$$= \frac{1}{2}(58\text{ mA})^2 \times 325\Omega = \mathbf{546\ mW}$$

(iii) D.C. input power, P_{dc} $= V_{CC} I_C = 20\text{ V} \times 58\text{ mA} = 1160\text{ mW}$

$\therefore$ Collector η $= \frac{546}{1160} \times 100 = \mathbf{47\%}$

12.11 Thermal Runaway

All semiconductor devices are very sensitive to temperature variations. If the temperature of a transistor exceeds the permissible limit, the transistor may be *permanently damaged. Silicon transistors can withstand temperatures upto 250ºC while the germanium transistors can withstand temperatures upto 100ºC.

There are two factors which determine the operating temperature of a transistor *viz.* (*i*) surrounding temperature and (*ii*) power dissipated by the transistor.

When the transistor is in operation, almost the entire heat is produced at the collector-base junction. This power dissipation causes the junction temperature to rise. This in turn increases the collector current since more electron-hole pairs are generated due to the rise in temperature. This produces an increased power dissipation in the transistor and consequently a further rise in temperature. Unless adequate cooling is provided or the transistor has built-in temperature compensation circuits to prevent excessive collector current rise, the junction temperature will continue to increase until the maximum permissible temperature is exceeded. If this situation occurs, the transistor will be permanently damaged.

The unstable condition where, owing to rise in temperature, the collector current rises and continues to increase is known as **thermal runaway.**

Thermal runaway must always be avoided. If it occurs, permanent damage is caused and the transistor must be replaced.

12.12 Heat Sink

As power transistors handle large currents, they always heat up during operation. Since transistor is a temperature dependent device, the heat generated must be dissipated to the surroundings in order to keep the temperature within permissible limits. Generally, the transistor is fixed on a metal sheet (usually aluminium) so that additional heat is transferred to the *Al* sheet.

The metal sheet that serves to dissipate the additional heat from the power transistor is known as **heat sink.**

Heat Sink

Most of the heat within the transistor is produced at the **collector junction. The heat sink increases the surface area and allows heat to escape from the collector junction easily. The result is that temperature of the transistor is sufficiently lowered. Thus heat sink is a direct practical means of combating the undesirable thermal effects *e.g.* thermal runaway.

* Almost the entire heat in a transistor is produced at the collector-base junction. If the temperature exceeds the permissible limit, this junction is destroyed and the transistor is rendered useless.

** Most of power is dissipated at the collector-base junction. This is because collector-base voltage is much greater than the base-emitter voltage, although currents through the two junctions are almost the same.

It may be noted that the ability of any heat sink to transfer heat to the surroundings depends upon its material, volume, area, shape, contact between case and sink and movement of air around the sink. Finned aluminium heat sinks yield the best heat transfer per unit cost.

It should be realised that the use of heat sink alone may not be sufficient to prevent thermal runaway under all conditions. In designing a transistor circuit, consideration should also be given to the choice of (*i*) operating point (*ii*) ambient temperatures which are likely to be encountered and (*iii*) the type of transistor *e.g.* metal case transistors are more readily cooled by conduction than plastic ones. Circuits may also be designed to compensate automatically for temperature changes and thus stabilise the operation of the transistor components.

12.13 Mathematical Analysis

The permissible power dissipation of the transistor is very important item for power transistors. The permissible power rating of a transistor is calculated from the following relation :

$$P_{total} = \frac{T_{J\,max} - T_{amb}}{\theta}$$

where P_{total} = total power dissipated within the transistor

$T_{J\,max}$ = maximum junction temperature. It is 90ºC for *germanium* transistors and 150ºC for *silicon* transistors.

T_{amb} = ambient temperature *i.e.* temperature of surrounding air

θ = *thermal resistance *i.e.* resistance to heat flow from the junction to the surrounding air

The unit of θ is ºC/ watt and its value is always given in the transistor manual. A low thermal resistance means that it is easy for heat to flow from the junction to the surrounding air. The larger the transistor case, the lower is the thermal resistance and *vice-versa*. It is then clear that by using heat sink, the value of θ can be decreased considerably, resulting in increased power dissipation.

