Output Stages and Power Amplifiers:

A power amplifier is simply an amplifier with a high-power output stage.

Classification of Output Stages:

- Output stages are classified according to the collector current waveform that results when an input signal is applied.
  - ❑ The class A stage:
  - ❑ The class B stage:
  - ❑ The class AB stage:
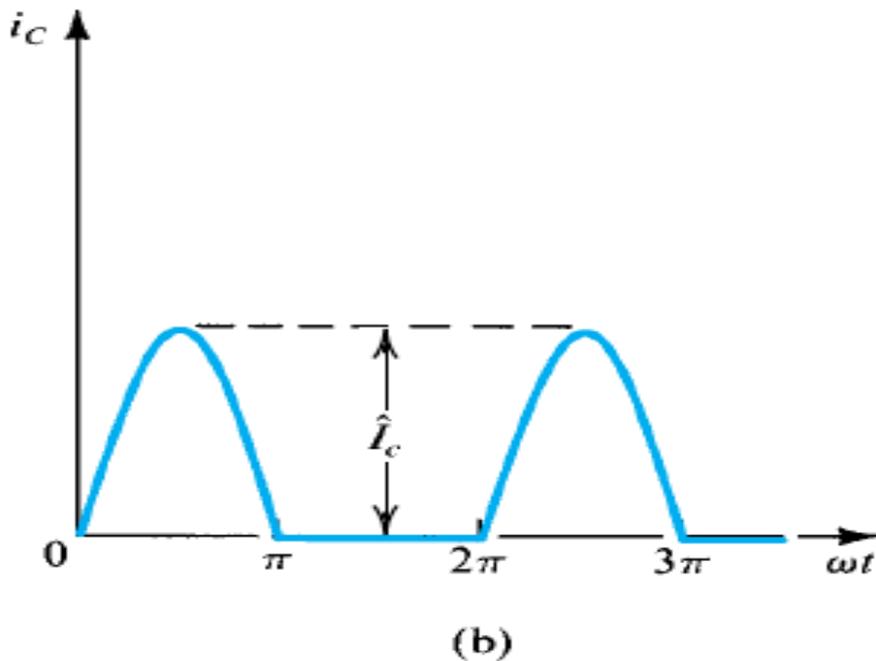 - ❑ The class C stage:

Classification of Output Stages:

❑ The class A stage:

➢ The class A stage, whose associated waveform is shown in Fig. (a), is biased at a current I_C greater than the amplitude of the signal current, $I^\wedge{}_C$.

➢ Thus the transistor in a class A stage conducts for the entire cycle of the input signal; that is, the conduction angle is 360°.
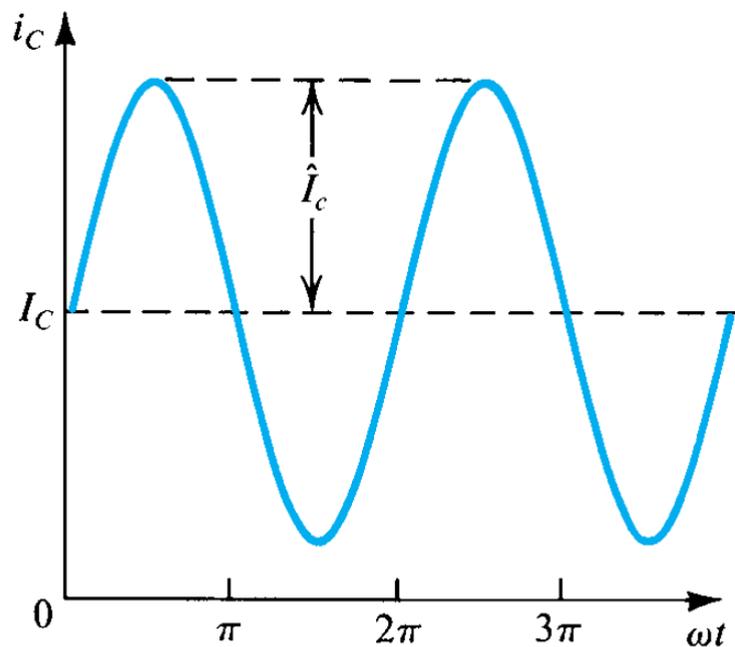

(a)

❑ The class B stage:

  ➢ The class B stage, whose associated waveform is shown in Fig. is biased at zero dc current.

  ➢ Thus a transistor in a class B stage conducts for only half the cycle of the input sine wave, resulting in a conduction angle of 180°.


(b)

❑ The class AB stage:

  ➢ An intermediate class between A and B, appropriately named class AB, involves biasing the transistor at a nonzero dc current much smaller than the peak current of the sine-wave signal.

  ➢ As a result, the transistor conducts for an interval slightly greater than half a cycle, as illustrated in Fig.

  ➢ The resulting conduction angle is greater than 180° but much less than 360°. The class AB stage has another transistor that conducts for an interval slightly greater than that of the negative half-cycle, and the currents from the two transistors are combined in the load.
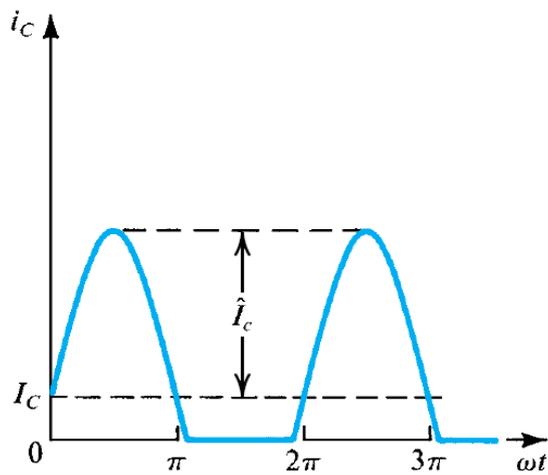
(c)

