

3. Single Stage Transistor Amplifiers

3.1 Introduction

Our purpose here will be to discuss *single stage transistor amplifier*. By a *stage* we mean a single transistor with its bias and auxiliary equipment. It may be emphasised here that a practical amplifier is always a multistage amplifier *i.e.* it has a number of stages of amplification. However, it is profitable to consider the multistage amplifier in terms of single stages that are connected together. In this chapter, we shall confine our attention to single stage transistor amplifiers.

3.2 Single Stage Transistor Amplifier

When only one transistor with associated circuitry is used for amplifying a weak signal, the circuit is known as **single stage transistor amplifier**.

A single stage transistor amplifier has one transistor, bias circuit and other auxiliary components. Although a practical amplifier consists of a number of stages, yet such a complex circuit can be conveniently split up into separate single stages. By analysing carefully only a single stage and using this single stage analysis repeatedly, we can effectively analyse the complex circuit. It follows, therefore, that single stage amplifier analysis is of great value in understanding the practical amplifier circuits.

3.3 How Transistor Amplifies?

Fig. 3.1 shows a single stage transistor amplifier. When a weak a.c. signal is given to the base of transistor, a small base current (which is a.c.) starts flowing. Due to transistor action, a much larger (β times the base current) a.c. current flows through the collector load R_C . As the value of R_C is quite high (usually 4-10 k Ω), therefore, a large voltage appears across R_C . Thus, a weak signal applied in the base circuit appears in amplified form in the collector circuit. It is in this way that a transistor acts as an amplifier.

The action of transistor amplifier can be beautifully explained by referring to Fig. 3.1. Suppose a change of 0.1V in signal voltage produces a change of 2 mA in the collector current. Obviously, a signal of only 0.1V applied to the base will give an output voltage = $2 \text{ mA} \times 5 \text{ k}\Omega = 10\text{V}$. Thus, the transistor has been able to raise the voltage level of the signal from 0.1V to 10V *i.e.* voltage amplification or stage gain is 100.

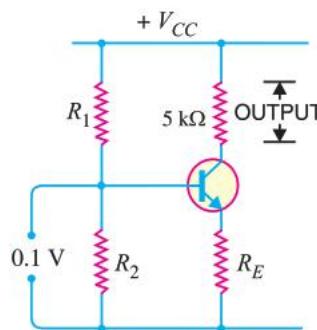


Fig. 3.1

3.4 Practical Circuit of Transistor Amplifier

It is important to note that a transistor can accomplish faithful amplification only if proper associated circuitry is used with it. Fig. 3.2 shows a practical single stage transistor amplifier.

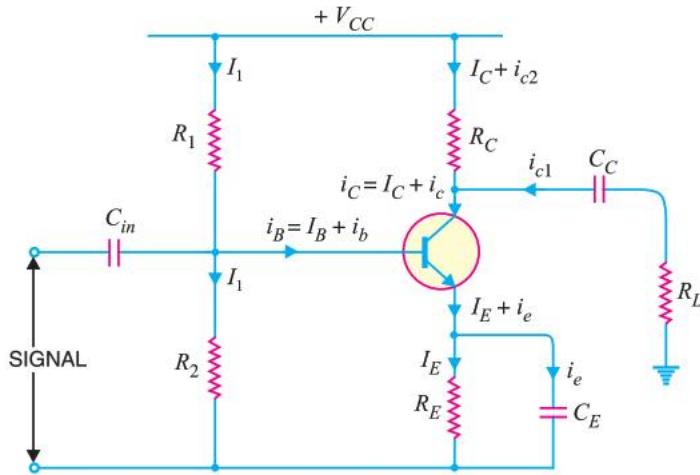


Fig. 3.2

The various circuit elements and their functions are described below:

(i) Biasing circuit.

The resistances R_1 , R_2 and R_E form the biasing and stabilisation circuit. The biasing circuit must establish a proper operating point otherwise a part of the negative half-cycle of the signal may be cut off in the output.

(ii) Input capacitor C_{in}

An electrolytic capacitor C_{in} ($\approx 10 \mu\text{F}$) is used to couple the signal to the base of the transistor. If it is not used, the signal source resistance will come across R_2 and thus change the bias. The capacitor C_{in} allows only a.c. signal to flow but isolates the signal source from R_2 .

(iii) Emitter bypass capacitor C_E

An emitter bypass capacitor C_E to provide a low reactance path to the amplified a.c. signal. If it is not used, then amplified a.c. signal flowing through R_E will cause a voltage drop across it, thereby reducing the output voltage.

