are compact, light and inexpensive.
- The circuit stability is good because there are no stray magnetic fields to couple circuits together.
- There is a voltage loss at low frequencies in the coupling elements. This loss decreases as the frequency is increased.

5.6 IMPEDANCE COUPLING. This is a form of resistance capacitance coupling in which an inductance is used as the load, instead of a resistor (Fig. 17).

This type of coupling has a high power efficiency since there is practically no D.C. power loss in the collector circuit of transistor SC1.

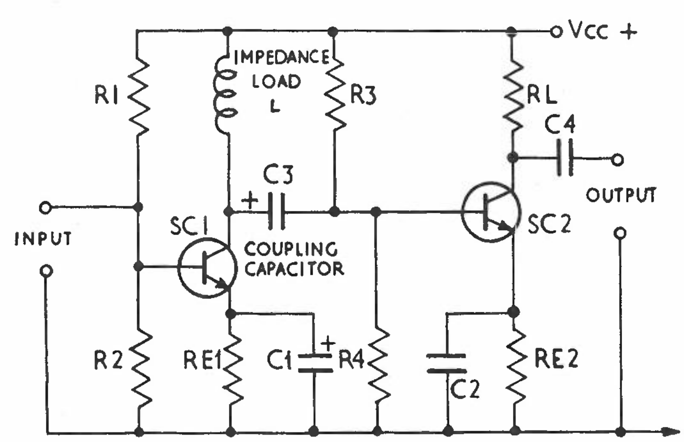


FIG. 17. IMPEDANCE COUPLED AMPLIFIER.

The output voltage of the stage depends upon the impedance of the inductance. Since this impedance varies with frequency, the frequency response of the stage is not as good as with RC coupling. High frequencies are amplified more than low frequencies because the inductive reactance of the load is directly proportional to the applied frequency. At some frequency the inductance becomes resonant with interwinding and stray capacitance and develops a high output voltage over a narrow range of frequencies close to resonance. At frequencies above the resonant frequency the various capacitances bypass the load thus the output voltage becomes very low.

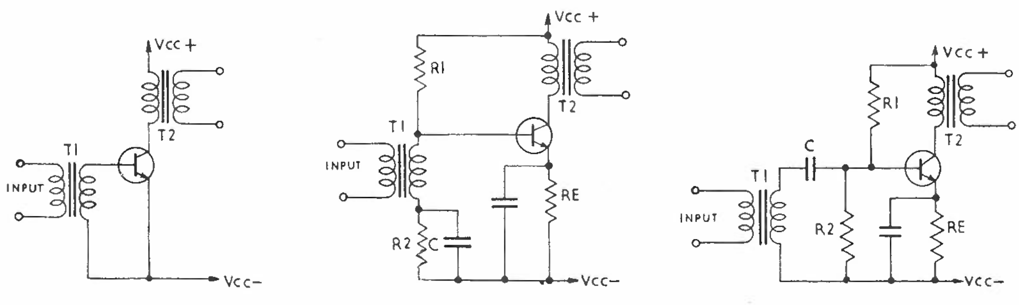
5.7 The characteristics of impedance coupling are summarised as follows:

- There is little power wasted in the load.
- The amplifier output varies with frequency more than in resistor capacitor coupled amplifiers.
- The inductor is bulky and heavy, and its cost is high.
- The supply voltage can be lower than in a similar RC coupled amplifier.
- The inductor produces stray magnetic fields which may couple circuits together causing instability.

5.8 TRANSFORMER COUPLING. A transformer is another circuit element commonly used to couple amplifying stages to each other, or to other circuits. The transformer isolates the DC potentials in the primary circuit from those in the secondary circuit, but couples AC signals from one circuit to the other.

Current variations in the primary winding produce a varying flux which induces a voltage into the secondary winding. The secondary voltage induced depends on the turns ratio and a voltage gain can be provided by the transformer.

In the simplified circuit shown in Fig. 18a both input and output signals are transformer coupled. The input signal current in the primary of T1 induces a voltage into the secondary which varies the base-emitter current of the transistor. The resultant current variations in the collector circuit vary the flux in the primary of T2 and thus induce the output voltage into the secondary winding.



(a) Basic circuit (b) Signal in Series with the Bias (c) Signal in Parallel with the Bias

FIG. 18. TRANSFORMER COUPLING.

Two methods of including bias in amplifiers using transformer coupling are shown in Figs. 18b and 18c. In Fig. 18b the input signal is coupled in series with the bias voltage. In this method the bias resistor is by-passed by capacitor C to prevent signal voltages being dropped across the resistor. The input signal induced into the secondary of T1 aids or opposes the bias potential thus varying the base current. This variation causes an amplified variation in the collector current.