❑ The class C stage:

The transistor conducts for an interval shorter than that of a halfcycle; that is, the conduction angle is less than 180°.
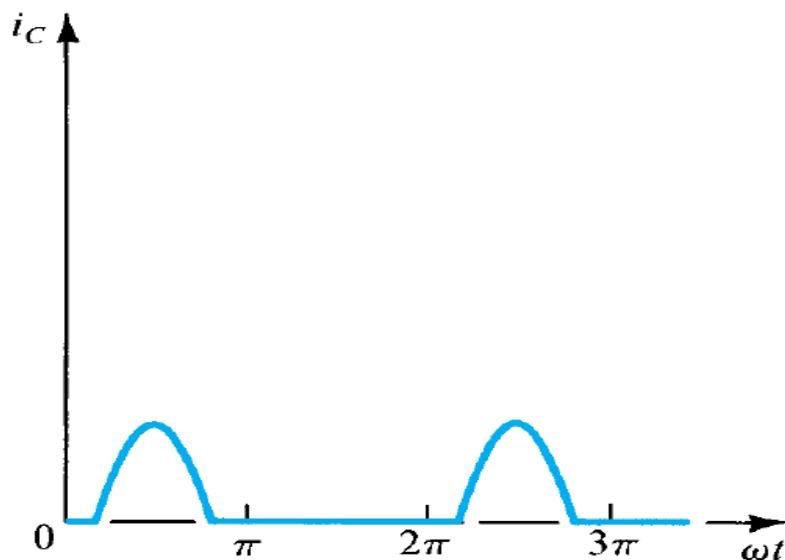
(d)

❑ Applications:

➤ Class A, AB, and B amplifiers are employed as output stages of op amps and audio power amplifiers.

➤ Class AB is the preferred choice

➤ Class C amplifiers are usually employed for radio-frequency (RF) power amplification (required, e.g., in mobile phones and radio and TV transmitters).
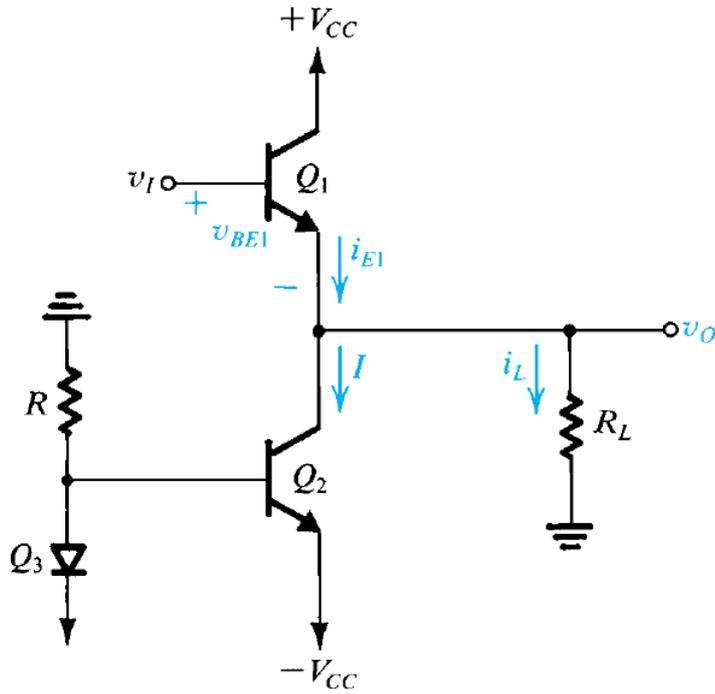
Class A Output Stage:

Figure 11.2 An emitter follower (Q_1) biased with a constant current I supplied by transistor Q_2.

As indicated, the positive limit of the linear region is determined by the saturation of Q_1; thus

$$v_{Omax} = V_{CC} - V_{CE1sat} \qquad (11.2)$$

In the negative direction, depending on the values of I and R_L, the limit of the linear region is determined either by Q_1 turning off,

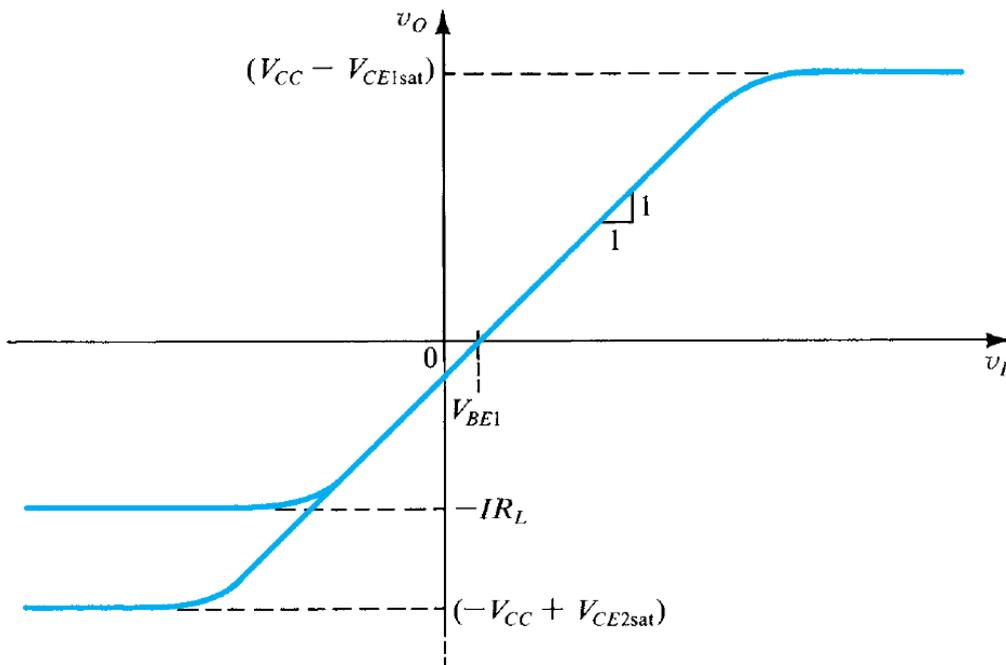$$v_{Omin} = -IR_L \qquad (11.3)$$

Figure 11.3 Transfer characteristic of the emitter follower in Fig. 11.2. This linear characteristic is obtained by neglecting the change in v_{BE1} with i_L. The maximum positive output is determined by the saturation of Q_1. In the negative direction, the limit of the linear region is determined either by Q_1 turning off or by Q_2 saturating, depending on the values of I and R_L.