(iv) Coupling capacitor C_C

The coupling capacitor C_C ($\approx 10 \mu\text{F}$) couples one stage of amplification to the next stage. If it is not used, the bias conditions of the next stage will be drastically changed due to the shunting effect of R_C . This is because R_C will come in parallel with the upper resistance R_1 of the biasing network of the next stage, thereby altering the biasing conditions of the latter. In short, the coupling capacitor C_C isolates the d.c. of one stage from the next stage, but allows the passage of a.c. signal.

Various circuit currents. It is useful to mention the various currents in the complete amplifier circuit. These are shown in the circuit of Fig. 3.2.

(i) Base current. When no signal is applied in the base circuit, d.c. base current I_B flows due to biasing circuit. When a.c. signal is applied, a.c. base current i_b also flows. Therefore, with the application of signal, total base current i_B is given by:

$$i_B = I_B + i_b$$

(ii) Collector current. When no signal is applied, a d.c. collector current I_C flows due to biasing circuit. When a.c. signal is applied, a.c. collector current i_c also flows. Therefore, the total collector current i_C is given by:

$$i_C = I_C + i_c$$

where

$$I_C = \beta I_B = \text{zero signal collector current}$$

$$i_c = \beta i_B = \text{collector current due to signal}$$

- (iii) **Emitter current.** When no signal is applied, a d.c. emitter current I_E flows. With the application of signal, total emitter current i_E is given by:

$$i_E = I_E + i_e$$

It is useful to keep in mind that:

$$I_E = I_B + I_C$$

$$i_e = i_b + i_c$$

Now base current is usually very small, therefore, as a reasonable approximation,

$$I_E \cong I_C \quad \text{and} \quad i_e \cong i_c$$

Example 3.1

What is the role of emitter bypass capacitor C_E in the Common Emitter (CE) amplifier circuit shown in Fig. 3.2 ? Illustrate with a numerical example.

Solution

The emitter bypass capacitor C_E (See Fig. 3.2) connected in parallel with R_E plays an important role in the circuit. If it is not used, the amplified a.c. signal flowing through R_E will cause a voltage drop across it, thereby reducing the a.c. output voltage and hence the voltage gain of the amplifier.

Let us illustrate the effect of C_E with a numerical example. Suppose $R_E = 1000\Omega$ and capacitive reactance of C_E at the signal frequency is 100Ω (i.e. $X_{C_E} = 100\Omega$). Then 10/11 of a.c. emitter current will flow through C_E and only 1/11 through R_E . The signal voltage developed across R_E is, therefore, only 1/11 of the voltage which would have been developed if C_E were not present. In practical circuits, the value of C_E is so selected that it almost entirely bypasses the a.c. signal (the name for C_E is obvious). *For all practical purposes, we consider C_E to be a short for a.c. signals.*

3.5 Phase Reversal

In common emitter connection, when the input signal voltage increases in the positive sense, the output voltage increases in the negative direction and *vice-versa*. In other words, there is a phase difference of 180° between the input and output voltage in CE connection. This is called *phase reversal*.

The phase difference of 180° between the signal voltage and output voltage in a common emitter amplifier is known as phase reversal.

The total instantaneous output voltage v_{CE} is given by:

$$v_{CE} = V_{CC} - i_C R_C$$

When the signal voltage increases in the positive half-cycle, the base current also increases. The result is that collector current and hence voltage drop $i_C R_C$ increases. As V_{CC} is constant, therefore, output voltage v_{CE} decreases. In other words, as the signal voltage is increasing in the positive half cycle, the output voltage is increasing in the negative sense i.e. output is 180° out of phase with the input. It follows, therefore, that in a common emitter amplifier, the positive half-cycle of the signal appears as amplified negative half-cycle in the output and *vice-versa*. It may be noted that amplification is not affected by this phase reversal.

Note. No phase reversal of voltage occurs in common base and common collector amplifier. The a.c. output voltage is in phase with the a.c. input signal. For all three amplifier configurations, input and output currents are in phase.

3.6 Input/Output Phase Relations

The following points regarding the input/output phase relationships between currents and voltages for the various transistor configurations may be noted:

(i) *For every amplifier type (CE, CB and CC), the input and output currents are in phase.*

(ii) When the input current decreases, the output current also decreases and vice-versa.

(ii) Remember that common emitter (CE) circuit is the **only configuration** that has input and output voltages 180° out of phase.

(iii) For both common base (CB) and common collector (CC) circuits, the input and output voltages are in phase. If the input voltage decreases, the output voltage also decreases and vice-versa.