An alternative method of coupling the input signal into the transistor is shown in Fig. 18c. Here the input signal is applied in parallel with bias resistor R2. A capacitor C is needed to prevent the low resistance of the transformer winding from providing a DC shunt across R2 and thus reducing the bias voltage.

5.9 The characteristics of transformer coupling are summarised as follows:

- A transformer can provide a voltage gain, depending on the turns ratio used.
- A transformer can be used to match two circuits with different impedances.
- The voltage induced into the secondary of an ideal transformer increases as the frequency of the primary current is increased. In a well designed practical transformer the various inherent losses are carefully balanced against this effect to produce a flat response over the required frequency range.
- The voltage coupled into the secondary at low frequencies is small. Therefore the gain of a transformer coupled amplifier falls to zero at a low frequency.
- The inductance of a transformer becomes resonant with interwinding and stray capacitances at some high frequency. At this frequency the coupled voltage is high but falls off rapidly at frequencies above resonance. By careful design the resonant frequency is usually made to occur outside the required frequency range.
- Transformers produce stray magnetic fields which can couple adjacent circuits together and cause instability. Specially shielded transformers are used in low level amplifiers to reduce the voltage pick-up from stray fields.
- Transformers are bulky, heavy and costly compared to other coupling circuit components.
- There is little D.C. power wasted in the load.

5.10 DIRECT COUPLING. Two amplifying stages can be directly coupled together without the use of additional circuit components, provided the D.C. potentials at the points to be coupled are the same. Because there is no current flow between points of equal potential, no D.C. isolation is required.

The collector potentials of the transistor SC1 in the amplifier shown in Fig. 19 is at almost the same potential as the emitter of SC2. It differs only by the bias potential required at the base of SC2.

The load resistor of transistor SC1 drops the collector voltage to a suitable value. The emitter resistor of SC2 is large and raises the emitter potential to the same voltage as the collector voltage of SC1 (less the required bias voltage). It should be noted that transistor SC2 has the same potentials relative to its emitter as transistor SC1, but all potentials on SC2 are raised relative to the negative supply potential. The output voltage of the stage is taken from the collector of SC2. Transistor SC2 is used as an emitter follower stage in some applications.

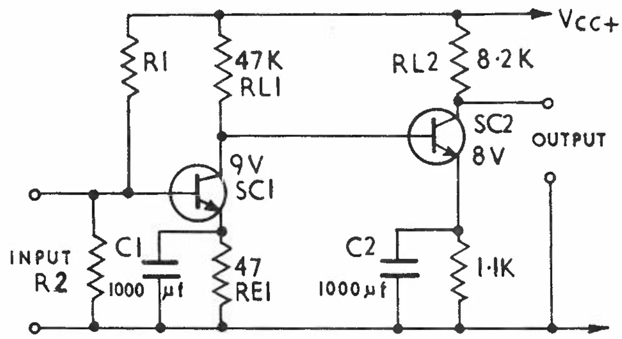


FIG. 19. DIRECTLY COUPLED AMPLIFIER.

5.11 CIRCUIT OPERATION. Transistor SC1 is biassed by resistors R1, R2 and RE1. Changes in base current caused by an input signal produce collector voltage variations which are applied to the base of transistor SC2. The bias voltage for this transistor is obtained from the difference between the directly coupled DC collector potential of transistor SC1 (9 volt) and the DC emitter potential of SC2 (8 volt). In this case a bias voltage of 1 volt is obtained between the base and the emitter of transistor SC2. The base voltage and current of transistor SC2 are varied by the collector voltage changes of transistor SC1 thus producing corresponding changes in collector current and voltage in transistor SC2. Capacitor C2 prevents the bias from being changed by signal currents, because this would greatly reduce the gain of the amplifier.

This method of direct coupling requires the collector supply voltage to be greater than that of an RC coupled amplifier. Some amplifier designers overcome this by using an NPN and PNP transistor directly coupled as shown in Fig. 20. It should be noted that SC2 is a PNP transistor and to simplify the circuit the symbol for SC2 is drawn with the emitter at the top.

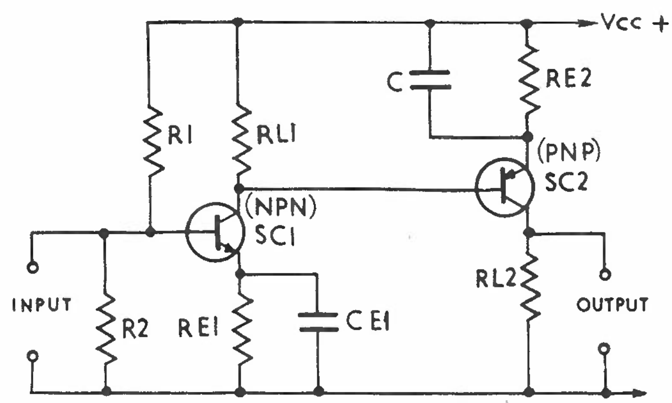


FIG. 20. DIRECTLY COUPLED NPN-PNP AMPLIFIER.