or by Q_2 saturating,

$$v_{O\min} = -V_{CC} + V_{CE2\text{sat}} \qquad (11.4)$$

Signal Waveforms:

Consider the operation of the emitter-follower circuit of Fig. 11.2 for sine-wave input. Neglecting $V_{CE\text{sat}}$, we see that if the bias current I is properly selected, the output voltage can swing from $-V_{CC}$ to $+V_{CC}$ with the quiescent value being zero, as shown in Fig. 11.4(a). Figure 11.4(b) shows the corresponding waveform of $v_{CE1} = V_{CC} - v_O$. Now, assuming that the bias current I is selected to allow a maximum negative load current of V_{CC}/R_L, that is,

$$I = V_{CC}/R_L$$

the collector current of Q_1 will have the waveform shown in Fig. 11.4(c). Finally, Fig. 11.4(d) shows the waveform of the **instantaneous power dissipation** in Q_1,

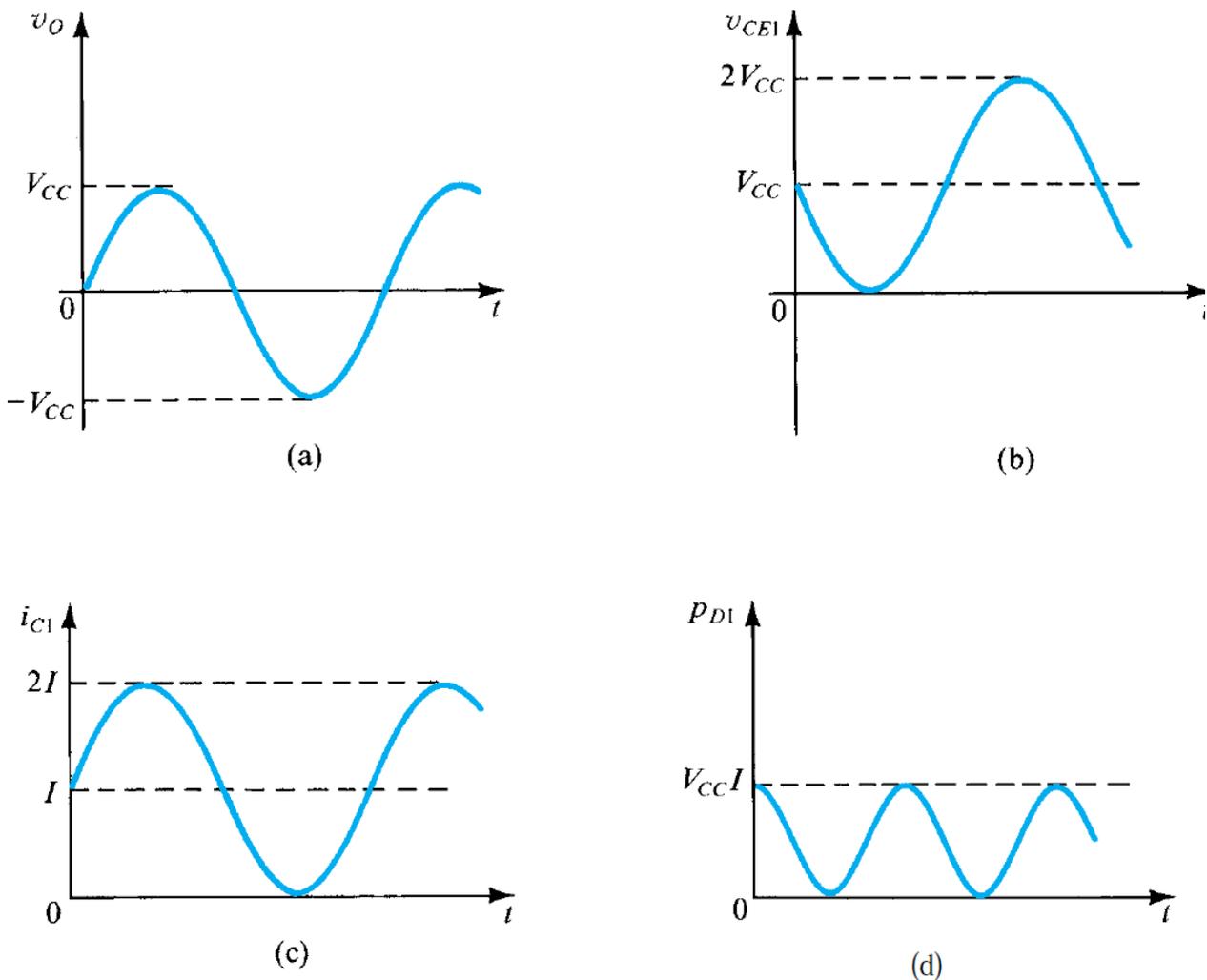$$p_{D1} \equiv v_{CE1}i_{C1} \qquad (11.6)$$

(a)

(b)

(c)

(d)

Figure 11.4 Maximum signal waveforms in the class A output stage of Fig. 11.2 under the condition $I = V_{CC}/R_L$ or, equivalently, $R_L = V_{CC}/I$. Note that the transistor saturation voltages have been neglected.