Example 12.15. *A power transistor dissipates 4 W. If T_{Jmax} = 90ºC, find the maximum ambient temperature at which it can be operated. Given θ = 10ºC/W.*

Solution.

$$P_{total} = 4\text{ W}$$
$$T_{J\,max} = 90\text{ºC}$$
$$\theta = 10\text{ºC/W}$$

Now $$P_{total} = \frac{T_{J\,max} - T_{amb}}{\theta}$$

or $$4 = \frac{90 - T_{amb}}{10}$$

∴ Ambient temperature, T_{amb} = 90 – 40 = **50ºC**

The above example shows the effect of ambient temperature on the permissible power dissipation in a transistor. The lower the ambient temperature, the greater is the permissible power dissipation. Thus, a transistor can pass a higher collector current in winter than in summer.

Example 12.16. (*i*) *A power transistor has thermal resistance θ = 300ºC/W. If the maximum junction temperature is 90ºC and the ambient temperature is 30ºC, find the maximum permissible power dissipation.*

* The path of heat flow generated at the collector-base junction is from junction to case, from case to sink and from sink to atmosphere.

(ii) If a heat sink is used with the above transistor, the value of θ is reduced to 60ºC/W. Find the maximum permissible power dissipation.

Solution.

(i) *Without heat sink*

$$T_{J\,max} = 90ºC$$
$$T_{amb} = 30ºC$$
$$\theta = 300ºC/W$$

$$\therefore \quad P_{total} = \frac{T_{J\,max} - T_{amb}}{\theta} = \frac{90-30}{300} = 0.2 \text{ W} = \mathbf{200\ mW}$$

(ii) *With heat sink*

$$T_{J\,max} = 90ºC$$
$$T_{amb} = 30ºC$$
$$\theta = 60ºC/W$$

$$\therefore \quad P_{total} = \frac{T_{J\,max} - T_{amb}}{\theta} = \frac{90-30}{60} = 1 \text{ W} = \mathbf{1000\ mW}$$

It is clear from the above example that permissible power dissipation with heat sink is 5 times as compared to the case when no heat sink is used.

Example 12.17. *The total thermal resistance of a power transistor and heat sink is 20°C/W. The ambient temperature is 25°C and $T_{J\,max}$ = 200°C. If V_{CE} = 4 V, find the maximum collector current that the transistor can carry without destruction. What will be the allowed value of collector current if ambient temperature rises to 75°C ?*

Solution.

$$P_{total} = \frac{T_{Jmax} - T_{amb}}{\theta} = \frac{200-25}{20} = 8.75 \text{ W}$$

This means that maximum permissible power dissipation of the transistor at ambient temperature of 25°C is 8.75 W *i.e.*

$$V_{CE}\, I_C = 8.75$$

$$\therefore \quad I_C = 8.75/4 = \mathbf{2.19\ A}$$

Again $$P_{total} = \frac{T_{J\,max} - T_{amb}}{\theta} = \frac{200-75}{20} = 6.25 \text{ W}$$

$$\therefore \quad I_C = 6.25/4 = \mathbf{1.56\ A}$$

This example clearly shows the effect of ambient temperature.

12.14 Stages of A Practical Power Amplifier

The function of a practical power amplifier is to amplify a weak signal until sufficient power is available to operate a loudspeaker or other output device. To achieve this goal, a power amplifier has generally three stages *viz. voltage amplification stage*, *driver stage* and *output stage*. Fig. 12.12 shows the block diagram of a practical power amplifier.