5.12 CIRCUIT OPERATION. The first stage is an NPN amplifier with combination bias obtained from R1, R2 and RE1. The voltage across the load resistor provides the bias potential for PNP transistor SC2. This bias is applied between the base and emitter of SC2. Any variation in collector current in SC1 thus varies the base current of SC2. The resultant collector current variations develop an output voltage across the load resistor RL2.

5.13 The circuit shown in Fig. 21 is another variation of a directly coupled amplifier This three stage amplifier uses a stepped voltage supply to obtain the higher potentials required for the second and third stages. The emitter resistors are again chosen to bring each emitter to the same voltage as the collector of the previous stage (less the required forward bias).

5.14 CIRCUIT OPERATION. Transistors SC2 and SC3 are biassed by the difference in potential between the collector potential of the previous stage and the emitter potential of each transistor. The potential difference makes the emitter 0.7 volt negative to the base and forward bias is thus produced. Any variation in the base current of SC1 changes its collector potential. This change alters the base emitter potential of SC2 by an amplified amount and causes a larger change in the collector current of SC3. The resultant amplified voltage change at the collector of SC3 alters the base current of SC2 which in turn varies the collector current and produces an amplified voltage output at the collector of SC3.

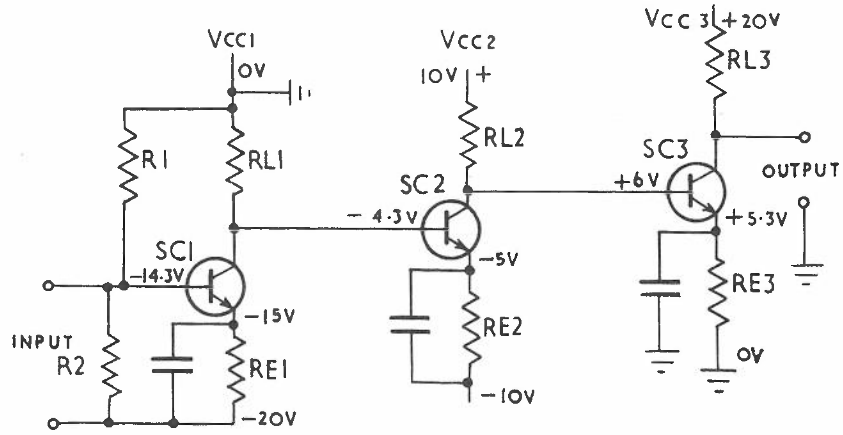


FIG. 21. THREE STAGE DIRECTLY COUPLED AMPLIFIER.

5.15 DC amplifiers. The gain of each of the directly coupled amplifiers considered so far decreases at low frequencies. This loss of gain is produced as follows. The reactance of the emitter by-pass capacitor increases at low frequencies and the signal currents produce voltage variations across this reactance. These voltage changes oppose the effective signal voltage between the base and the emitter of the stage and thus decrease the resultant collector current changes and, therefore, the gain of the stage. A directly coupled amplifier without emitter by-pass capacitors has a lower gain but can amplify low frequencies down to D.C. This is a great advantage in many control circuits in which varying D.C. signals have to be amplified or where the A.C. signal has a D.C. component which must be maintained, such as in some television signals.

5.16 CHARACTERISTICS. The characteristics of direct coupling are:

- Directly coupled circuits can be designed to contain fewer components and save cost.
- Directly coupled circuits can be made to amplify varying D.C. signals.
- Generally, higher supply potentials are required.
- The difficulty in maintaining thermal stability and in obtaining supply potentials increases with each stage directly coupled. Directly coupled amplifiers seldom exceed three stages for these reasons.

6. FIELD EFFECT TRANSISTORS.

6.1 GENERAL. FETs are used as amplifying devices in a similar way to bipolar transistors. A FET is used instead of a bipolar transistor when the circuit requires a higher input resistance than is readily available with a single bipolar transistor. Also FETs are built into integrated circuits because they can be formed easily with other components in the I.C., and require as little as 2 square mils of base area.

The circuits described in this paper use N channel JFETS. P channel FETs use the same circuits with reversed polarities. The circuits also apply to Insulated Gate FETs (IGFETs and MOSFETs) unless otherwise stated. A MOSFET is an IGFET in which the gate is insulated from the channel material by a layer of metal oxide.

In this paper the terms collector and emitter are used in conjunction with FETs. In some publications the terms drain and source are also used extensively to denote the collector and emitter respectively.