11.2.4 Power-Conversion Efficiency

The power-conversion efficiency of an output stage is defined as

$$\eta \equiv \frac{\text{Load power } (P_L)}{\text{Supply power } (P_S)} \tag{11.7}$$

For the emitter follower of Fig. 11.2, assuming that the output voltage is a sinusoid with the peak value $\hat{V}_o$, the average load power will be

$$P_L = \frac{(\hat{V}_o/\sqrt{2})^2}{R_L} = \frac{1}{2}\frac{\hat{V}_o^2}{R_L} \tag{11.8}$$

Since the current in Q_2 is constant (I), the power drawn from the negative supply[1] is $V_{CC}I$. The *average* current in Q_1 is equal to I, and thus the average power drawn from the positive supply is $V_{CC}I$. Thus the total average supply power is

$$P_S = 2V_{CC}I \tag{11.9}$$

Equations (11.8) and (11.9) can be combined to yield

$$\eta = \frac{1}{4}\frac{\hat{V}_o^2}{IR_L V_{CC}}$$

$$= \frac{1}{4}\left(\frac{\hat{V}_o}{IR_L}\right)\left(\frac{\hat{V}_o}{V_{CC}}\right) \tag{11.10}$$

Since $\hat{V}_o \leq V_{CC}$ and $\hat{V}_o \leq IR_L$, maximum efficiency is obtained when

$$\hat{V}_o = V_{CC} = IR_L \tag{11.11}$$

The maximum efficiency attainable is 25%. Because this is a rather low figure, the class A output stage is rarely used in high-power applications (>1 W). Note also that in practice the output voltage swing is limited to lower values to avoid transistor saturation and associated nonlinear distortion. Thus the efficiency achieved in practice is usually in the 10% to 20% range.

Class B Output Stage:

It consists of a complementary pair of transistors (an *npn* and a *pnp*) connected in such a way that both cannot conduct simultaneously. (circuit is referred to as **a *push–pull circuit*)**
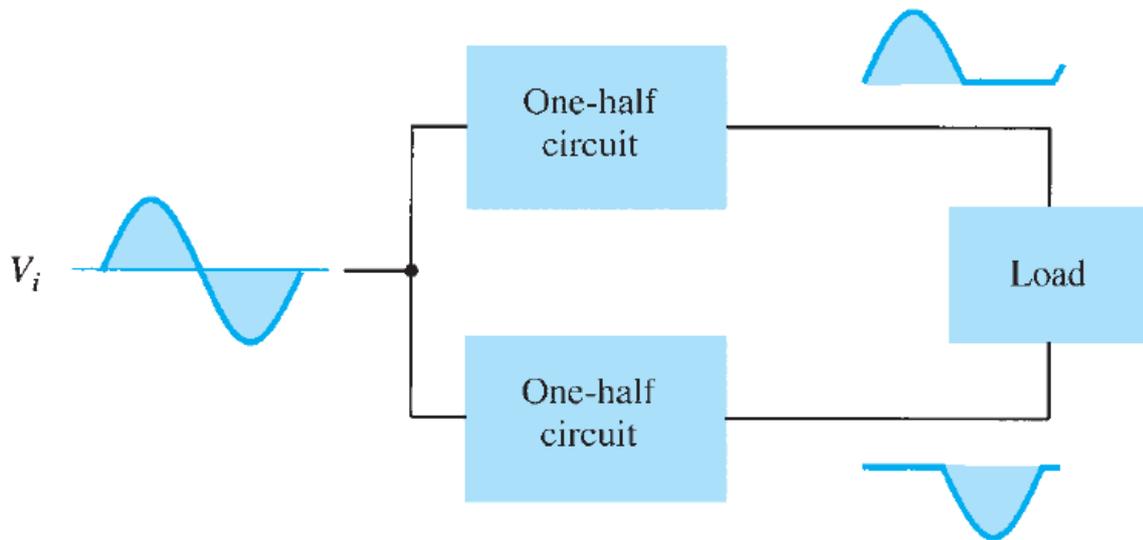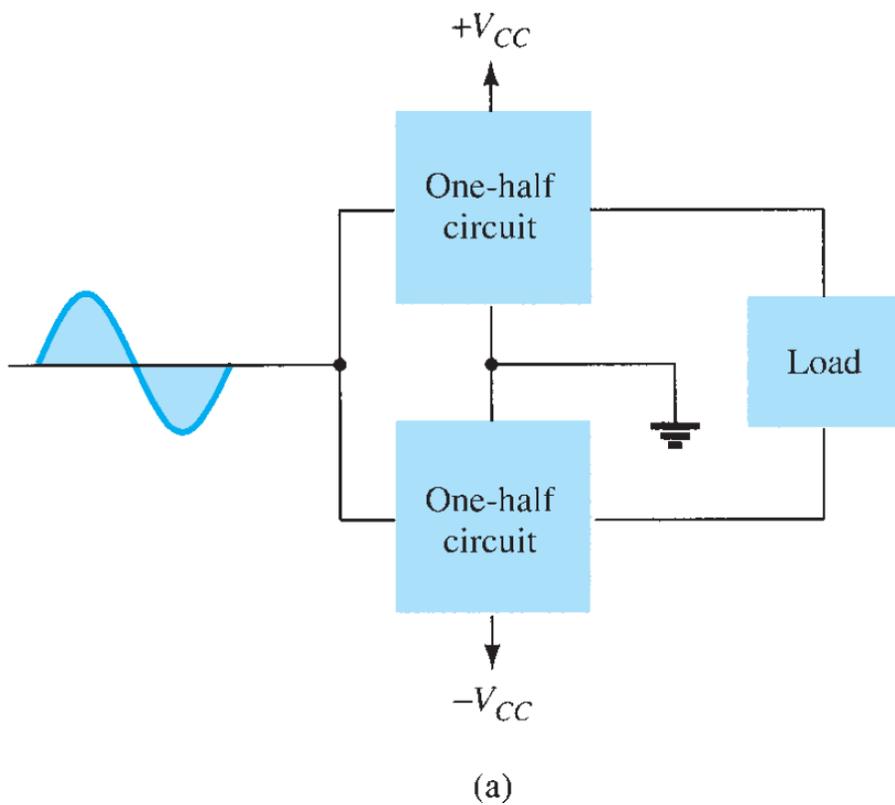