3.7 D.C and A.C Equivalent Circuits

In a transistor amplifier, both d.c. and a.c. conditions prevail. The d.c. sources set up d.c. currents and voltages whereas the a.c. source (*i.e.* signal) produces fluctuations in the transistor currents and voltages. Therefore, a simple way to analyse the action of a transistor is to split the analysis into two parts *viz.* a d.c. analysis and an a.c. analysis. In the d.c. analysis, we consider all the d.c. sources at the same time and work out the d.c. currents and voltages in the circuit. On the other hand, for a.c. analysis, we consider all the a.c. sources at the same time and work out the a.c. currents and voltages. By adding the d.c. and a.c. currents and voltages, we get the total currents and voltages in the circuit. For example, consider the amplifier circuit shown in Fig. 3.3. This circuit can be easily analysed by splitting it into **d.c. equivalent circuit** and **a.c. equivalent circuit**.

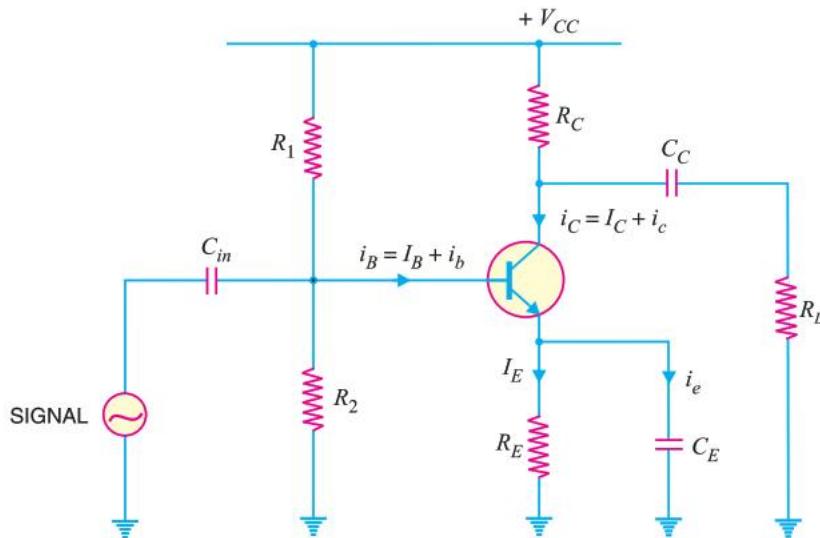


Fig. 3.3

(i) D. C. equivalent circuit. In the d.c. equivalent circuit of a transistor amplifier, only d.c. conditions are to be considered *i.e.* it is presumed that no signal is applied. As direct current cannot flow through a capacitor, therefore, **all the capacitors look like open circuits in the d.c. equivalent circuit.** It follows, therefore, that in order to draw the equivalent d.c. circuit, the following two steps are applied to the transistor circuit:

- (a) Reduce all a.c. sources to zero.
- (b) Open all the capacitors.

Applying these two steps to the circuit shown in Fig. 3.3, we get the d.c. equivalent circuit shown in Fig. 3.4. We can easily calculate the d.c. currents and voltages from this circuit.

(ii) A.C. equivalent circuit. In the a.c. equivalent circuit of a transistor amplifier, only a.c. conditions are to be considered. Obviously, the d.c. voltage is not important for such a circuit and may be considered zero. The capacitors are generally used to couple or bypass the a.c. signal. The designer intentionally selects capacitors that are large enough to appear as **short** circuits to the a.c. signal. It follows, therefore, that in order to draw the a.c. equivalent circuit, the following two steps are applied to the transistor circuit:

- (a) Reduce all d.c. sources to zero (*i.e.* $V_{CC} = 0$).
- (b) Short all the capacitors.

Applying these two steps to the circuit shown in Fig. 3.3, we get the a.c. equivalent circuit shown in Fig. 3.5. We can easily calculate the a.c. currents and voltages from this circuit.

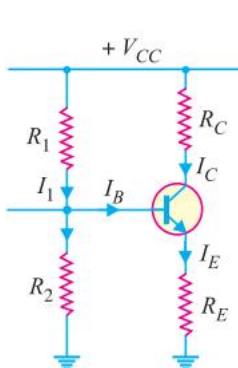


Fig. 3.4

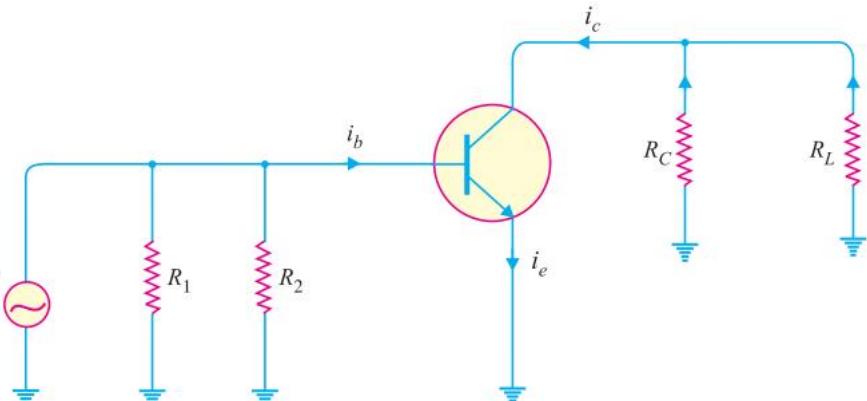


Fig. 3.5

It may be seen that total current in any branch is the sum of d.c. and a.c. currents through that branch. Similarly, the total voltage across any branch is the sum of d.c. and a.c. voltages across that branch.