6.2 BIAS. We saw in para. 3.1 that linear amplifiers are those in which all variations of gate voltage cause corresponding changes in collector current, without alteration to the voltage waveshape. These amplifiers require the gate to be biassed to a point which allows equal negative and positive signals to be amplified without distortion. Field effect transistors are made in three distinct types, with different bias requirements for each group.

These are:

- Depletion only type (TYPE A). All JFETs are of this type, and some IGFETs are made with these characteristics.
- Depletion/enchancement type (TYPE B). This is the most widely used group and are usually IGFETs.
- Enhancement only type (TYPE C). Some IGFETs are made with these characteristics.

6.3 BIAS FOR DEPLETION ONLY TYPE FETs. In this type of FET, current flows from emitter to collector with zero voltage on the gate. For this reason, depletion only type FETs are said to be 'normally on'. In this respect they are different to bipolar transistors which are 'normally off' with zero base voltage.

When used for linear amplification, depletion only FETs are generally biassed to the centre of the most linear section of their gate voltage versus collector current graph, usually called the transfer characteristic. Fig. 22 shows a typical depletion only type transfer characteristic graph. Depending on the amplitude of the signal to be applied, a bias point between -1 volt and -4 volt would be suitable for this FET. For example, assume an applied input signal of ±1.5 volt peak. In this case, a bias voltage of -3 volt would provide satisfactory bias for linear amplification and both half cycles would be amplified without distortion. A similar P channel FET would require a bias of +3 volt for linear amplification in the same circumstances.

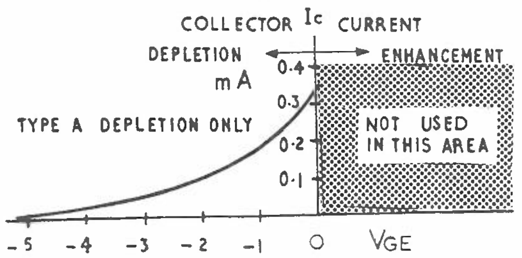


FIG. 22. DEPLETION TYPE FET CHARACTERISTICS.

6.4 BIAS FOR DEPLETION/ENHANCEMENT TYPE FETs. These IGFETS are also 'normally on' transistors and differ from JFETs in that forward bias applied to the gate increases or enhances the collector current without any decrease in the input resistance. This type of FET is usually biassed into the depletion mode, similar to depletion only transistors. However, the applied signal is sometimes large enough to make the transistor operate momentarily in the enhancement mode during signal peaks. Fig. 23 shows the transfer characteristics of a type B FET. A typical bias point for this FET (with a 2V peak AC signal applied) is -1 volt. The 2V input signal would cause the gate voltage to vary between -3 volt and +1 volt and the collector current to vary between 2 milli amp and 17 milli amp.

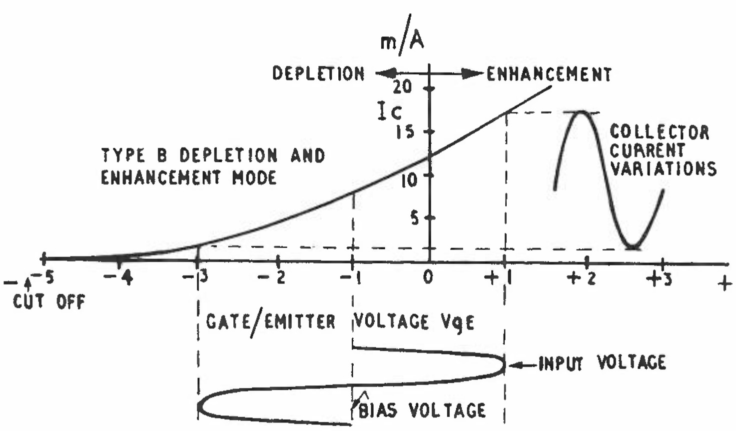


FIG. 23. CHARACTERISTICS OF TYPE B FETs.

6.5 BIAS FOR ENHANCEMENT ONLY TYPE FETs. FETs with these characteristics are less common than type A and type B FETs. However, they have some advantages over bipolar transistors in pulse circuits. Type C FETs require a bias voltage which is greater than the threshold voltage. The value of the threshold voltage depends on the FET construction.

Fig. 24 shows transfer characteristics for an enhancement only type FET. It shows that this type of FET has not significant collector current unless the bias exceeds a threshold voltage of +1.25 volt. This threshold voltage varies with the construction of the FET and is located between +1.24 volt and +5 volt.

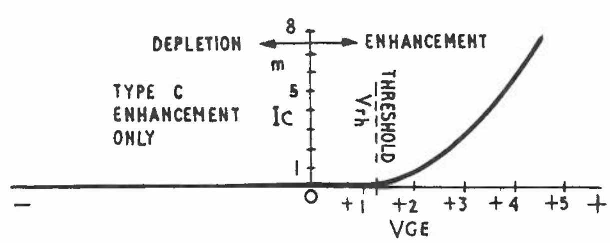


FIG. 24. CHARACTERISTICS OF TYPE C FETs.