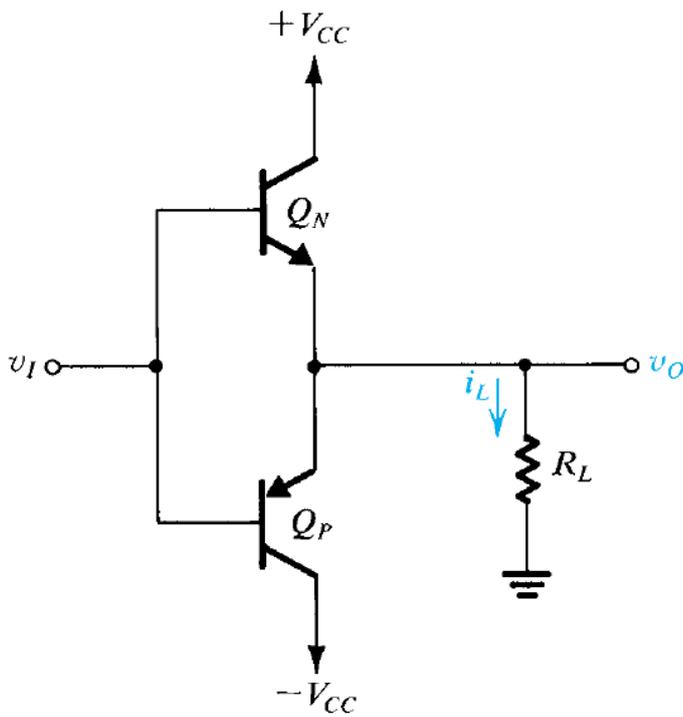Fig.: *Block representation of push–pull operation.*

(a)

Figure 11.5 A class B output stage.

11.3.2 Transfer Characteristic

A sketch of the transfer characteristic of the class B stage is shown in Fig. 11.6. Note that there exists a range of v_I centered around zero where both transistors are cut off and v_O is zero. This **dead band** results in the **crossover distortion** illustrated in Fig. 11.7 for the case of an input sine wave. The effect of crossover distortion will be most pronounced when the
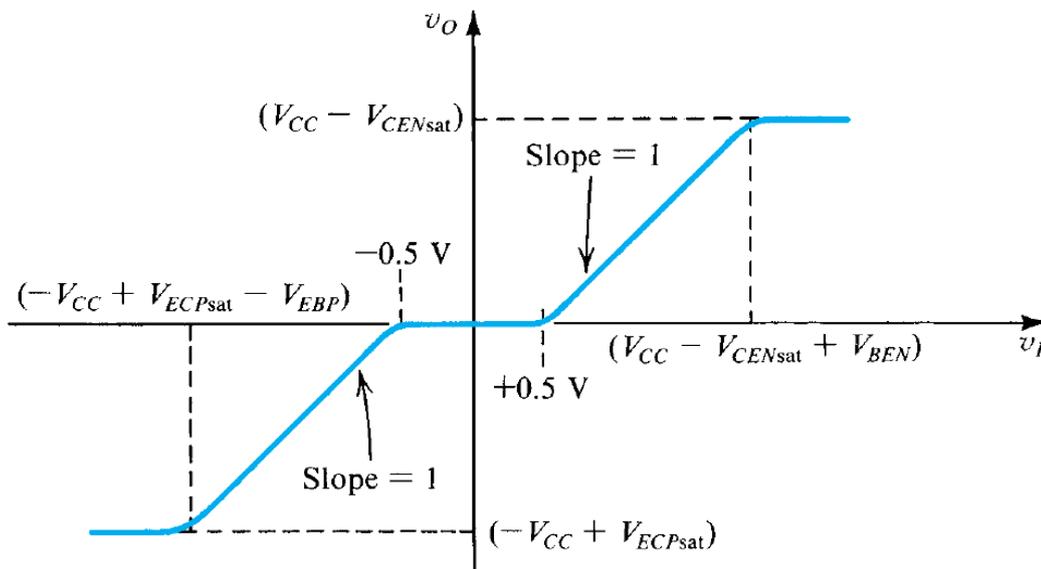