3.8 Load Line Analysis

The output characteristics are determined experimentally and indicate the relation between V_{CE} and I_C . However, the same information can be obtained in a much simpler way by representing the mathematical relation between I_C and V_{CE} graphically. As discussed before, the relationship between V_{CE} and I_C is linear so that it can be represented by a straight line on the output characteristics. This is known as a **load line**. The points lying on the load line give the possible values of V_{CE} and I_C in the output circuit. As in a transistor circuit both d.c. and a.c. conditions exist, therefore, there are two types of load lines, namely; d.c. load line and a.c. load line. The former determines the locus of I_C and V_{CE} in the zero signal conditions and the latter shows these values when the signal is applied.

(i) d.c. load line. It is the line on the output characteristics of a transistor circuit which gives the values of I_C and V_{CE} corresponding to zero signal or d.c. conditions.

Consider the transistor amplifier shown in Fig. 3.6. In the absence of signal, d.c. conditions prevail in the circuit as shown in Fig. 10.13 (i). Referring to this circuit and applying Kirchhoff's voltage law,

$$V_{CE} = V_{CC} - I_C R_C - I_E R_E$$

or

$$V_{CE} = V_{CC} - I_C (R_C + R_E) \quad (i) \quad \because I_E \cong I_C$$

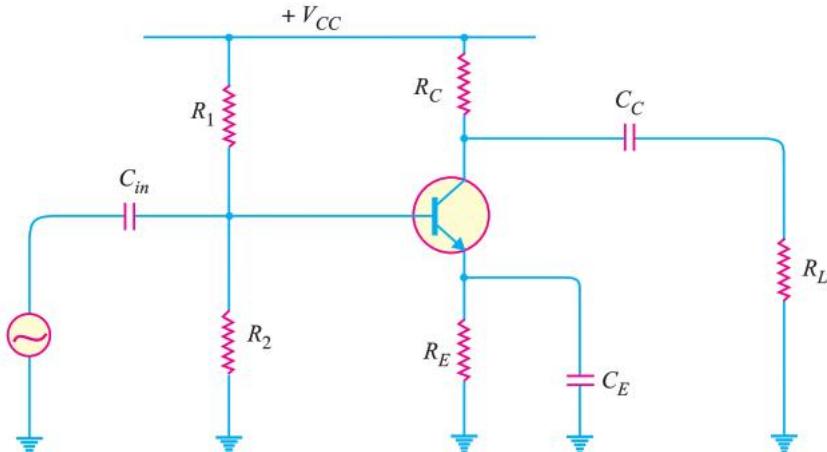


Fig. 3.6

For a given circuit, V_{CC} and $(R_C + R_E)$ are constant, therefore, it is a first degree equation and can be represented by a straight line on the output characteristics. This is known as **d.c. load line** and determines the loci of V_{CE} and I_C points in the zero signal conditions. (This equation is known as **load line equation** since it relates the collector-emitter voltage (V_{CE}) to the collector current (I_C) flowing through the load).

The d.c. load line can be readily plotted by locating two **end points** of the straight line.

The value of V_{CE} will be maximum when $I_C = 0$. Therefore, by putting $I_C = 0$ in exp. (i), we get,

$$\text{Max. } V_{CE} = V_{CC}$$

This locates the first point B ($OB = V_{CC}$) of the d.c. load line.

The value of I_C will be maximum when $V_{CE} = 0$.

Therefore;

$$\text{Max. } I_C = \frac{V_{CC}}{R_C + R_E}$$

This locates the second point A ($OA = \frac{V_{CC}}{R_C + R_E}$) of the d.c. load line. By joining points A and B , the d.c. load line AB is constructed [See Fig. 3.7 (ii)].

