2007 Fall: Electronic Circuits 2

CHAPTER 14

Output Stages and Power Amplifiers

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Introduction

- In this chapter, we will be covering…
  - Classification of Output Stages
  - Class A Output Stage
  - Class B Output Stage
  - Class AB Output Stage
  - Biasing the Class AB Circuit

14.1 Classification of Output Stages

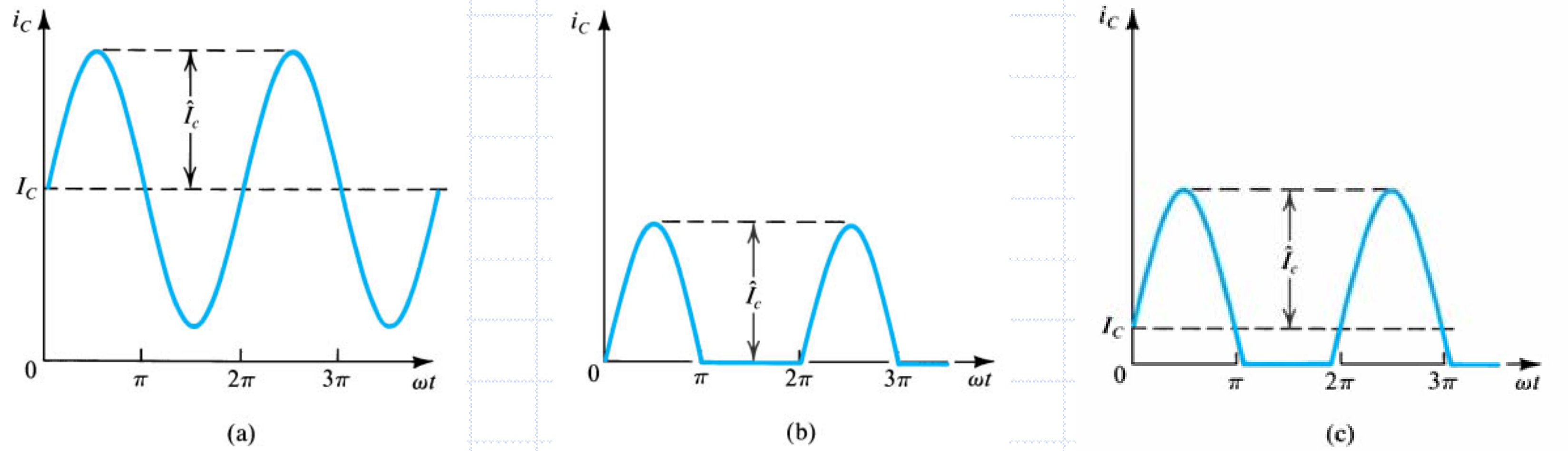
- Output stages are classified according to the collector current waveform when an input signal is applied.

- When a sinusoidal input signal is applied,
  - Class A : biased at a current greater than the amplitude of signal current.
  - Class B : biased at zero dc current.
  - Class AB : an intermediate class between A and B.
    biased at a nonzero dc current much smaller than the peak current of the sine-wave signal.

14.1 Classification of Output Stages

- Collector current waveforms for transistors operating in

(a) class A (b) class B (c) class AB



14.2 Class A Output Stage - Transfer Characteristic

- The emitter follower – the most popular class A ckt.

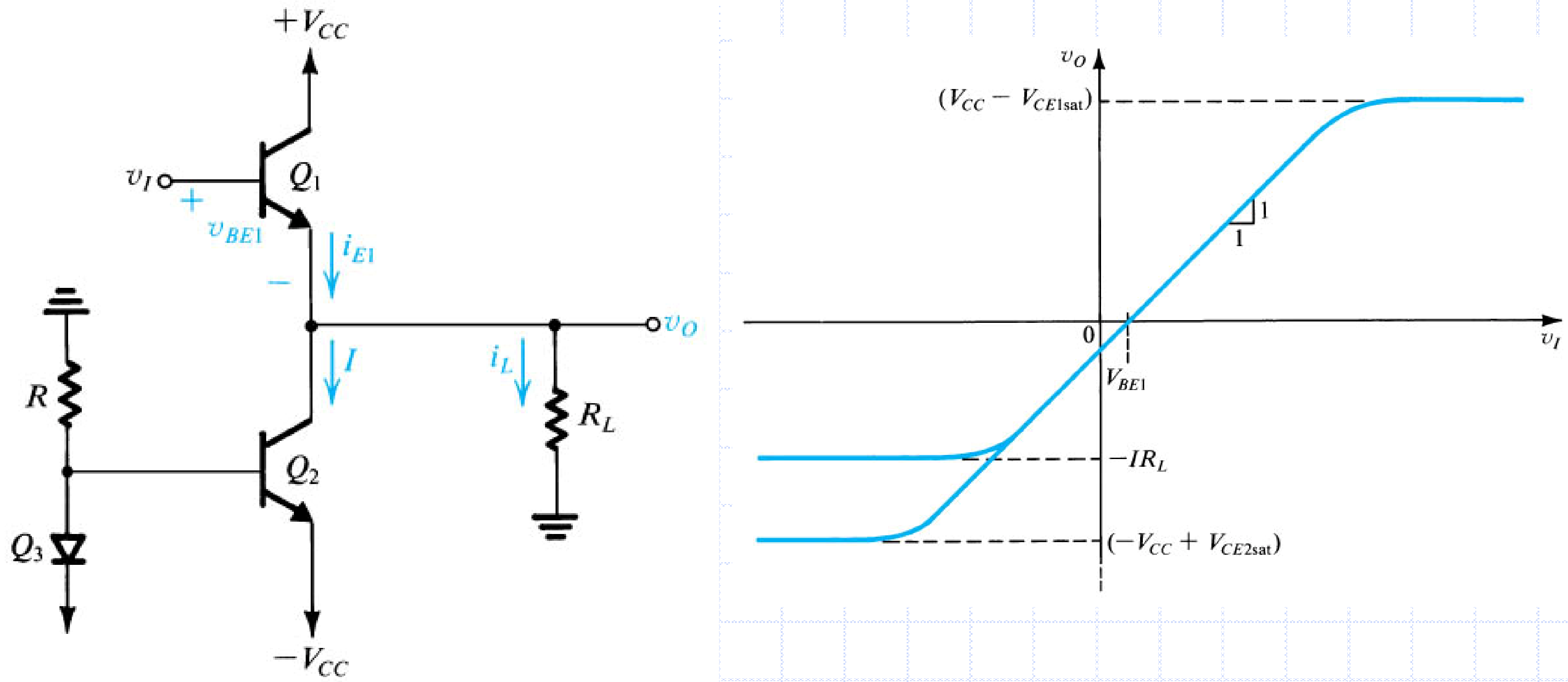


Figure 14.2 An emitter follower (Q_1) biased with a constant current I supplied by transistor Q_2.

14.2 Class A Output Stage - Transfer Characteristic

- The bias current must be greater than the largest negative load current.
- The transfer characteristic is