6.6 BIAS POLARITY. A bias polarity which reduces the collector current below the zero bias value is called a reverse bias. A bias polarity which increases the collector current from the zero bias value is called forward bias. In depletion only and depletion/enhancement type FETs, it should be noted that a gradual increase in reverse bias gradually reduces the collector current, until the gate cut off voltage is exceeded. At this stage the collector current ceases. This does not apply to enhancement only FETs, which behave similar to bipolar transistors in that they are cut off by forward bias voltage below the threshold voltage and by reverse bias voltages.

An N channel FET with a reverse biassed gate would require potentials as shown in Fig. 25a. A forward biassed gate would have potentials as shown in Fig. 25b. It should be noted that for linear amplification, depletion only (type A) and depletion/ enhancement (type B) FETs are reverse biassed and enhancement only (type C) FETs require forward bias.

(a) Reverse Bias (b) Forward Bias

FIG. 25. BIAS POLARITIES.

6.7 BIAS METHODS. Type C FETs use bias methods which closely follow those used with bipolar transistors. They require sufficient forward bias to overcome the threshold voltage and to prevent rectification of the applied signal.

Type A and type B FETs are usually biassed to a point between zero bias and cut off. As shown in Fig. 25a, the potential required to provide this reverse bias is opposite in polarity to the collector potential. This means that the bias methods used in bipolar transistor circuits are not suitable, because they provide forward bias instead of the reverse bias. However, bias of the correct polarity for type A and type B FETs can be obtained from the voltage drop produced across the emitter resistor by the emitter current. This form of bias is called self bias and provides the required reverse bias.

6.8 SELF BIAS. This is the most commonly used method of deriving bias in type A and B FET circuits. A typical FET circuit using self bias is shown in Fig. 26.

This is a common emitter circuit and is similar to the common emitter bipolar transistor circuit. The input signal voltage is applied between the gate and the emitter. The gate voltage controls the emitter to collector current. The current through the FET develops a voltage across resistor RE in the emitter lead. In an N channel FET the emitter current causes the end of the resistor nearest to the emitter to become positive, and the end nearest the gate to become negative. In this way the gate is negative with respect to the emitter (by the voltage dropped across the emitter resistor) and the correct bias polarity is obtained for a type A or a type B FET.

The emitter resistor is usually by-passed by a large value capacitor to prevent the bias being varied by signal current variations. Variations in the bias, caused by the signal current variations, would reduce the gain of the stage. Self bias is not suitable for type C FETs because these FETs are normally off and, in addition, require a forward bias to make them conduct.

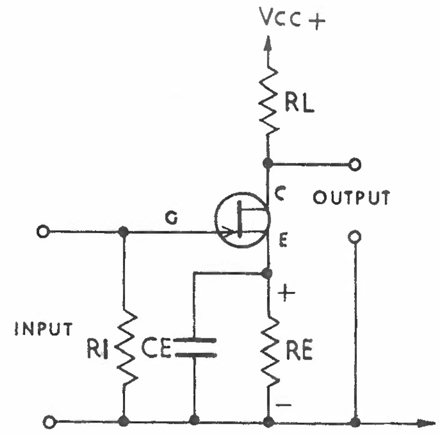


FIG. 26. FET AMPLIFIER WITH SELF BIAS.

6.9 STABILISATION. Production spread causes significant differences in the characteristics of FETs of the same nominal type. Consequently circuits must be designed so that no significant change takes place in the "no signal" value of collector current in the following circumstances:

- A faulty FET is replaced with another of the same nominal type.
- The conductivity of the channel is altered by changes in temperature.

Self bias provides a stabilising effect on the bias value as follows. The bias voltage is directly proportional to the emitter current. Therefore, any variation in this current (due to a replacement FET having slightly different characteristics, or to temperature changes) will change the bias voltage produced. When the collector current tends to increase above the nominal value the reverse bias increases and thus tends to decrease the collector current back to the nominal value. Conversely, when the collector current tends to decrease below the nominal value, the reverse bias decreases and thus tends to increase the collector current back to the nominal value.

6.10 FIXED VOLTAGE METHODS. The higher the emitter resistor the greater the stabilising effect becomes, but this also alters the bias working point (sometimes called the quiescent or rest point). The circuit designer frequently overcomes this conflict of requirements by providing another fixed voltage of opposite polarity from another source. The voltage derived across the emitter resistor is reduced by this fixed voltage to provide the correct bias, but the change of emitter voltage caused by a change in collector current is greater and, therefore, the stabilising effect is greater.