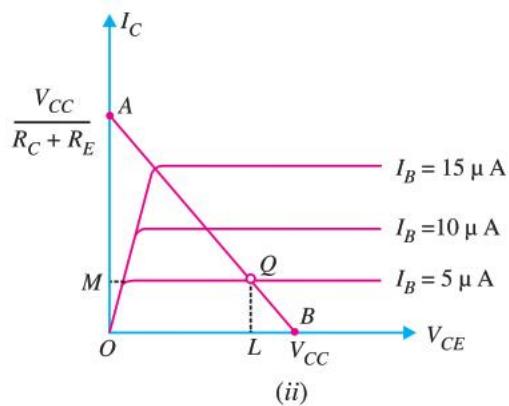
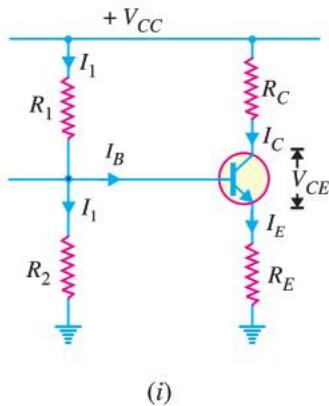


Fig. 3.7

(ii) a.c. load line. This is the line on the output characteristics of a transistor circuit which gives the values of i_C and v_{CE} when signal is applied.

Referring back to the transistor amplifier shown in Fig. 3.6, its a.c. equivalent circuit as far as output circuit is concerned is as shown in Fig. 3.8 (i). To add the a.c. load line to the output characteristics, we again require two end points, – one maximum collector-emitter voltage point and the other maximum collector current point. Under the application of a.c. signal, these values are:

$$\text{Max. collector emitter voltage} = V_{CE} + I_C R_{AC}$$

where

$$R_{AC} = R_C \parallel R_L = \frac{R_C R_L}{R_C + R_L}$$

This locates the point C of the a.c. load line on the collector-emitter voltage axis.

$$\text{Max. collector current} = I_C + \frac{V_{CE}}{R_{AC}}$$

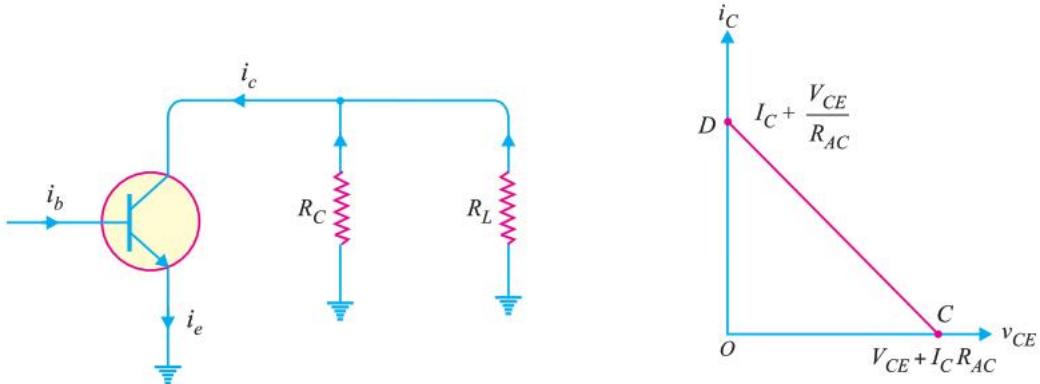


Fig. 3.8

3.9 Voltage Gain

The basic function of an amplifier is to raise the strength of an a.c. input signal. The voltage gain of the amplifier is the ratio of a.c. output voltage to the a.c. input signal voltage. Therefore, in order to find the voltage gain, we should consider only the a.c. currents and voltages in the circuit. For this purpose, we should look at the a.c. equivalent circuit of transistor amplifier. For ease of reference, the a.c. equivalent circuit of transistor amplifier is redrawn in Fig. 3.9.

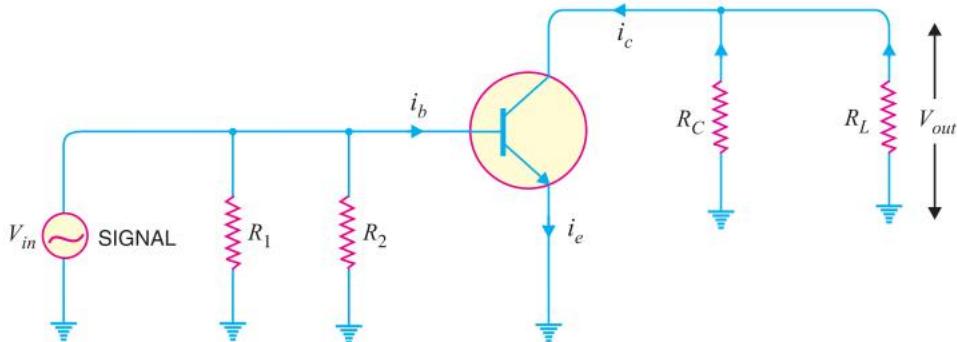


Fig. 3.9

It is clear that as far as a.c. signal is concerned, the load R_C appears in parallel with R_L . Therefore, effective load for a.c. is given by:

$$\text{a.c load, } R_{AC} = R_C \parallel R_L = \frac{R_C R_L}{R_C + R_L}$$

$$\text{output voltage, } V_{out} = i_c R_{AC}$$

$$\text{input voltage, } V_{in} = i_b R_{in}$$

$$\text{Voltage, } A_v = \frac{V_{out}}{V_{in}}$$

$$A_v = \frac{i_c R_{AC}}{i_b R_{in}} = \beta \times \frac{R_{AC}}{R_{in}}$$

Incidentally, power gain is given by;

$$A_v = \frac{i_c^2 R_{AC}}{i_b^2 R_{in}} = \beta^2 \times \frac{R_{AC}}{R_{in}}$$

Exercise

1. In the circuit shown in Fig. 3.10, find the voltage gain. Given that $\beta = 60$ and input resistance $R_{in} = 1 \text{ k}\Omega$.

2. In the circuit shown in Fig. 3.10, if $R_C = 10 \text{ k}\Omega$, $R_L = 10 \text{ k}\Omega$, $R_{in} = 2.5 \text{ k}\Omega$, $\beta = 100$, find the output voltage for an input voltage of 1mV r.m.s.

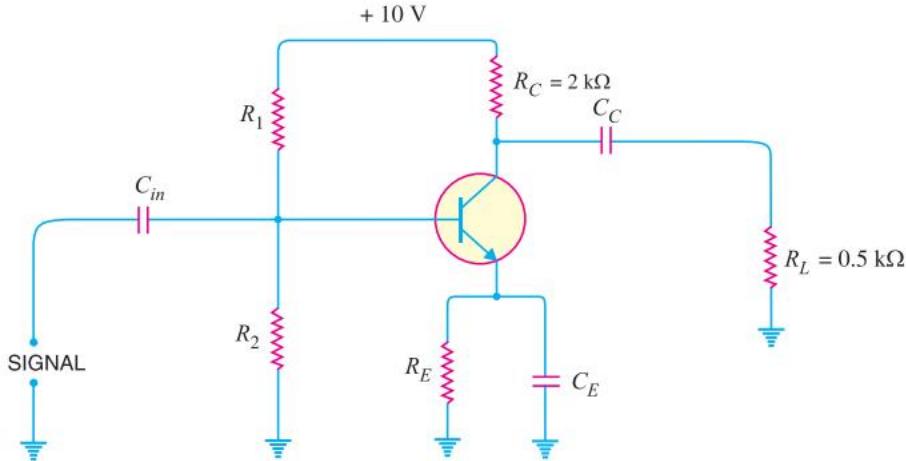


Fig. 3.10

3.10 A. C Emitter Resistance

The ac or dynamic resistance of emitter-base junction diode of a transistor is called *ac emitter resistance*. It is defined as the change in base-emitter voltage divided by change in corresponding emitter current [See Fig. 3.11] i.e.

$$R_{ac} = \frac{\Delta V_{BE}}{\Delta I_E}$$

3.11 Formula for A. C Emitter Resistance

It can be shown mathematically that the ac resistance of emitter diode is given by;

$$R_{ac} = \frac{25 \text{ mV}}{I_E}$$

where

$$I_E = \text{d.c emitter current} = V_E/R_E \text{ at Q - point}$$

Note the significance of this formula. It implies that ac emitter resistance can be found simply by substituting the quiescent value of emitter current into the equation. There is no need to have the characteristics available. It is important to keep in mind that this formula is accurate only for small signal operation. It is a usual practice to represent ac emitter resistance by r'_e .

The subscript e indicates emitter. The lower case r is used to indicate an ac resistance. The prime shows that it is an internal resistance.

$$r'_e = \frac{25 \text{ mV}}{I_E}$$

Example 3.2

Determine the ac emitter resistance for the transistor circuit shown in Fig. 3.11. Assume the transistor to be made of silicon.

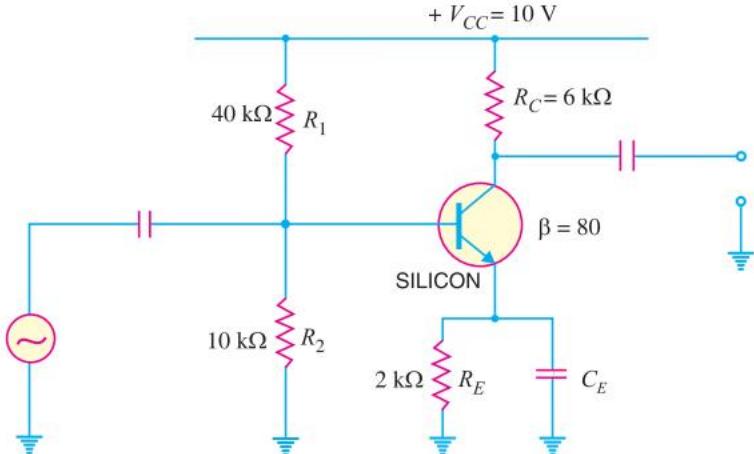


Fig. 3.11

Solution

$$\text{Voltage across } R_2, V_2 = \frac{R_2}{R_1 + R_2} \times V_{CC} = \frac{10 \text{ k}\Omega}{(40 + 10) \text{ k}\Omega} \times 10 \text{ V} = 2 \text{ V}$$