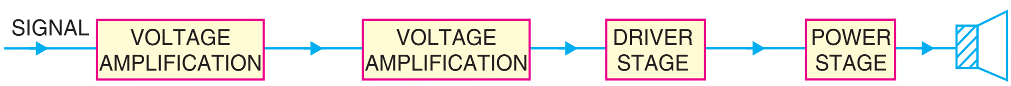

Fig. 12.12

(i) ***Voltage amplification stage.*** The signals found in practice have extremely low voltage level (< 10 mV). Therefore, the voltage level of the weak signal is raised by two or more voltage amplifiers. Generally, *RC* coupling is employed for this purpose.

(ii) ***Driver stage.*** The output from the last voltage amplification stage is fed to the driver stage. It supplies the necessary power to the output stage. The driver stage generally employs class *A* transformer coupled power amplifier. Here, concentrated effort is made to obtain *maximum power gain.*

(iii) ***Output stage.*** The output power from the driver stage is fed to the output stage. It is the final stage and feeds power directly to the speaker or other output device. The output stage is invariably transformer coupled and employs class *B* amplifiers in push-pull arrangement. Here, concentrated effort is made to obtain *maximum power output.*

12.15 Driver Stage

The stage that immediately precedes the output stage is called the *driver stage*. It operates as a class *A* power amplifier and supplies the drive for the output stage. Fig. 12.13 shows the driver stage. Note that transformer coupling is employed. The primary of this transformer is the collector load. The secondary is almost always centre-tapped so as to provide equal and opposite voltages to the input of push-pull amplifier (*i.e.* output stage). The driver transformer is usually a step-down transformer and facilitates impedance matching.

The output from the last voltage amplification stage forms the input to the driver stage. The driver stage renders power amplification in the usual way. It may be added that main consideration here is the maximum power gain. The output of the driver stage is taken from the centre-tapped secondary and is fed to the output stage.

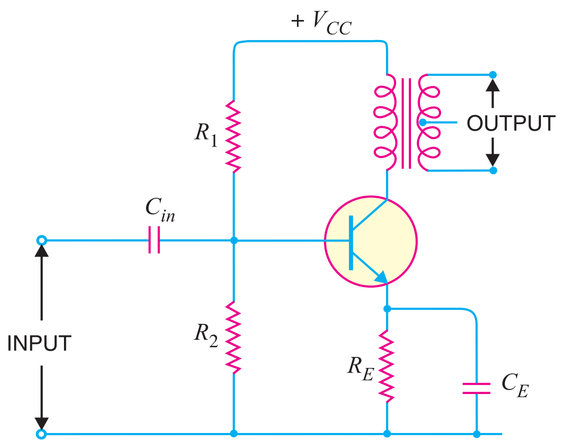

Fig. 12.13

12.16 Output Stage

The output stage essentially consists of a power amplifier and its purpose is to transfer maximum power to the output device. If a single transistor is used in the output stage, it can only be employed as class *A* amplifier for faithful amplification. Unfortunately, the power efficiency of a class *A* amplifier is very low (≃ 35%). As transistor amplifiers are operated from batteries, which is a costly source of power, therefore, such a low efficiency cannot be tolerated.

In order to obtain high output power at high efficiency, pushpull arrangement is used in the output stage. In this arrangement, we employ two transistors in class *B* operation. One transistor amplifies the positive half-cycle of the signal while the other transistor amplifies the negative half-cycle of the signal. In this way, output voltage is a complete sine wave. At the same time, the circuit delivers high output power to the load due to class *B* operation.

12.17 Push-Pull Amplifier

The push-pull amplifier is a power amplifier and is frequently employed in the output stages of electronic circuits. It is used whenever high output power at high efficiency is required. Fig. 12.14 shows the circuit of a push-pull amplifier. Two transistors T_{r1} and T_{r2} placed back to back are employed. Both transistors are operated in class *B* operation *i.e.* collector current is nearly zero in the absence of the signal. The centre-tapped secondary of driver transformer T_1 supplies equal and opposite voltages to the base circuits of two transistors.