Since the voltage polarity required for the fixed voltage is the same as the polarity of the collector, the fixed voltage is usually derived from the collector supply voltage. Fixed voltage can be derived from the following sources:

- The collector supply potential.
- Directly from the collector.

When either method is used the circuit resembles combination bias in bipolar transistor circuits, as explained in para. 3.12 of this paper. However, it should be noted that in FET circuits the emitter voltage is greater than the fixed voltage by the value of bias required, whereas in bipolar circuits the fixed voltage is greater than the emitter resistor voltage.

Fig. 27 shows a FET circuit using a fixed voltage derived from voltage divider network resistors R1 and R2. The voltage developed across R2 is in opposition to the voltage developed across RE and thus reduces the voltage developed to the required bias voltage.

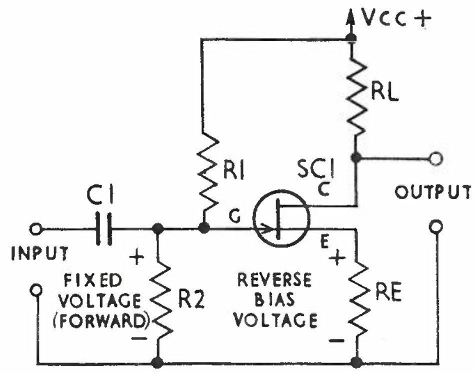


FIG. 27. COMBINATION OF A FIXED FORWARD VOLTAGE AND SELF BIAS.

6.11 INCREASED INPUT RESISTANCE. In circuits which obtain a fixed forward voltage from a voltage divider network (as shown in Fig. 27) it is sometimes necessary to increase the value of the resistance shunting the FET input (R2 in Figs. 27 and 28). In this case the bias is applied to the gate through a high value resistor (Rg in Fig. 28).

The circuit in Fig. 28 shows a common emitter FET circuit which is biassed by a combination of self bias and fixed forward voltage. The fixed voltage is developed across R2 and is applied through resistor Rg. Resistors R2 and Rg are in series across the amplifier input and thus provide a much higher input impedance than that in Fig. 28).

Resistor Rg has little effect on the bias voltage because of the very low value of current through the gate circuit.

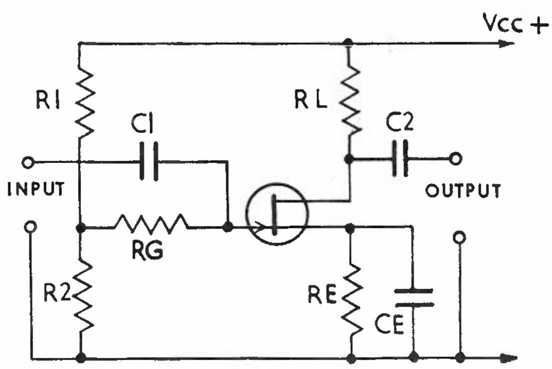


FIG. 28. INCREASED INPUT RESISTANCE WITH COMBINATION BIAS.

6.12 COLLECTOR BIAS. Collector bias is commonly used for type C FETs. In this method a single bias resistor provides satisfactory bias and good stability to the amplifier. The bias resistor affects the input impedance and must therefore be large; a typical value is 22 meg ohm.

Collector bias, as shown in Fig. 29, is used in some type C FET circuits. The FET is operated with a bias voltage equal to the collector voltage. By a suitable choice of load resistor value the designer can provide a circuit which is stable against supply voltage variations and temperature drift of collector current.

The circuit is stabilised as follows. An increase in collector current causes a decrease in collector voltage and in the voltage returned to the gate. This reduction in bias reduces the collector current to the stable collector current operating value.

Similarly a decrease in the collector current increases the collector voltage and increases the bias voltage thus restoring the collector current to its stable value before the change.

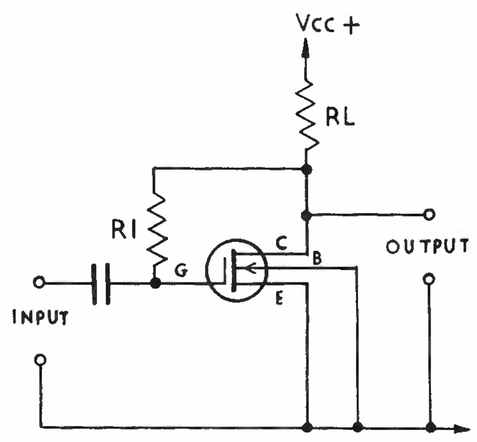


FIG. 29. IGFET WITH COLLECTOR BIAS.

6.13 FET CIRCUIT CONFIGURATIONS. The same three basic circuit configurations are used as in bipolar transistor circuits. There are:

- Common emitter (also called Common source and collector follower)
- Common collector (also called Common drain and emitter follower)
- Common gate

The general characteristics of each type are listed in table 3 with the basic circuit configuration for each type.