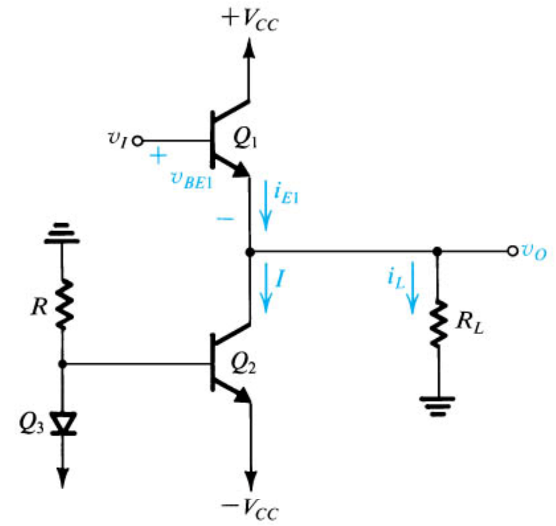
$$v_o = v_I - v_{BE1}$$

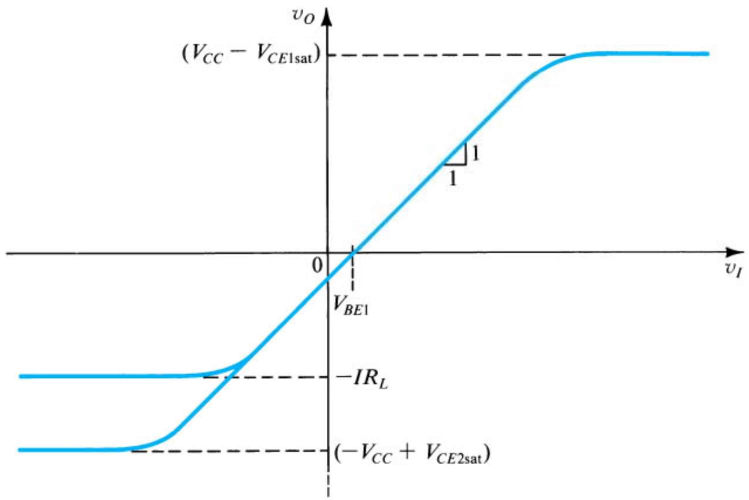
- The positive limit of the linear region is given by

$$v_{O\max} = V_{CC} - V_{CE1sat}$$

- In the negative direction, the limit of the linear region is

$$v_{O\min} = -IR_L \quad or \quad -V_{CC} + V_{CE2sat}$$

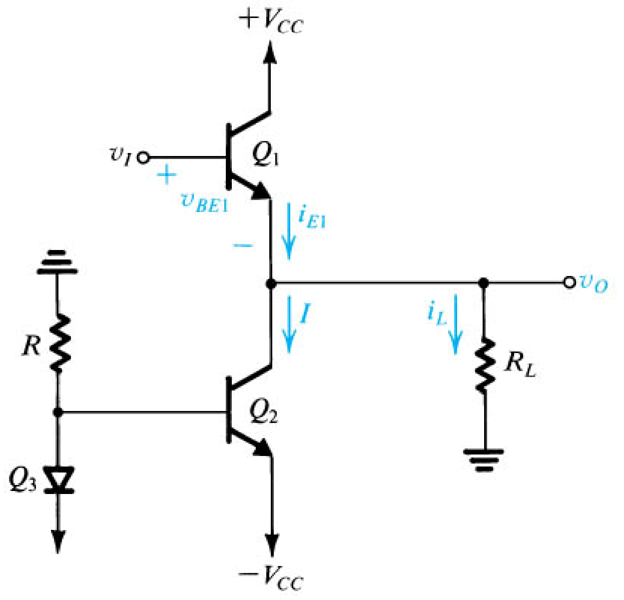




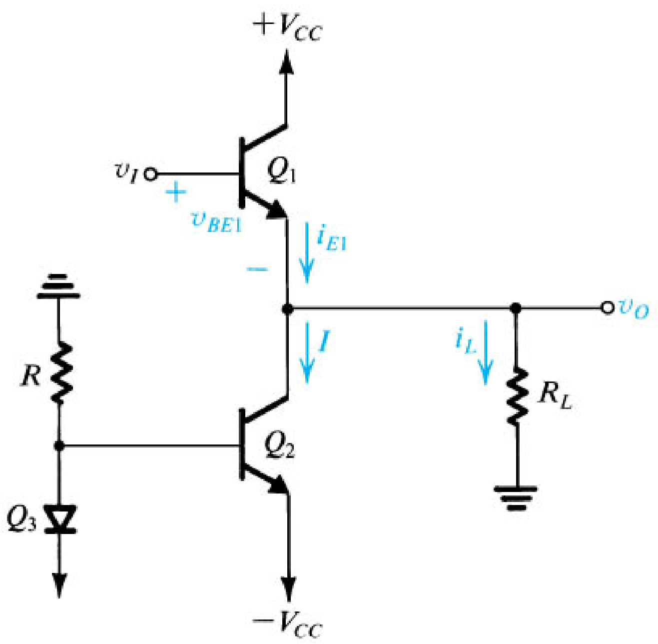
14.2 Class A Output Stage - Exercise 14.1

Exercise 14.1

For the emitter follower in the figure below, V_{CC} = 15 V, V_{CEsat} = 0.2 V, V_{BE}=0.7 V, and β is very high. Find the value of R that will establish a bias current sufficiently large to allow the largest possible output signal swing for R_L = 1 kΩ. Determine the resulting output signal swing and the minimum and maximum emitter currents.



14.2 Class A Output Stage - Exercise 14.1



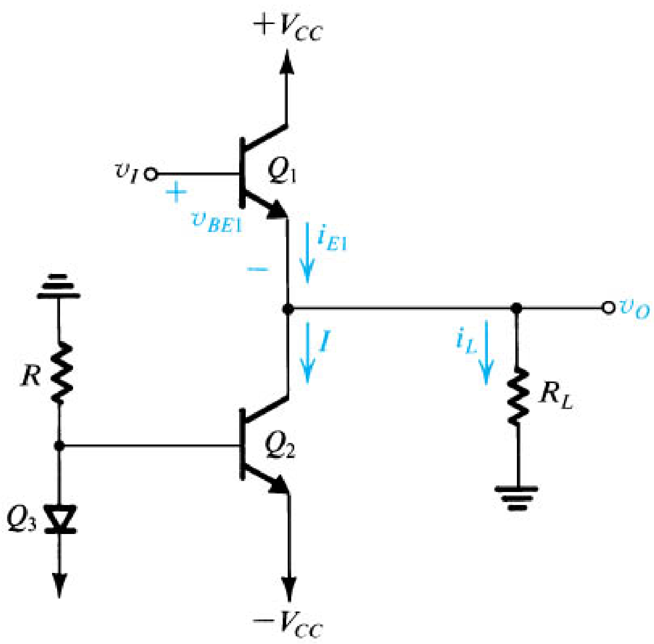
- R=?
  - The minimum bias current is given by

$$I_{\text{bias,min}} = \frac{|-V_{CC} + V_{CE2sat}|}{R_L} = \frac{14.8\,V}{1\,k\Omega} = 14.8\,mA$$

  - Since β is large, the current through R = I_{bias} , so

$$R = \frac{|-V_{CC} + V_{BE2}|}{I_{\min}} = \frac{14.3\,V}{14.8\,mA} = 0.97\,k\Omega$$

14.2 Class A Output Stage - Exercise 14.1



- Output signal swing?
  - For bias current greater than $I_{biasmin}$, the output stage function correctly as long as all BJTs are in linear region.