Push-Pull Amplifier

The output transformer T_2 has the centre-tapped primary winding. The supply voltage V_{CC} is connected between the bases and this centre tap. The loudspeaker is connected across the secondary of this transformer.

Circuit operation. The input signal appears across the secondary *AB* of driver transformer. Suppose during the first half-cycle (marked 1) of the signal, end *A* becomes positive and end *B* negative. This will make the base-emitter junction of T_{r1} reverse biased and that of T_{r2} forward biased. The circuit will conduct current due to T_{r2} only and is shown by solid arrows. Therefore, this half-cycle of the signal is amplified by T_{r2} and appears in the lower half of the primary of output transformer. In the next half-cycle of the signal, T_{r1} is forward biased whereas T_{r2} is reverse biased. Therefore, T_{r1} conducts and is shown by dotted arrows. Consequently, this half-cycle of the signal is amplified by T_{r1} and appears in the upper half of the output transformer primary. The centre-tapped primary of the output transformer combines two collector currents to form a sine wave output in the secondary.

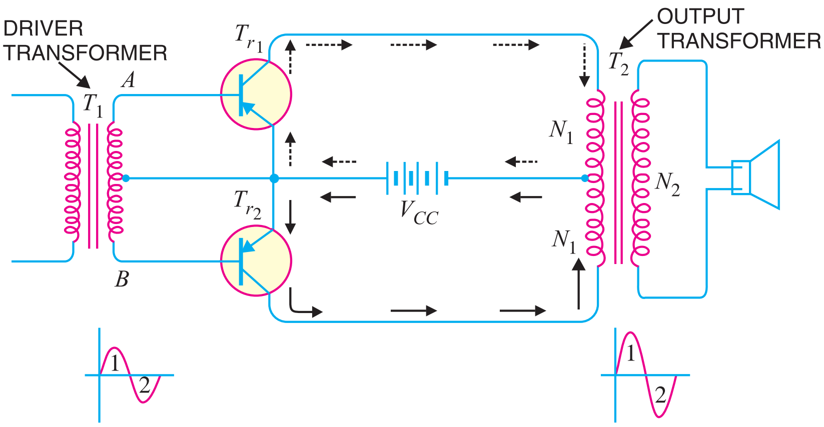

Fig. 12.14

It may be noted here that push-pull arrangement also permits a maximum transfer of power to the load through impedance matching. If R_L is the resistance appearing across secondary of output transformer, then resistance R'_L of primary shall become :

$$R'_L = \left(\frac{2N_1}{N_2}\right)^2 R_L$$

where N_1 = Number of turns between either end of primary winding and centre-tap

N_2 = Number of secondary turns

Advantages

(*i*) The efficiency of the circuit is quite high ($\simeq$ 75%) due to class *B* operation.

(*ii*) A high a.c. output power is obtained.

Disadvantages

(*i*) Two transistors have to be used.

(*ii*) It requires two equal and opposite voltages at the input. Therefore, push-pull circuit requires the use of driver stage to furnish these signals.

(*iii*) If the parameters of the two transistors are not the same, there will be unequal amplification of the two halves of the signal.

(*iv*) The circuit gives more distortion.

(*v*) Transformers used are bulky and expensive.

12.18 Maximum Efficiency for Class B Power Amplifier

We have already seen that a push-pull circuit uses two transistors working in class *B* operation. For class *B* operation, the Q-point is located at cut-off on both d.c. and a.c. load lines. For maximum signal operation, the two transistors in class B amplifier are alternately driven from cut-off to saturation. This is shown in Fig. 12.15 (*i*). It is clear that a.c. output voltage has a peak value of V_{CE} and a.c. output current has a peak value of $I_{C\,(sat)}$. The same information is also conveyed through the a.c. load line for the circuit [See Fig. 12.15 (*ii*)].