Figure 11.6 Transfer characteristic for the class B output stage in Fig. 11.5.
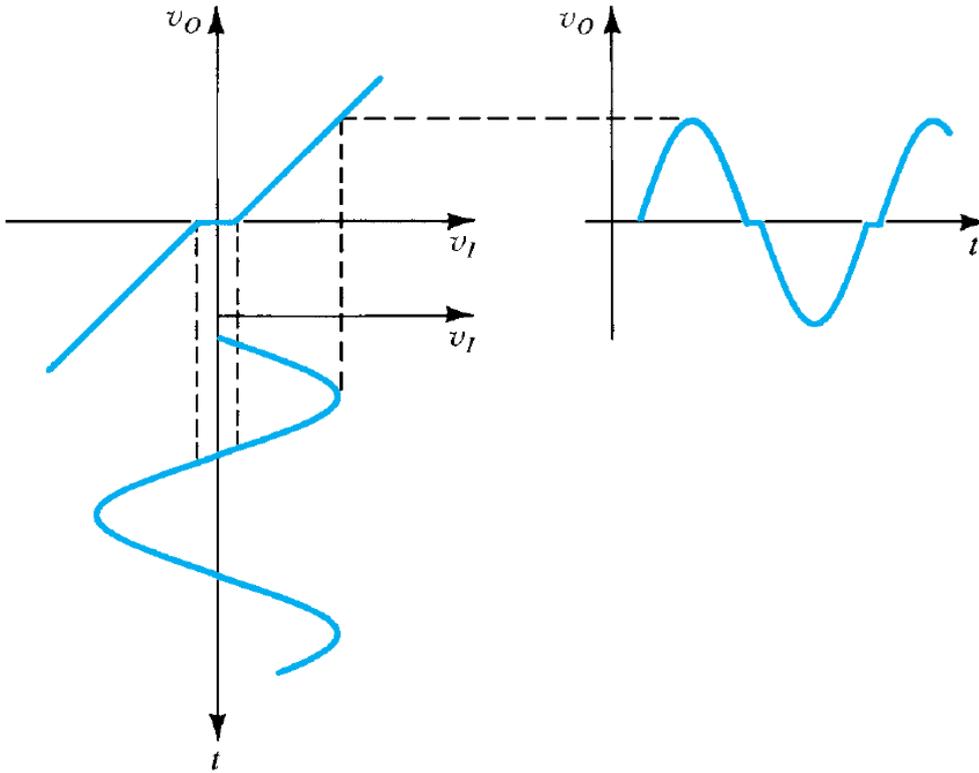
Figure 11.7 Illustrating how the dead band in the class B transfer characteristic results in crossover distortion.

11.3.3 Power-Conversion Efficiency

To calculate the power-conversion efficiency, η, of the class B stage, we neglect the crossover distortion and consider the case of an output sinusoid of peak amplitude $\hat{V}_o$. The average load power will be

$$P_L = \frac{1}{2}\frac{\hat{V}_o^2}{R_L} \tag{11.12}$$

The current drawn from each supply will consist of half-sine waves of peak amplitude $(\hat{V}_o/R_L)$. Thus the average current drawn from each of the two power supplies will be $\hat{V}_o/\pi R_L$. It follows that the average power drawn from each of the two power supplies will be the same,

$$P_{S+} = P_{S-} = \frac{1}{\pi}\frac{\hat{V}_o}{R_L}V_{CC} \tag{11.13}$$

and the total supply power will be

$$P_S = \frac{2\hat{V}_o}{\pi R_L}V_{CC} \tag{11.14}$$

Thus the efficiency will be given by

$$\eta = \left(\frac{1}{2}\frac{\hat{V}_o^2}{R_L}\right) \Big/ \left(\frac{2\hat{V}_o}{\pi R_L}V_{CC}\right) = \frac{\pi}{4}\frac{\hat{V}_o}{V_{CC}} \tag{11.15}$$

It follows that the maximum efficiency is obtained when $\hat{V}_o$ is at its maximum. This maximum is limited by the saturation of Q_N and Q_P to $V_{CC} - V_{CEsat} \simeq V_{CC}$. At this value of peak output voltage, the power-conversion efficiency is

$$\eta_{max} = \frac{\pi}{4} = 78.5\% \tag{11.16}$$

This value is much larger than that obtained in the class A stage (25%). Finally, we note that the maximum average power available from a class B output stage is obtained by substituting $\hat{V}_o = V_{CC}$ in Eq. (11.12),

$$P_{Lmax} = \frac{1}{2} \frac{V_{CC}^2}{R_L} \tag{11.17}$$

11.3.4 Power Dissipation

Unlike the class A stage, which dissipates maximum power under quiescent conditions ($v_O = 0$), the quiescent power dissipation of the class B stage is zero. When an input signal is applied, the *average* power dissipated in the class B stage is given by

$$P_D = P_S - P_L \tag{11.18}$$

Substituting for P_S from Eq. (11.14) and for P_L from Eq. (11.12) results in

$$P_D = \frac{2}{\pi} \frac{\hat{V}_o}{R_L} V_{CC} - \frac{1}{2} \frac{\hat{V}_o^2}{R_L} \tag{11.19}$$

From symmetry we see that half of P_D is dissipated in Q_N and the other half in Q_P. Thus Q_N and Q_P must be capable of safely dissipating $\frac{1}{2}P_D$ watts. Since P_D depends on $\hat{V}_o$, we must find the worst-case power dissipation, P_{Dmax}. Differentiating Eq. (11.19) with respect to $\hat{V}_o$ and equating the derivative to zero gives the value of $\hat{V}_o$ that results in maximum average power dissipation as

$$\hat{V}_o\big|_{P_{Dmax}} = \frac{2}{\pi} V_{CC} \tag{11.20}$$

Substituting this value in Eq. (11.19) gives

$$P_{Dmax} = \frac{2 V_{CC}^2}{\pi^2 R_L} \tag{11.21}$$

At the point of maximum power dissipation, the efficiency can be evaluated by substituting for $\hat{V}_o$ from Eq. (11.20) into Eq. (11.15); hence, $\eta = 50\%$.