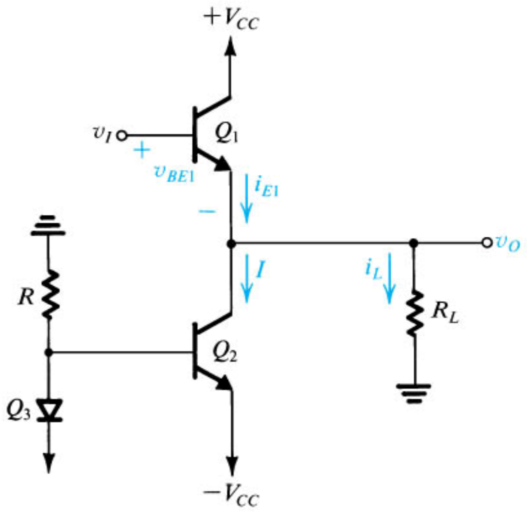
$$-14.8\,V \le V_o \le 14.8\,V$$

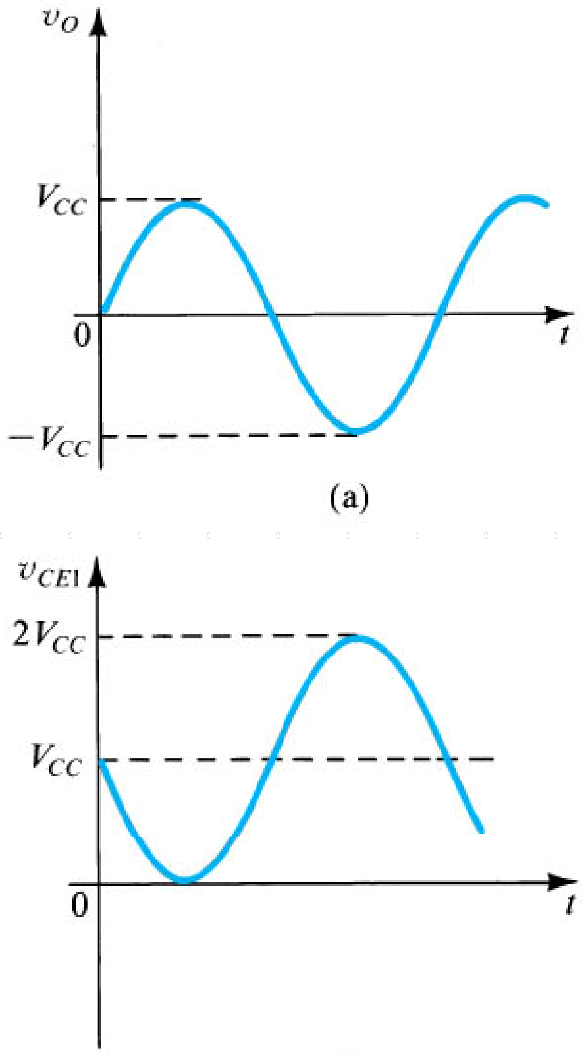
- Minimum and maximum current?
  - $I_{E1,max} = I_{bias,min} + i_{L,max} = 29.6$ mA
  - $I_{E1,min} = 0$ A

14.2 Class A Output Stage - Signal Waveforms

- For sine-wave input, neglecting V_{CEsat}, the output voltage can swing from $-V_{CC}$ to $+V_{CC}$ with the quiescent value being zero.

- Since $v_{CE1} = V_{CC} - v_o$,



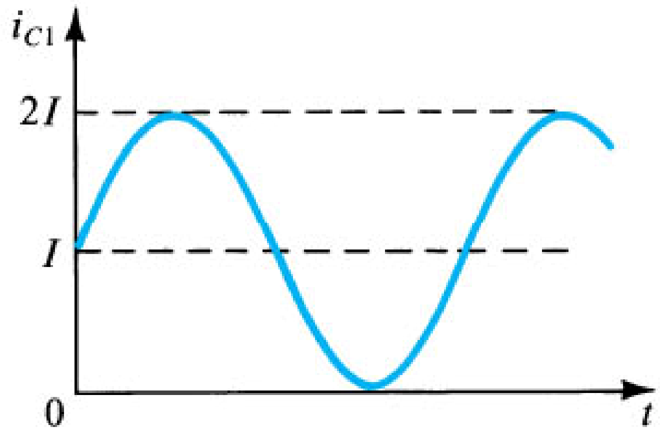


(a)

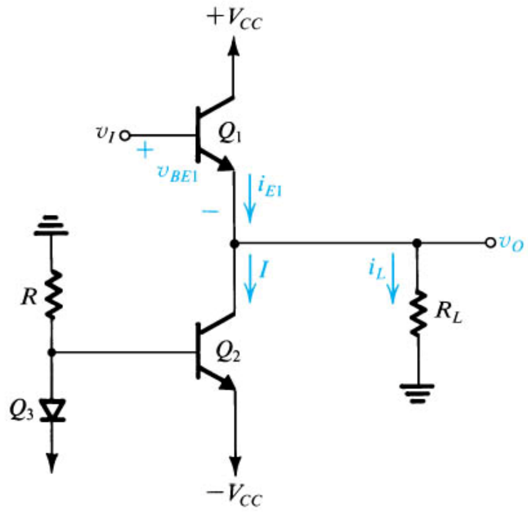
(b)

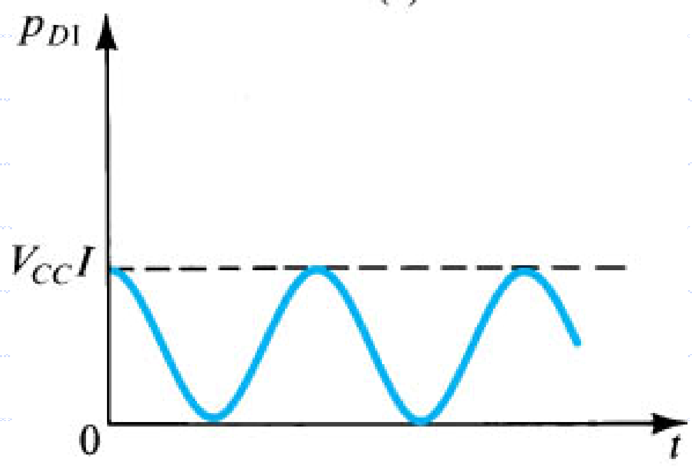
14.2 Class A Output Stage - Signal Waveforms (cont.)

- Assuming that the bias current is selected to allow a maximum negative load current of V_{cc}/R_L,
- The instantaneous power dissipation in Q1, $p_{D1}=v_{CE1}\cdot i_{C1}$



(c)





(d)

14.2 Class A Output Stage - Power Dissipation

- The maximum instantaneous power dissipation in Q_1
  $= V_{CC} \cdot I$
  = The quiescent power dissipation in Q_1.
  - The emitter follower transistor dissipates the largest amount of power when $v_o=0$: The transistor Q_1 must be able to withstand a continuous power dissipation of $V_{CC} \cdot I$.
  - The power dissipation in Q_1 depends on the value of R_L: When $R_L=0$, a very large current may flow through Q_1: short circuit protection is needed.

- The maximum instantaneous power dissipation in Q_2
  $=2 \cdot V_{CC} \cdot I$

14.2 Class A Output Stage - Power-Conversion Efficiency

- Power-Conversion Efficiency of an output stage is defined as

$$\eta = \frac{Load\ \ power(P_L)}{Supply\ \ power(P_S)}$$

  - For the emitter follower, the average load power will be

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

  - The average (positive + negative) supply power is,

$$P_S = 2V_{CC} I$$

  - Thus, the PCE is,

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

14.2 Class A Output Stage - Power-Conversion Efficiency (cont)

- The maximum efficiency is 25%, obtained when

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

- Because 25% is a rather low figure, the class A output stage is rarely used in high-power applications (>1W).

- In practice the output voltage swing is limited to lower values to avoid transistors saturation and associated nonlinear distortion. Thus the efficiency achieved is usually in the 10% to 20% range.

14.3 Class B Output Stage

- The class B output stage consists of a complementary pare of transistors connected in such a way that both cannot conduct simultaneously.

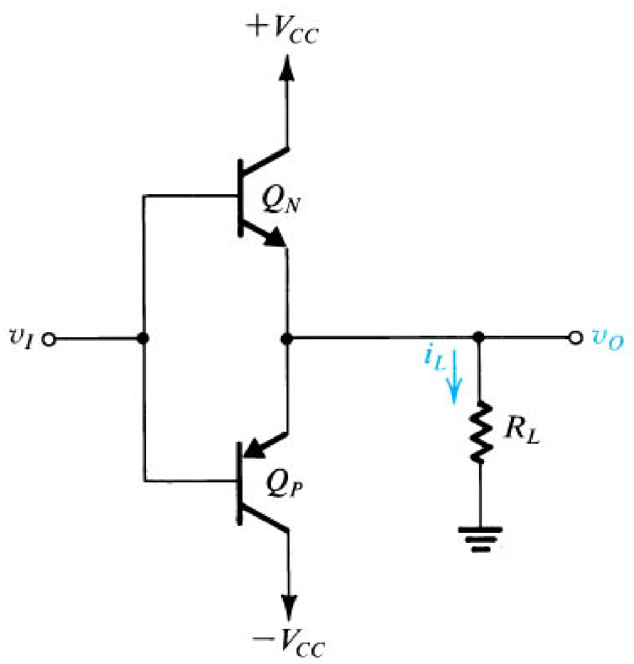
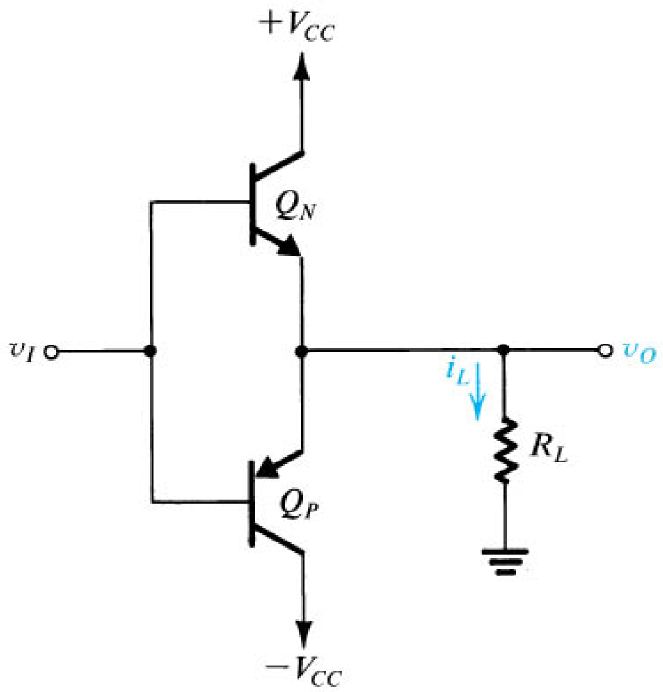