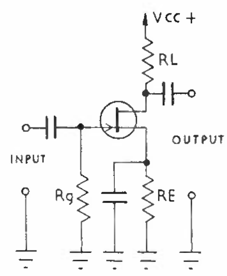
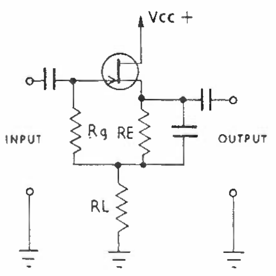
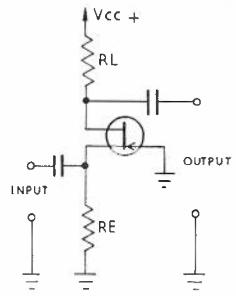
CHARACTERISTIC	COMMON EMITTER	COMMON COLLECTOR	COMMON GATE
			
INPUT IMPEDANCE	HIGH	VERY HIGH	LOW
OUTPUT IMPEDANCE	MEDIUM	LOW	HIGH
CURRENT GAIN	HIGH	HIGH	LESS THAN UNITY
AUDIO VOLTAGE GAIN	MEDIUM	LESS THAN UNITY	MEDIUM
R.F. VOLTAGE GAIN	LOW	LESS THAN UNITY	MEDIUM
POWER GAIN	HIGH	MEDIUM	MEDIUM
NOISE INTRODUCED	VERY LOW	VERY LOW	VERY LOW
OUTPUT VOLTAGE POLARITY	INVERTED	SAME AS INPUT	SAME AS INPUT

TABLE 3.

6.14 COUPLING METHODS. Field effect transistor circuits are connected together using the same coupling methods as those explained in section 5 of this paper for bipolar transistors. FETs are widely used in conjunctions with bipolar transistors in amplifier circuits and are, therefore, usually shown coupled to a bipolar transistor in this section.

6.15 RC COUPLING IN FET AMPLIFIERS. The circuit in Fig. 30 shows a high input impedance amplifier. The N channel JFET (SCI) is self biassed by resistor R2 and is coupled by capacitor C1 to the input of bipolar transistor SC2. The input impedance of transistor SC2 is approximately the same as the output impedance of the FET and therefore provides a good impedance match. Transistor SC2 is an NPN transistor biassed by combination bias.

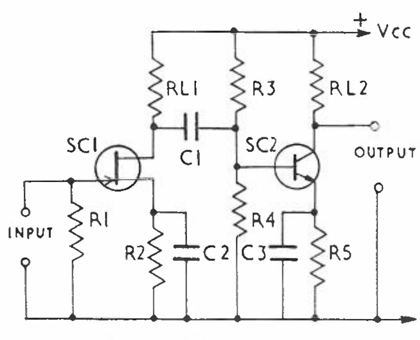


FIG. 30. FET RC-COUPLED TO A BIPOLAR TRANSISTOR.

6.16 DIRECT COUPLING IN FET AMPLIFIERS. Direct coupling is a common method of connecting a FET amplifier stage to the next stage of amplification. The circuit in Fig. 31 shows a typical example in which JFET(SCI) is directly coupled to the bipolar transistor SC2.

The difference in potential between the collector of SC1 and the emitter of SC2 provides the bias required for linear operation. SC1 is biassed by self bias obtained from the emitter resistor RE1.

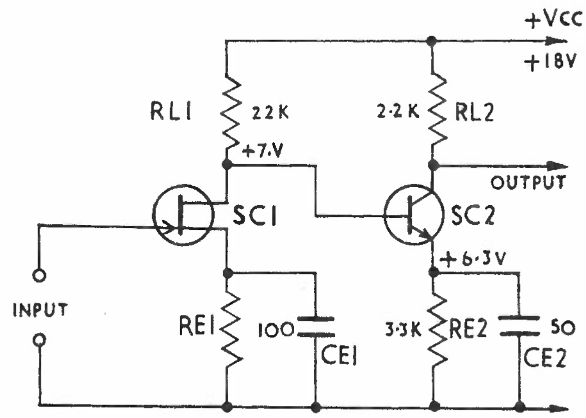


FIG. 31. FET DIRECTLY COUPLED TO A BIPOLAR TRANSISTOR.

6.17 TRANSFORMER COUPLING IN FET AMPLIFIERS. One of the main advantages of FETs is their satisfactory operation at high radio frequencies. It is in this type of circuit that transformer coupling is most commonly used.

The circuit shown in Fig. 32 is used to amplify a narrow band of radio frequencies. To obtain the maximum gain over the required range the load of SC1 is formed by a resonant circuit. The inductance is obtained from the primary of a transformer T1.