$$\text{Voltage across } R_E, V_E = V_2 - V_{BE} = 2 - 0.7 = 1.3 \text{ V}$$

$$\text{Emitter current, } I_E = \frac{V_E}{R_E} = \frac{1.3 \text{ V}}{2 \text{ k}\Omega} = 0.65 \text{ mA}$$

$$\text{a.c emitter resistance, } r'_e = \frac{25 \text{ mV}}{I_E} = \frac{25 \text{ mV}}{0.65 \text{ mA}} = 38.46 \Omega$$

3.12 Voltage Gain of Common Emitter (CE) Amplifier With C_E

The voltage gain (A_v) of an amplifier is equal to a.c. output voltage (v_{out}) divided by a.c. input voltage (v_{in}) i.e. $A_v = v_{out}/v_{in}$. We have already seen that voltage gain of a CE amplifier is given by;

$$\text{Voltage gain, } A_v = \beta \times \frac{R_C}{R_{in}} \dots \text{for unloaded amplifier}$$

$$\text{Voltage gain, } A_v = \beta \times \frac{R_{AC}}{R_{in}} \dots \text{for loaded amplifier}$$

$$\text{Recall } R_{AC} = R_C \parallel R_L$$

The above formula for A_v can be used if we know the values of R_C (or R_{AC}), β and R_{in} . Generally, all these values are not known. In that case, we can find the value of A_v in terms of **total a.c. collector resistance** and **total a.c. emitter resistance**. For the circuit shown in Fig. 3.12 (with C_E connected across R_E), it can be proved that the voltage gain is given by;

$$\text{Voltage gain, } A_v = \frac{R_C}{r'_e} \dots \text{for unloaded amplifier}$$

$$\text{Voltage gain, } A_v = \frac{R_{AC}}{r'_e} \dots \text{for loaded amplifier}$$

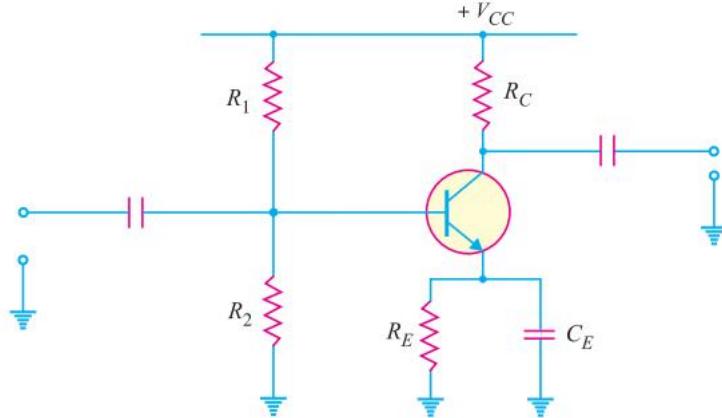


Fig. 3.12

3.13 Voltage Gain of Common Emitter (CE) Amplifier Without \$C_E\$

When we remove the emitter bypass capacitor (\$C_E\$) from the CE amplifier shown in Fig. 3.12 above, the voltage gain of the circuit is greatly reduced. The reason is simple. Without the emitter bypass capacitor \$C_E\$, the emitter is no longer at the ac ground as shown in Fig. 3.13. Therefore, for the a.c. signal, both \$r'_e\$ and \$R_E\$ are in series. As a result, the voltage gain of the amplifier becomes:

$$\text{Voltage gain, } A_v = \frac{R_C}{r'_e + R_E} \dots \text{for unloaded amplifier}$$

$$\text{Voltage gain, } A_v = \frac{R_{AC}}{r'_e + R_E} \dots \text{for loaded amplifier}$$

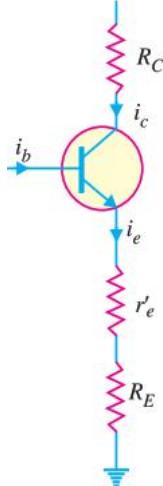


Fig. 3.13

Exercise

1. For the amplifier circuit shown in Fig. 3.14, find the voltage gain of the amplifier with; (i) \$C_E\$ connected in the circuit (ii) \$C_E\$ removed from the circuit.
2. If in the above example, a load of \$6\text{ k}\Omega\$ is connected (with \$C_E\$ connected) to the collector terminal through a capacitor, what will be the voltage gain of the amplifier?