Figure 14.5 A class B output stage.

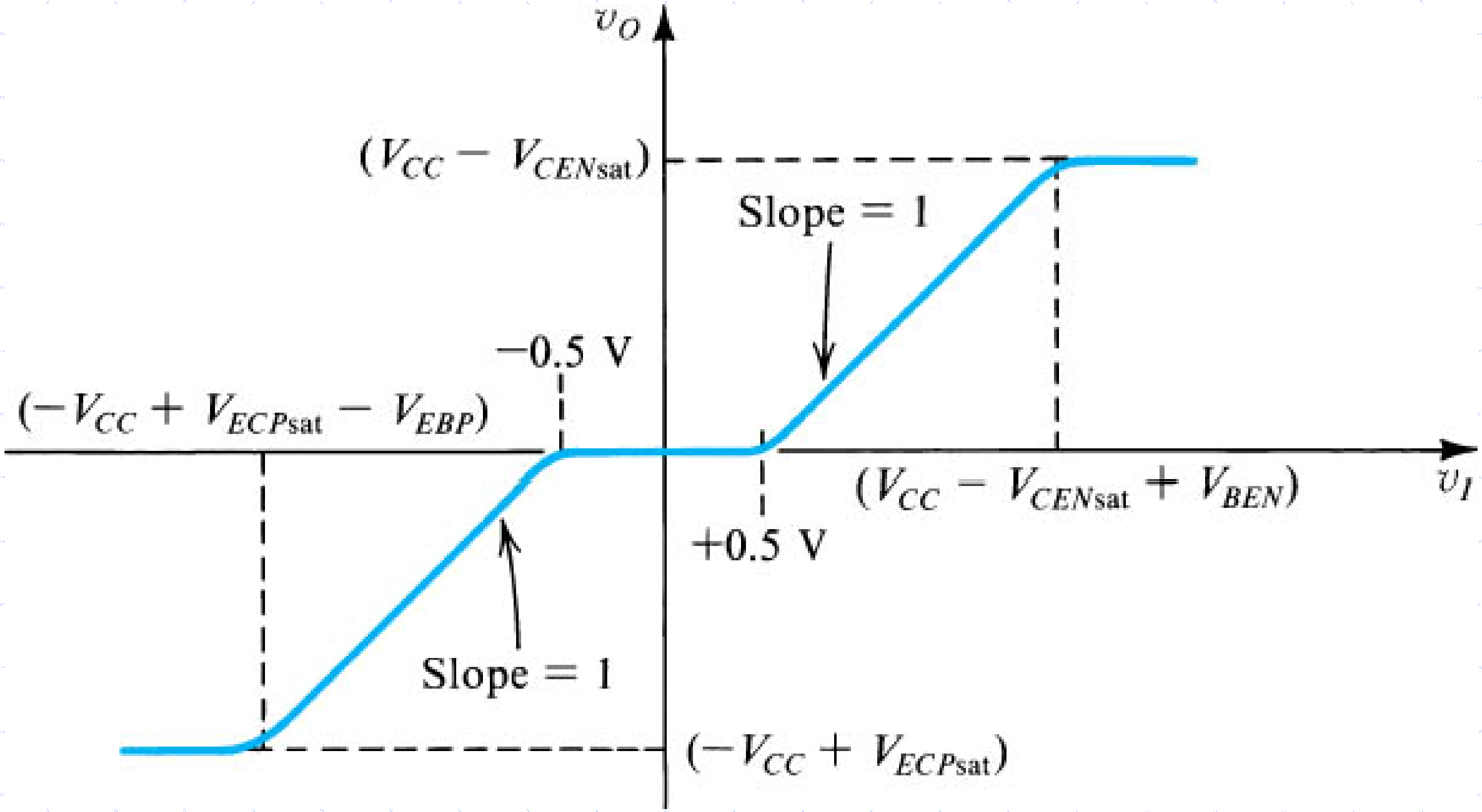
14.3 Class B Output Stage - Circuit Operation

- When the input voltage v_i is zero,
  - both transistors are cut off – v_o is zero.
- When v_i exceeds about 0.5 V,
  - Q_N conducts and operates as an emitter follower.
  - v_o follows v_i, Q_P cut off.
- When v_i goes negative by more than 0.5 V,
  - Q_P conducts and operates as an emitter follower.
  - v_o follows v_i Q_N cut off.
- The circuit operates in a push-pull fashion.



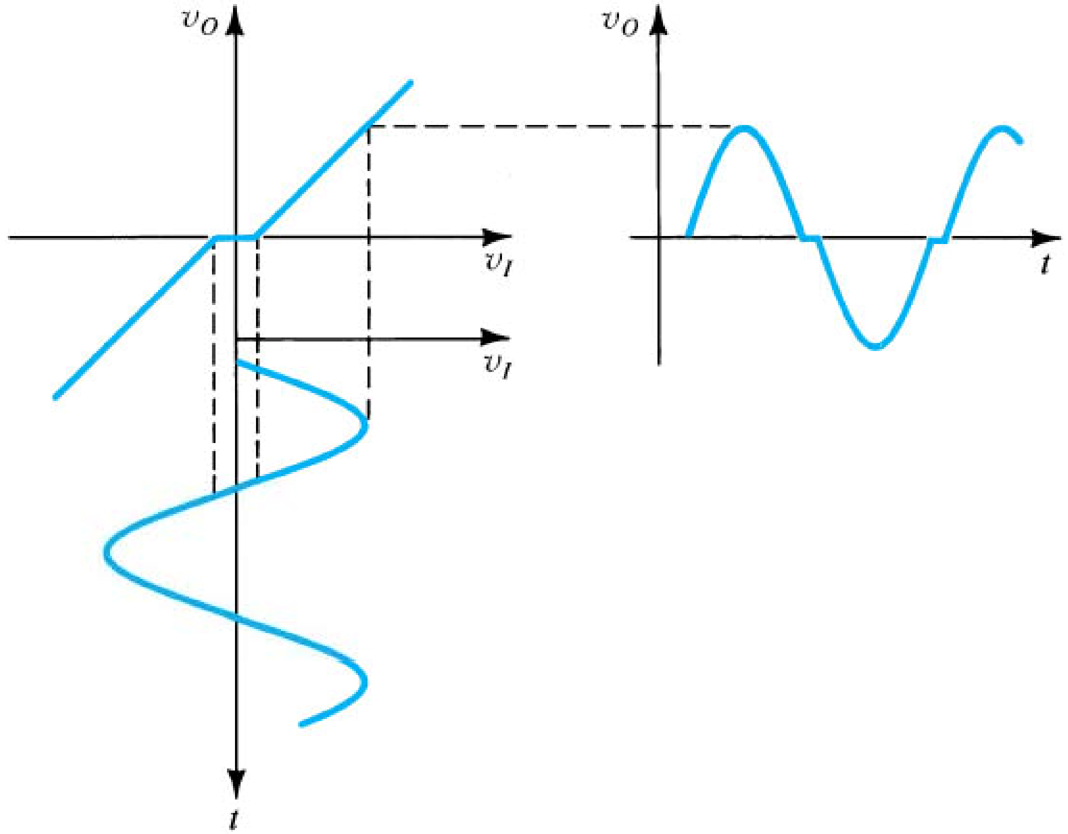
14.3 Class B Output Stage - Transfer Characteristic

- The transfer characteristic of the class B stage



14.3 Class B Output Stage - Transfer Characteristic

- The dead band results in the crossover distortion.