$\therefore$ Peak a.c. output voltage $= V_{CE}$

Peak a.c. output current $= I_{C\,(sat)} = {}^{*}\dfrac{V_{CE}}{R_L} = \dfrac{V_{CC}}{2\,R_L} \qquad \left(\because V_{CE} = \dfrac{V_{CC}}{2}\right)$

Maximum average a.c. output power $P_{o\,(max)}$ is

$P_{o\,(max)}$ = Product of r.m.s. values of a.c. output voltage and a.c. output current

$$= \frac{V_{CE}}{\sqrt{2}} \times \frac{I_{C\,(sat)}}{\sqrt{2}} = \frac{V_{CE}\,I_{C\,(sat)}}{2}$$

$$= \frac{V_{CC}}{2} \times \frac{I_{C\,(sat)}}{2} = \frac{V_{CE}\,I_{C\,(sat)}}{4} \qquad \left(\because V_{CE} = \frac{V_{CC}}{2}\right)$$

$$\therefore \quad P_{o\,(max)} = 0.25\,V_{CC}\,I_{C\,(sat)}$$

The input d.c. power from the supply V_{CC} is

$$P_{dc} = V_{CC}\,I_{dc}$$

* Since the two transistors are identical, half the supply voltage is dropped across each transistor's collector-emitter terminals *i.e.* $V_{CE} = \dfrac{V_{CC}}{2}$

Also peak voltage across each transistor is V_{CE} and it appears across R_L.

$$\therefore I_{C\,(sat)} = \frac{V_{CE}}{R_L} = \frac{V_{CC}}{2} \times \frac{1}{R_L} = \frac{V_{CC}}{2\,R_L}$$

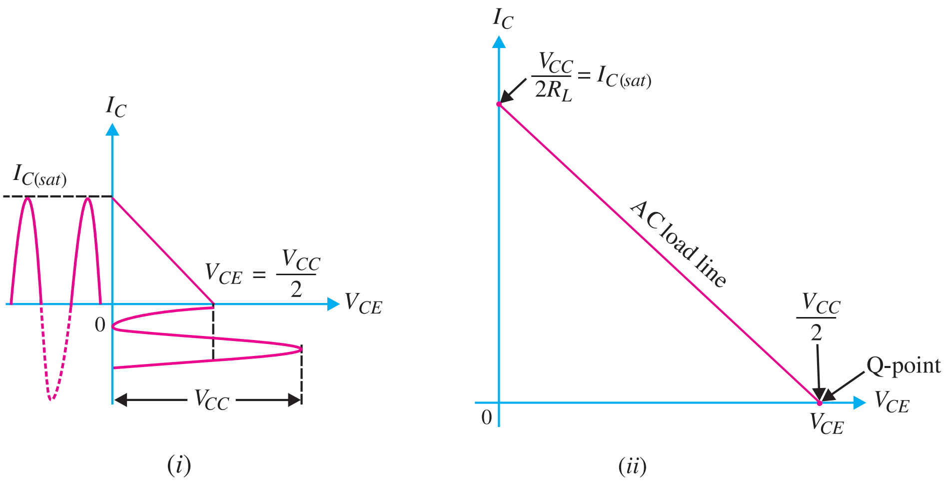

Fig. 12.15

where I_{dc} is the average current drawn from the supply V_{CC}. Since the transistor is on for alternating half-cycles, it effectively acts as a half-wave rectifier.

$$\therefore \quad I_{dc} = \frac{I_{C\,(sat)}}{\pi}$$

$$\therefore \quad P_{dc} = \frac{V_{CC}\ I_{C\,(sat)}}{\pi}$$

$$\therefore \quad \text{Max. collector } \eta = \frac{P_{o\,(max)}}{P_{dc}} = \frac{0.25\,V_{CC}\ \ I_{C\,(sat)}}{\left(V_{CC}\ I_{C\,(sat)}\right)/\pi} \times 100 = 0.25\pi \times 100 = 78.5\%$$

Thus the maximum collector efficiency of class *B* power amplifier is 78.5%. Recall that maximum collector efficiency for class A transformer coupled amplifier is 50%.