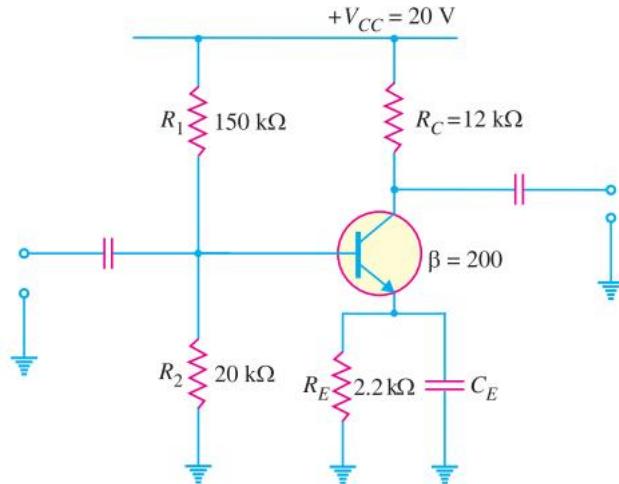


Fig. 3.14

3.14 Input Impedance of Common Emitter (CE) Amplifier

When one CE amplifier is being used to drive another, the input impedance of the second amplifier will serve as the load resistance of the first. Therefore, in order to calculate the voltage gain (A_v) of the first amplifier stage correctly, we must calculate the input impedance of the second stage. The input impedance of an amplifier can be found by using the ac equivalent circuit of the amplifier as shown in Fig. 3.15.

$$Z_{in} = R_1 \parallel R_2 \parallel Z_{in(base)}$$

where

Z_{in} = input impedance of the amplifier

$Z_{in(base)}$ = input impedance of the transistor base

Now;

$$Z_{in(base)} = \beta r'_e$$

The input impedance [Z_{in}] is always less than the input impedance of the base [$Z_{in(base)}$].

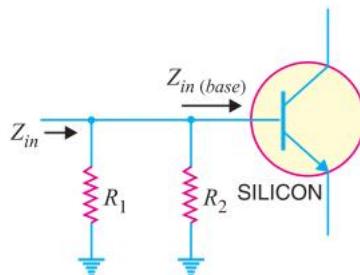


Fig. 3.15

Example 3.3

Determine the input impedance of the amplifier circuit shown in Fig. 3.16. Assume V_{BE} to be negligible.

Solution

$$\text{Voltage across } R_2, V_2 = \frac{R_2}{R_1 + R_2} \times V_{CC} = \frac{15 \text{ k}\Omega}{(45 + 15) \text{ k}\Omega} \times 30 \text{ V} = 7.5 \text{ V}$$

$$\text{Voltage across } R_E, V_E = V_2 - V_{BE} = 7.5 - 0 = 7.5 \text{ V}$$

$$\text{Emitter current, } I_E = \frac{V_E}{R_E} = \frac{7.5 \text{ V}}{7.5 \text{ k}\Omega} = 1 \text{ mA}$$

$$\text{a.c emitter resistance, } r'_e = \frac{25 \text{ mV}}{I_E} = \frac{25 \text{ mV}}{1 \text{ mA}} = 25 \Omega$$

$$Z_{in(base)} = \beta r'_e = 200 \times 25 = 5 \times 10^3 = 5 \text{ k}\Omega$$

$$Z_{in} = R_1 \parallel R_2 \parallel Z_{in(base)}$$

$$= 45 \text{ k}\Omega \parallel 15 \text{ k}\Omega \parallel 5 \text{ k}\Omega = 3.45 \text{ k}\Omega$$

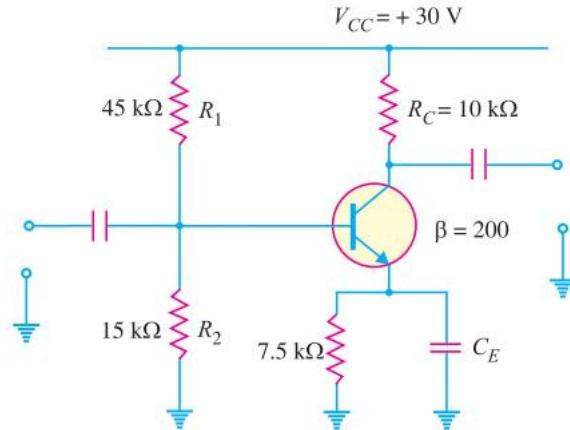


Fig. 3.16