14.3 Class B Output Stage - Power-Conversion Efficiency

- The average load power will be,

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

- The average current drawn from each of the two power supplies will be,

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

- The total supply power will be,

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

- Thus the PCE is given by

$$\eta = \frac{\pi}{4}\frac{\hat{V}_o}{V_{CC}}$$

14.3 Class B Output Stage - Power-Conversion Efficiency(cont.)

- The maximum efficiency is obtained when $\hat{V}_o$ is maximum ($=V_{CC}-V_{CESAT} \approx V_{CC}$)
- At this value of peak output voltage, the PCE is

$$\eta_{\max} = \frac{\pi}{4} = 78.5\% \; (>> 25\% \; in\ the\ class\ A\ case)$$

- The maximum average power available from a class B output stage is,

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

14.3 Class B Output Stage - Power Dissipation

- 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

$$P_D = P_S - P_L$$

- Substituting for $P_S = \frac{2}{\pi}\frac{\hat{V}_o}{R_L}V_{CC}$ and for $P_L = \frac{1}{2}\frac{\hat{V}_o^{\,2}}{R_L}$ results in

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

- The maximum average power dissipation is (given by differentiating above eqn.)

$$P_{D\max} = \frac{2V_{CC}^{\;2}}{\pi^2 R_L}$$

14.3 Class B Output Stage - Power Dissipation (cont.)

- The maximum average power dissipation

$$P_{DP\max} = P_{DN\max} = \frac{2V_{CC}^{\ 2}}{\pi^2 R_L}$$

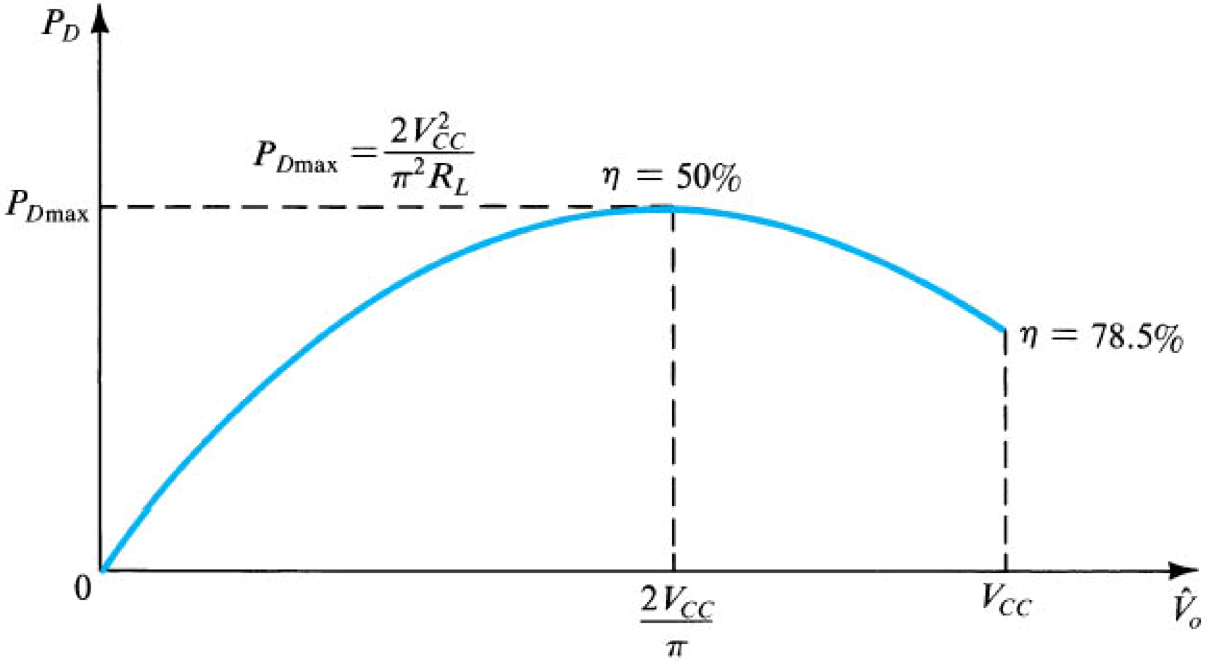
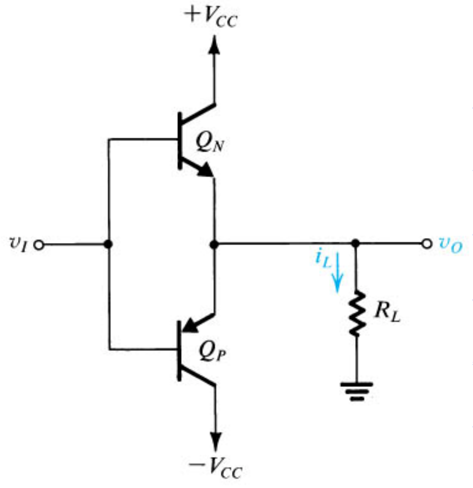


Figure 14.8 Power dissipation of the class B output stage versus amplitude of the output sinusoid.

14.3 Class B Output Stage - Example 14.1

- Example 14.1

  It is required to design a class B output stage to deliver an average power of 20 W to an 8-Ω load. The power supply is to be selected such that V_{CC} is about 5V greater than the peak output voltage. This avoids transistor saturation and the associated nonlinear distortion, and allows for including short-circuit protection circuitry. Determine the supply voltage required, the peak current drawn from each supply, the total supply power, and the power-conversion efficiency. Also determine the maximum power that each transistor must be able to dissipate safely.