Figure 11.8 shows a sketch of P_D (Eq. 11.19) versus the peak output voltage $\hat{V}_o$. Curves such as this are usually given on the data sheets of IC power amplifiers. [Usually, however, P_D is plotted versus P_L, as $P_L = \frac{1}{2}(\hat{V}_o^2/R_L)$, rather than $\hat{V}_o$.] An interesting observation follows from Fig. 11.8: Increasing $\hat{V}_o$ beyond $2V_{CC}/\pi$ decreases the power dissipated in the
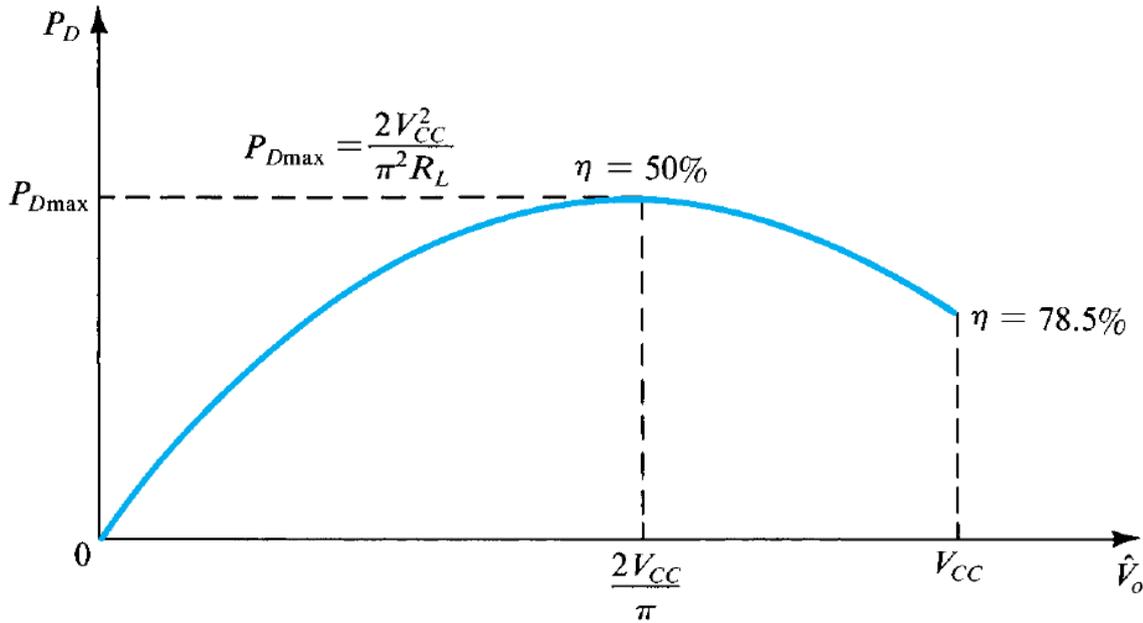

Figure 11.8 Power dissipation of the class B output stage versus amplitude of the output sinusoid.

class B stage while increasing the load power. The price paid is an increase in nonlinear distortion as a result of approaching the saturation region of operation of Q_N and Q_P. Transistor saturation flattens the peaks of the output sine waveform. Unfortunately, this type of distortion cannot be significantly reduced by the application of negative feedback (see Section 10.2), and thus transistor saturation should be avoided in applications requiring low THD.
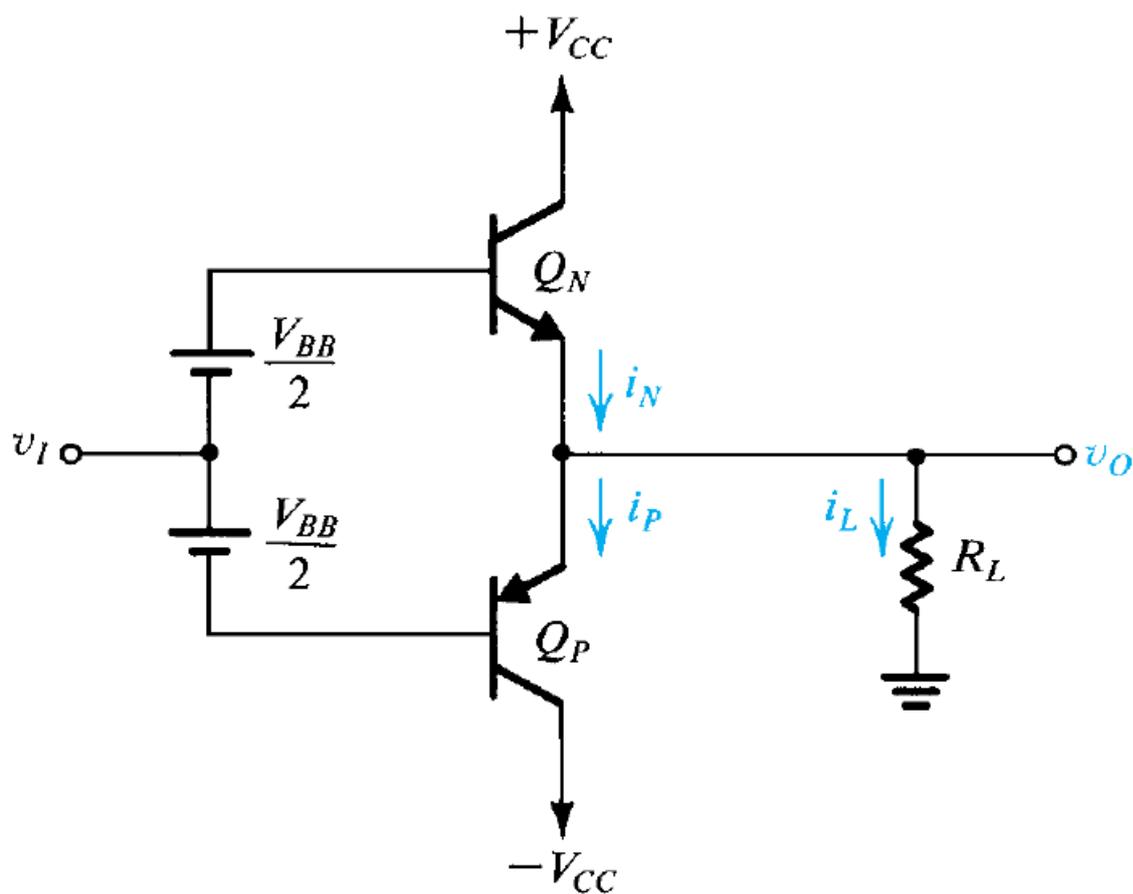
11.4 Class AB Output Stage

Crossover distortion can be virtually eliminated by biasing the complementary output transistors at a small nonzero current. The result is the class AB output stage shown in Fig. 11.11. A bias voltage V_{BB} is applied between the bases of Q_N and Q_P. For $v_I = 0$, $v_O = 0$, and a voltage $V_{BB}/2$ appears across the base–emitter junction of each of Q_N and Q_P. Assuming matched devices,

$$i_N = i_P = I_Q = I_s e^{V_{BB}/2V_T} \tag{11.23}$$

The value of V_{BB} is selected to yield the required quiescent current I_Q.