Power dissipated by transistors. The power dissipated (as heat) by the transistors in class *B* amplifier is the difference between the input power delivered by V_{CC} and the output power delivered to the load *i.e.*

$$P_{2T} = P_{dc} - P_{ac}$$

where P_{2T} = power dissipated by the two transistors

$\therefore$ Power dissipated by each transistor is

$$P_T = \frac{P_{2T}}{2} = \frac{P_{dc} - P_{ac}}{2}$$

Note. For collector efficiency of class *C* amplifiers, the reader may refer to Chapter 15 (Transistor tuned amplifiers).

Example 12.18. *For a class B amplifier using a supply of V_{CC} = 12V and driving a load of 8Ω, determine (i) maximum load power (ii) d.c. input power (iii) collector efficiency.*

Solution. V_{CC} = 12 V ; $R_L = 8\Omega$

(i) Maximum load power, $P_{o\,(max)} = 0.25\ V_{CC}\ I_{C\,(sat)}$

$$= 0.25\ V_{CC} \times \frac{V_{CC}}{2\ R_L} \qquad \left(\because I_{C\,(sat)} = \frac{V_{CC}}{2\ R_L}\right)$$

$$= 0.25 \times 12 \times \frac{12}{2 \times 8} = \mathbf{2.25\ W}$$

(ii) D.C. input power, $P_{dc} = \dfrac{V_{CC}\, I_{C\,(sat)}}{\pi} = \dfrac{V_{CC}}{\pi} \times \dfrac{V_{CC}}{2\,R_L}$

$$= \frac{12}{\pi} \times \frac{12}{2 \times 8} = \mathbf{2.87\ W}$$

(iii) Collector $\eta = \dfrac{P_{o\,(max)}}{P_{dc}} \times 100 = \dfrac{2.25}{2.87} \times 100 = \mathbf{78.4\%}$

Example 12.19. *A class B push-pull amplifier with transformer coupled load uses two transistors rated 10 W each. What is the maximum power output one can obtain at the load from the circuit?*

Solution. The power dissipation by each transistor is $P_T = 10$W. Therefore, power dissipated by two transistors is $P_{2T} = 2 \times 10 = 20$W.

Now $\quad P_{dc} = P_{o\,(max)} + P_{2T}\ ;\ \text{Max. } \eta = 0.785$

$\therefore \quad \text{Max } \eta = \dfrac{P_{o\,(max)}}{P_{dc}} = \dfrac{P_{o\,(max)}}{P_{o\,(max)} + P_{2T}} = \dfrac{P_{o\,(max)}}{P_{o\,(max)} + 20}$

or $\quad 0.785 = \dfrac{P_{o\,(max)}}{P_{o\,(max)} + 20}$

or $\quad 0.785\, P_{o\,(max)} + 15.7 = P_{o\,(max)}$

or $\quad P_{o\,(max)}\,(1 - 0.785) = 15.7$

$\therefore \quad P_{o\,(max)} = \dfrac{15.7}{1 - 0.785} = \dfrac{15.7}{0.215} = \mathbf{73.02\ W}$

Example 12.20. *A class B amplifier has an efficiency of 60% and each transistor has a rating of 2.5W. Find the a.c. output power and d.c. input power*

Solution. The power dissipated by each transistor is $P_T = 2.5$W.

Therefore, power dissipated by the two transistors is $P_{2T} = 2{\times}2.5 = 5$W.