14.3 Class B Output Stage - Example 14.1

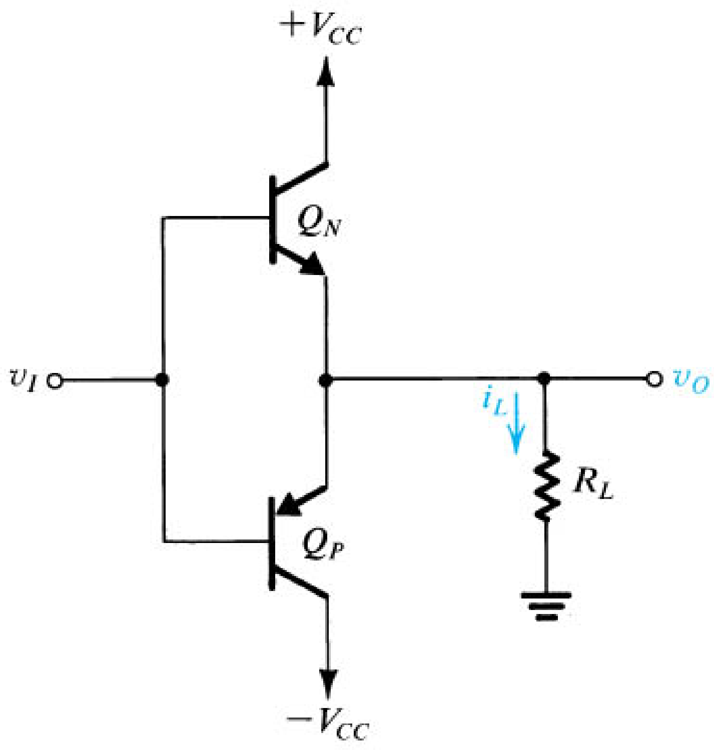
- Example 14.1
  - Since

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

  - Then

$$\hat{V}_o = \sqrt{2P_L R_L} = 17.9V$$

  - Therefore we select V_{CC} = 23 V



14.3 Class B Output Stage - Example 14.1

- Example 14.1
  - The peak current drawn from each supply is

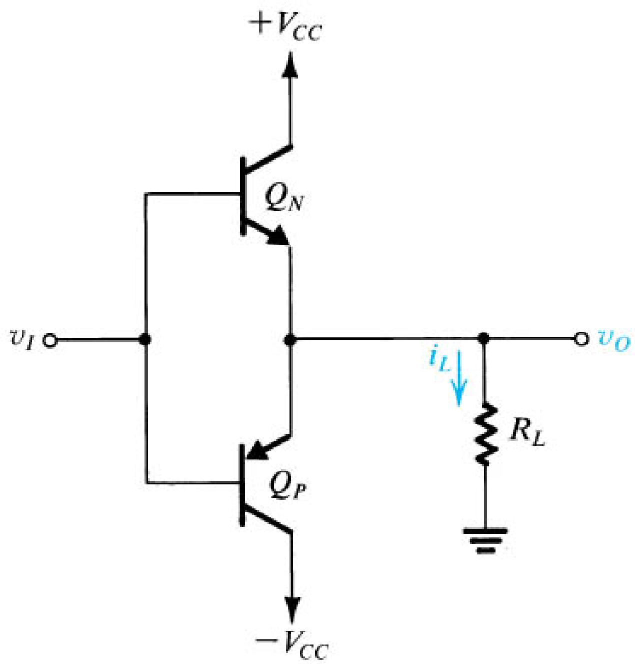
$$\hat{I}_o = \frac{\hat{V}_o}{R_L} = 2.24A$$

  - The average power drawn from each supply is

$$P_{s+} = P_{s-} = \frac{1}{\pi}(2.24 \times 23) = 16.4W$$

  - For a total supply power of 32.8W. The power-conversion efficiency is

$$\eta = \frac{P_L}{P_S} = \frac{20}{32.8} \times 100 = 61\%$$

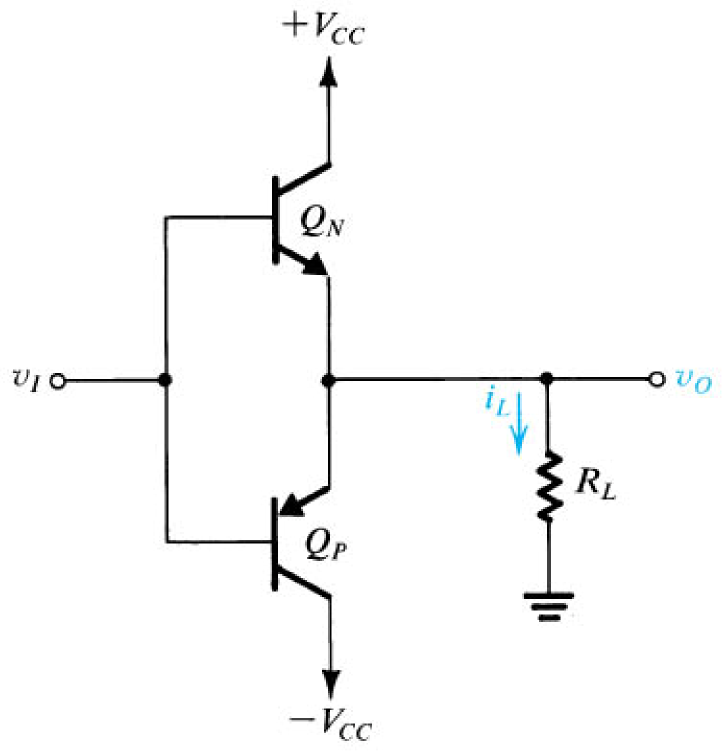


14.2 Class B Output Stage - Example 14.1

- Example 14.1
  - The maximum power dissipated in each transistor is given by,

$$P_{DN\max} = P_{DP\max} = \frac{V_{CC}}{\pi^2 R_L}$$

$$= \frac{(23)^2}{\pi^2 \times 8} = 6.7W$$



14.3 Class B Output Stage - Reducing Crossover Distortion

- Reducing crossover distortion by employing a high-gain op amp and overall negative feedback.
  - The ± 0.7 V deadband is reduced to $\pm 0.7/A_o$ V

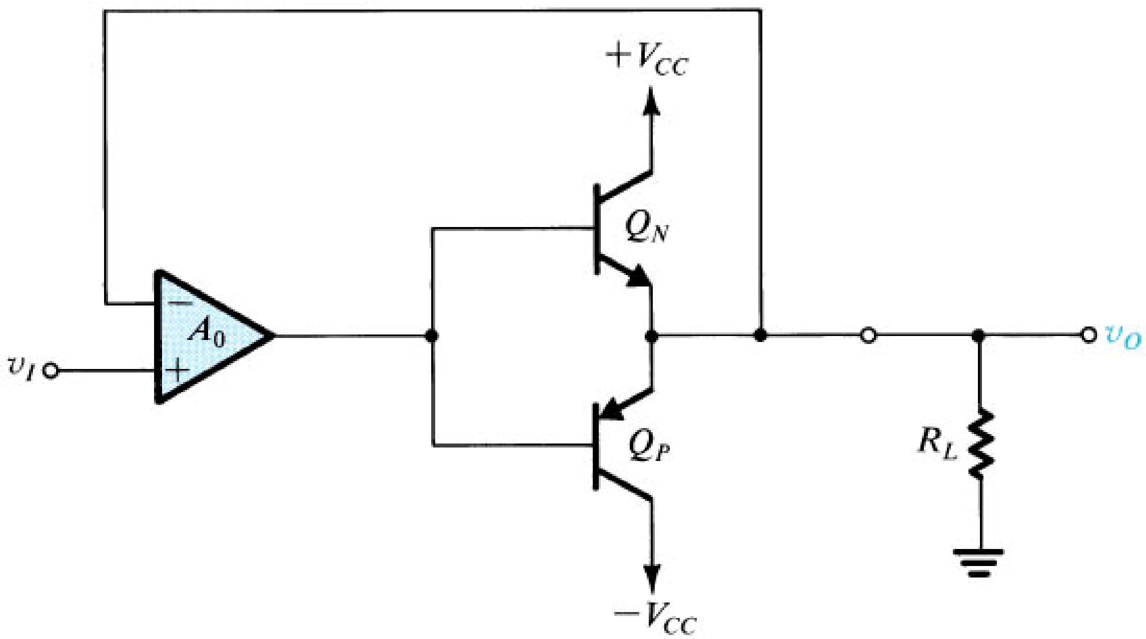


Figure 14.9 Class B circuit with an op amp connected in a negative-feedback loop to reduce crossover distortion.

14.3 Class B Output Stage - Single-Supply Operation

- Class B operation from a single power supply

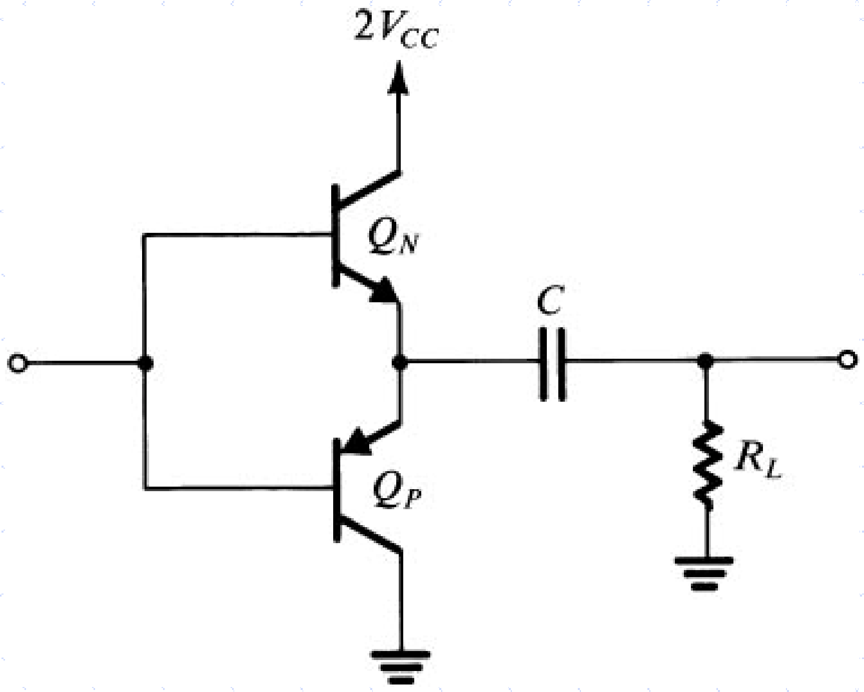


Figure 14.10 Class B output stage operated with a single power supply.