11.4.1 Circuit Operation

When v_I goes positive by a certain amount, the voltage at the base of Q_N increases by the same amount and the output becomes positive at an almost equal value,

$$v_O = v_I + \frac{V_{BB}}{2} - v_{BEN} \tag{11.24}$$

The positive v_O causes a current i_L to flow through R_L, and thus i_N must increase; that is,

$$i_N = i_P + i_L \tag{11.25}$$

The increase in i_N will be accompanied by a corresponding increase in v_{BEN} (above the quiescent value of $V_{BB}/2$). However, since the voltage between the two bases remains constant at V_{BB}, the increase in v_{BEN} will result in an equal decrease in v_{EBP} and hence in i_P. The relationship between i_N and i_P can be derived as follows:

$$v_{BEN} + v_{EBP} = V_{BB}$$

$$V_T \ln \frac{i_N}{I_S} + V_T \ln \frac{i_P}{I_S} = 2 V_T \ln \frac{I_Q}{I_S}$$

$$i_N i_P = I_Q^2 \tag{11.26}$$

Thus, as i_N increases, i_P decreases by the same ratio while the product remains constant.
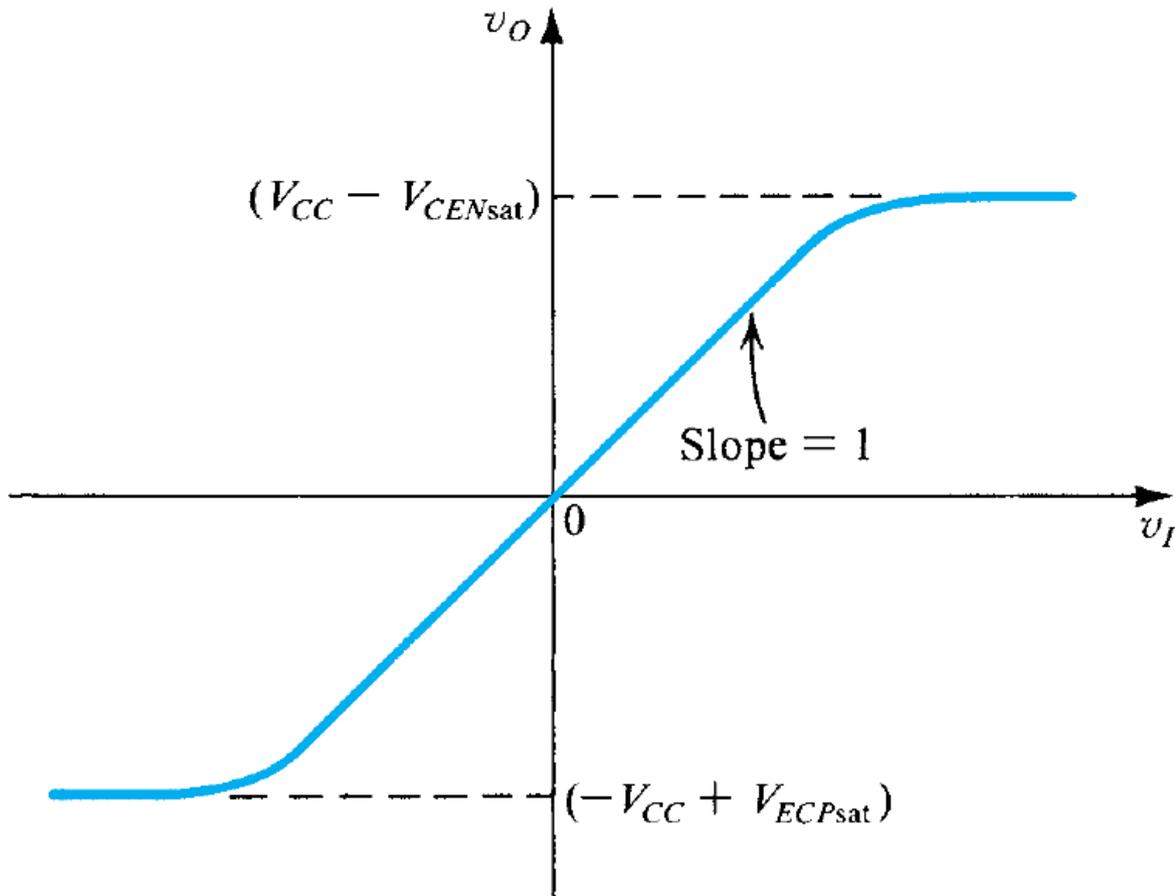

Figure 11.12 Transfer characteristic of the class AB stage in Fig. 11.11.

In Class-AB amplifier, actually we are clubbing all the advantages of class- and class B to reduce the distortion.

Current will flow even if input is less than cut voltage VBE

Efficiency = same as class B

Conduction angle = More than 180 degree

Circuit 1

+Vcc

NPN
TR$_1$

Input
Signal

C

$+$
V$_{BIAS}$

$+$
V$_{BIAS}$

TR$_2$
PNP

-Vcc

C

Output

R$_L$

Circuit 2

+Vcc

R$_1$

Biasing
Diodes

NPN

V$_{IN}$ + 0.7v

TR$_1$

Input
Signal   V$_{IN}$

C

$+$

D$_1$ 0.7V

D$_2$ 0.7V

$-$

1.4V

V$_{IN}$ - 0.7v

R$_2$

PNP

TR$_2$

C

Output

R$_L$

0V