Now $\quad P_{dc} = P_{ac} + P_{2T}\ ;\ \eta = 0.6$

$\therefore \quad \eta = \dfrac{P_{ac}}{P_{dc}} = \dfrac{P_{ac}}{P_{ac} + P_{2T}}$

or $\quad 0.6 = \dfrac{P_{ac}}{P_{ac} + 5}$ $\quad$ or $\quad 0.6\ P_{ac} + 3 = P_{ac}$

$\therefore \quad P_{ac} = \dfrac{3}{1 - 0.6} = \dfrac{3}{0.4} = \mathbf{7.5\ W}$

and $\quad P_{dc} = P_{ac} + P_{2T} = 7.5 + 5 = \mathbf{12.5\ W}$

Example 12.21. *A class B amplifier uses V_{CC} = 10V and drives a load of 10Ω. Determine the end point values of the a.c. load line.*

Solution.

$$I_{C\,(sat)} = \frac{V_{CC}}{2\,R_L} = \frac{10\text{V}}{2\,(10\ \Omega)} = \mathbf{500\ mA}$$

This locates one end-point of the a.c. load line on the collector current axis.

$$V_{CE\,(off)} = \frac{V_{CC}}{2} = \frac{10\text{V}}{2} = \mathbf{5V}$$

This locates the second end-point of the a.c load line on the collector-emitter voltage axis. By joining these two points, the a.c. load line of the amplifier is constructed.

12.19 Complementary-Symmetry Amplifier

By complementary symmetry is meant a principle of assembling push-pull class *B* amplifier without requiring centre-tapped transformers at the input and output stages. Fig. 12.16 shows the transistor push-pull amplifier using complementary symmetry. It employs one *npn* and one *pnp* transistor and requires no centre-tapped transformers. The circuit action is as follows. During the positive-half of the input signal, transistor T_1 (the *npn* transistor) conducts current while T_2 (the *pnp* transistor) is cut off. During the negative half-cycle of the signal, T_2 conducts while T_1 is cut off. In this way, *npn* transistor amplifies the positive half-cycles of the signal while the *pnp* transistor amplifies the negative half-cycles of the signal. Note that we generally use an output transformer (not centre-tapped) for impedance matching.

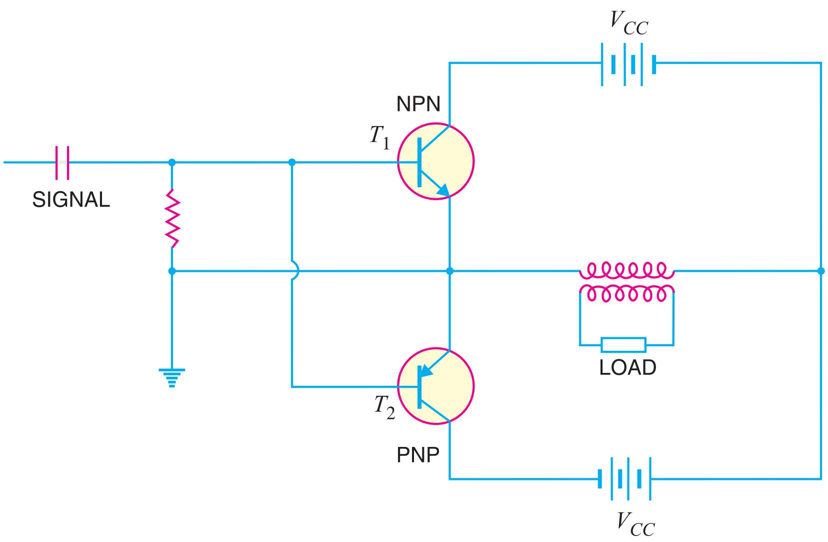

Fig.12.16

Advantages

(i) This circuit does not require transformer. This saves on weight and cost.

(ii) Equal and opposite input signal voltages are not required.

Disadvantages

(i) It is difficult to get a pair of transistors (*npn* and *pnp*) that have similar characteristics.

(ii) We require both positive and negative supply voltages.

MULTIPLE-CHOICE QUESTIONS

1. The output stage of a multistage amplifier is also called ....

(*i*) mixer stage (*ii*) power stage

(*iii*) detector stage (*iv*) R.F. stage

2. .... coupling is generally employed in power amplifiers.

(*i*) transformer (*ii*) *RC*

(*iii*) direct (*iv*) impedance