The transformer secondary is connected to the base of transistor SC2 which is a bipolar transistor amplifier.

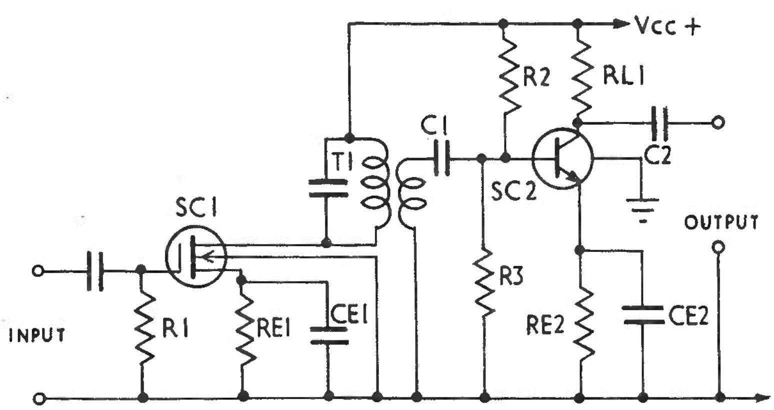


FIG. 32. TRANSFORMED COUPLED FET AMPLIFIER.

NOTES

NOTES

7. TEST QUESTIONS.

1. *Briefly explain why a load resistor is required in a transistor amplifier.*

2. *A signal which makes the base of an NPN transistor negative with respect to the emitter has the following effects.*

The transistor resistance	*increases / decreases*
The collector current	*increases / decreases*
The collector voltage	*increases / decreases*

3. (a) *State two reasons why a transistor in a linear amplifier requires a bias voltage.*

   (b) *Calculate a suitable bias for a germanium transistor so that a 0.4 volt peak A.C. signal can be amplified with minimum distortion.*

4. (a) *Explain how thermal runaway occurs in an unstabilised transistor circuit.*

   (b) *Why does thermal runaway occur more readily in germanium transistor circuits than in silicon transistor circuits?*

5. *State an advantage and a disadvantage of connecting the voltage divider bias network to the collector of a transistor instead of to the supply voltage.*

6. (a) *What is the function of the capacitor placed across the emitter resistor in a transistor circuit?*

   (b) *Why is this capacitor usually of a large value?*

7. *Briefly explain how combination bias compensates for an increase in collector current caused by a change in ambient temperature.*

8. (a) *What are the three main circuit configurations used with bipolar transistors?*

   (b) *With the aid of simple circuits show where:*

   (i) *the input signal is applied on each configuration,*

   (ii) *the output signal is obtained on each configuration.*

9. *What is the main advantage of each configuration?*

10. *What is the polarity of the output signal relative to the input signal for each configuration?*

11. *What are the functions of a coupling circuit?*

12. *Draw a simple circuit of a two stage amplifier using RC coupling between the stages.*

13. *With the aid of an amplitude versus frequency curve explain the type of frequency response which could be expected from an RC coupled amplifier.*

14. *List the characteristics of transformer coupling.*

TEST QUESTIONS (CONTD.)

15. *Explain how an A.C. signal is amplified by the directly coupled amplifier shown in Fig. 33.*

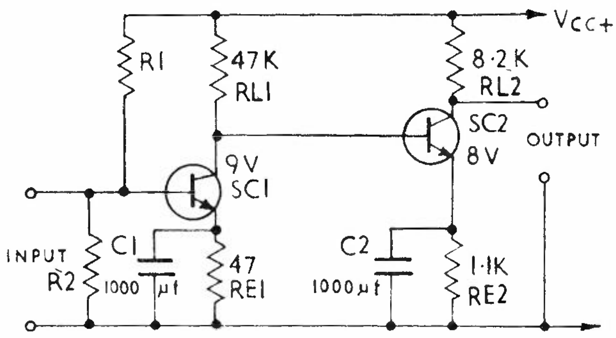


FIG. 33.

16. *List the characteristics of direct coupling between amplifier stages.*

17. *List the three main types of FET used in amplifier circuits and briefly explain the characteristics of each type.*

18. *With the aid of the circuit symbol for a FET, show what polarity of gate signal must be to be applied to (a) Increase the collector current.*
    (b) Cut off the collector current.

19. *Explain how combination bias used in a linear FET amplifier differs from that used with bipolar transistors.*

20. *With the aid of simple circuits show the three main FET amplifier configurations.*

21. *List the main advantage and disadvantage of each configuration.*

22. *Draw the circuit of a simple amplifier using a FET amplifier stage RC coupled to a bipolar second stage.*

23. *Explain how an A.C.signal applied to the input of a FET amplifier produces an amplified signal at the output.*

24. *State the advantages of using a FET input stage followed by a bipolar transistor stage in an amplifier.*

END OF PAPER.