14.4 Class AB Output Stage

- Crossover distortion can be virtually eliminated by biasing the complementary output transistors at a small nonzero current.

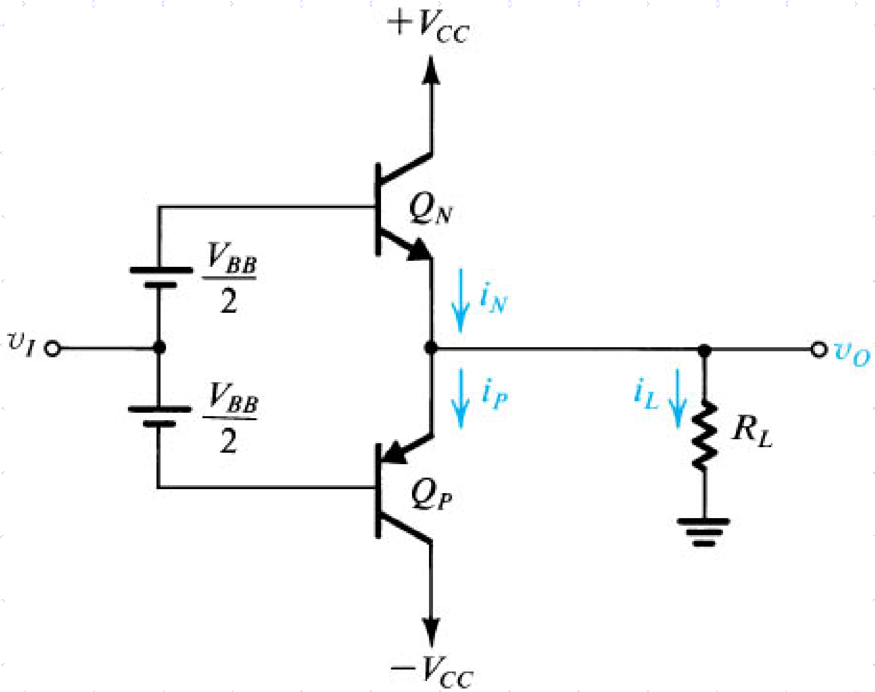


Figure 14.11 Class AB output stage. A bias voltage V_{BB} is applied between the bases of Q_N and Q_P, giving rise to a bias current I_Q given by Eq. (14.23). Thus, for small v_I, both transistors conduct and crossover distortion is almost completely eliminated.

14.4 Class AB Output Stage - Circuit Operation

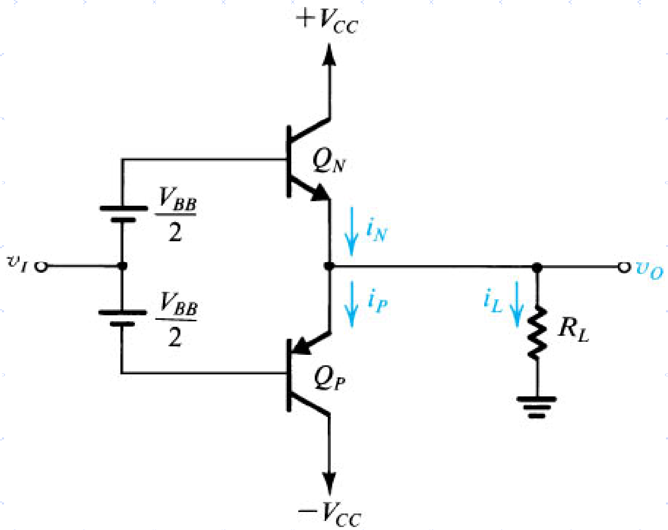
- When v_I goes positive, the output becomes positive at almost equal value,

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

- v_O causes a current i_L to flow through R_L, and i_N must increase

$$i_N = i_P + i_L$$

- Since the V_{BB} voltage remains constant, the increase in v_{BEN} will result in an equal decrease in v_{EBP} and in i_P. The relationship between i_N and i_P is,



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

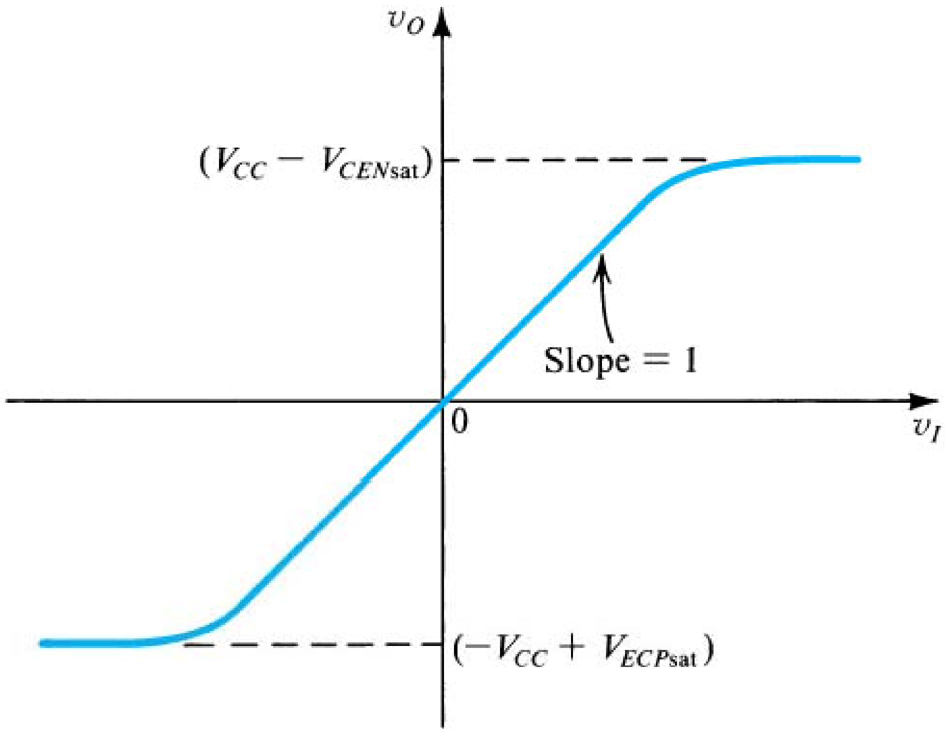
$$V_T \ln\left(\frac{i_N}{I_S}\right) + V_T \ln\left(\frac{i_P}{I_S}\right) = 2V_T \ln\left(\frac{I_Q}{I_S}\right)$$

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

$$\therefore i_N^{\ 2} - i_L i_N - I_Q^{\ 2} = 0$$

14.4 Class AB Output Stage - Circuit Operation (cont.)

- Transfer characteristic of the class AB stage
  - For small v_I, both transistors conduct, and as v_I is increased or decreased, one of the two transistors takes over the operation → crossover distortion is eliminated



14.4 Class AB Output Stage - Output Resistance

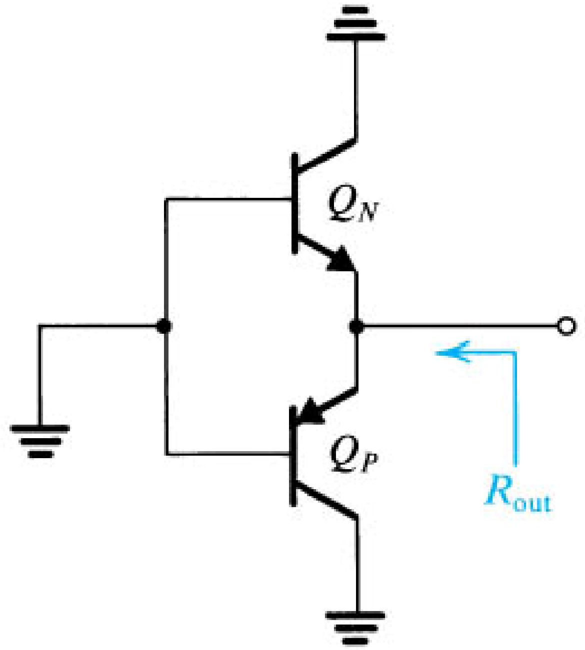
- The output resistance of the class AB can be derived as follows

$$R_{out} = r_{eN} \| r_{eP}$$

$$r_{eN} = \frac{V_T}{i_N}, \quad r_{eP} = \frac{V_T}{i_P}$$

$$\therefore \ R_{out} = \frac{V_T}{i_N} \| \frac{V_T}{i_P} = \frac{V_T}{i_P + i_N}$$

- The output resistance remains approximately constant in the region around v_I=0.
- At larger load currents, R_{out} decreases as the load current increases.



14.4 Class AB Output Stage - Problem 14.16

Problem 14.16

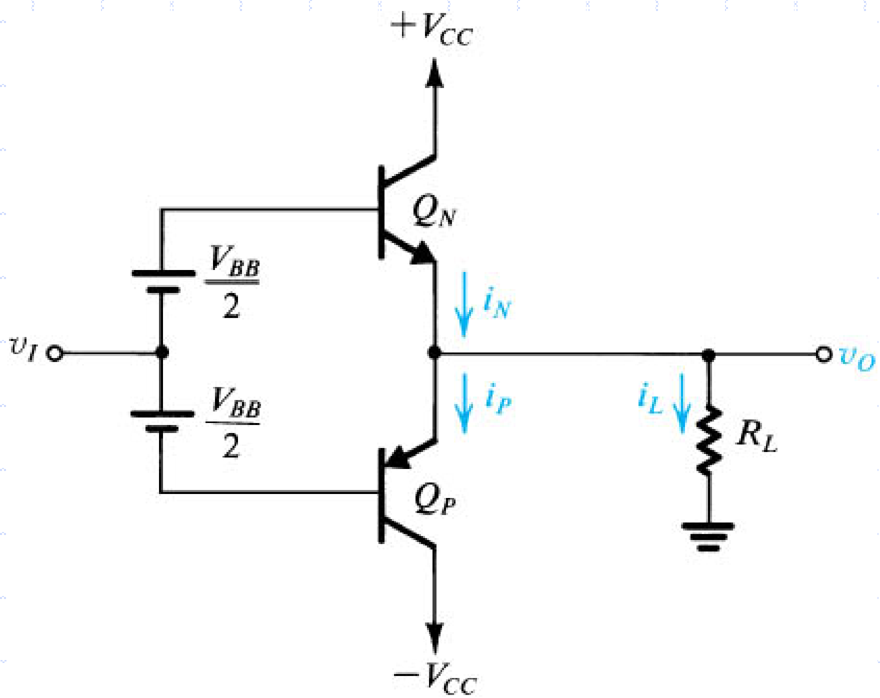
Design the quiescent current of a class AB BJT output stage so that the incremental voltage gain for vi in the vicinity of the origin is in excess of 0.99V/V for loads larger than 100 Ω. Assume that the BJTs have V_{BE} of 0.7V at a current of 100mA and determine the value of V_{BB} required.

- The voltage gain of the output stage is given by

$$A_v = \frac{R_L}{R_L + R_{out}}$$

- Since A_v must be greater than 0.99 with $R_L \geq 100\ \Omega$,

$$R_{out} \leq \left(\frac{1}{A_v} - 1\right) R_L \approx 1\Omega$$



14.4 Class AB Output Stage - Problem 14.16

- Problem 14.16
  - R_{out} has a relationship to the circuit parameters, in a way that

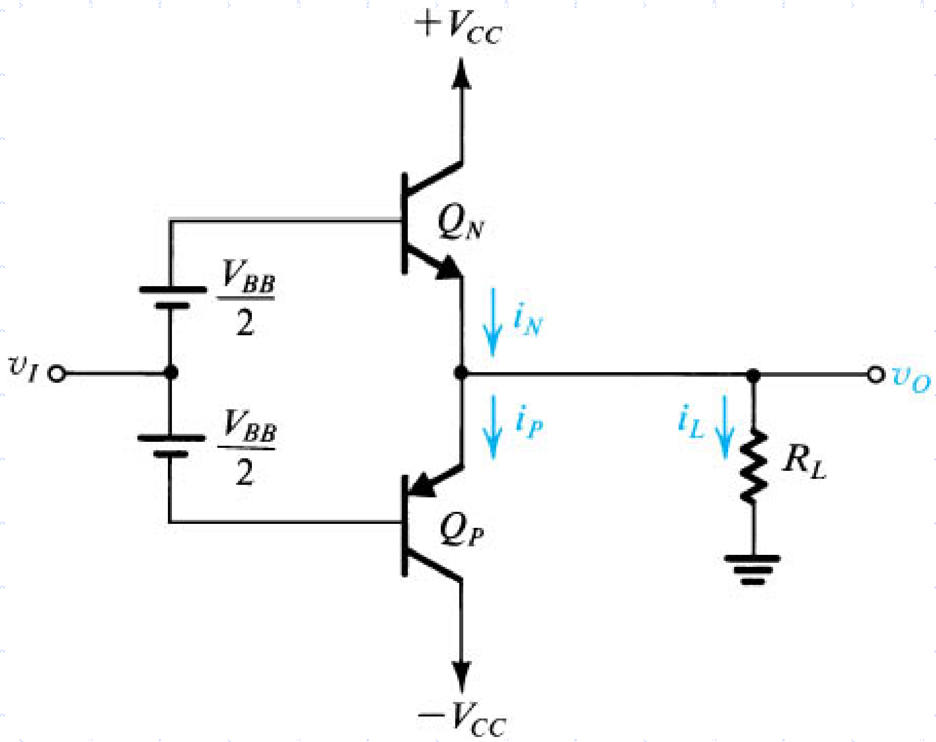
$$R_{out} = \frac{r_e}{2} = \frac{V_T}{2I_Q}$$

  - So, the needed I_Q to get $R_{out} \le 1\ \Omega$ is 12.5 mA.
  - V_{BB} = 2 V_{BE}. Therefore,

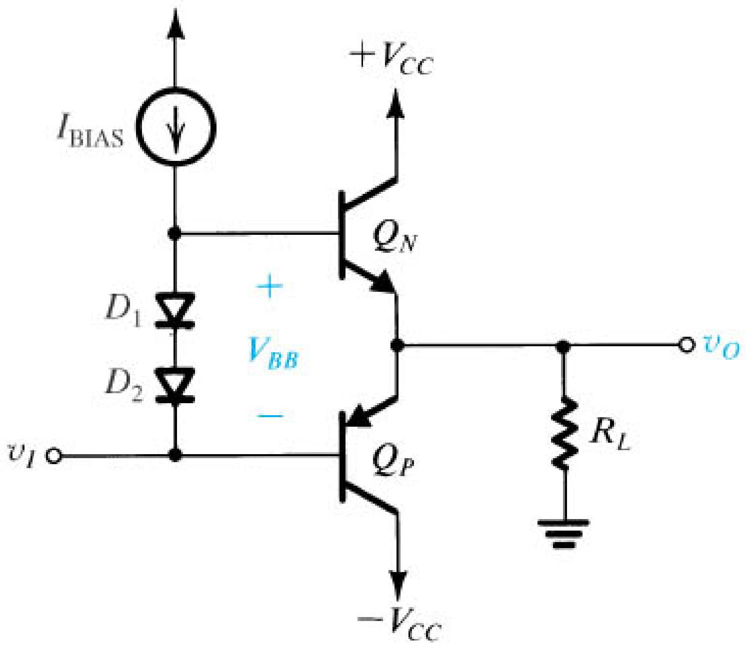
$$V_{BB} = 2V_{BE}$$

$$= 2[0.7 + V_T \ln\frac{12.5}{100}]$$

$$= 1.296V$$



14.5 Biasing The Class AB Circuit - Biasing Using Diodes



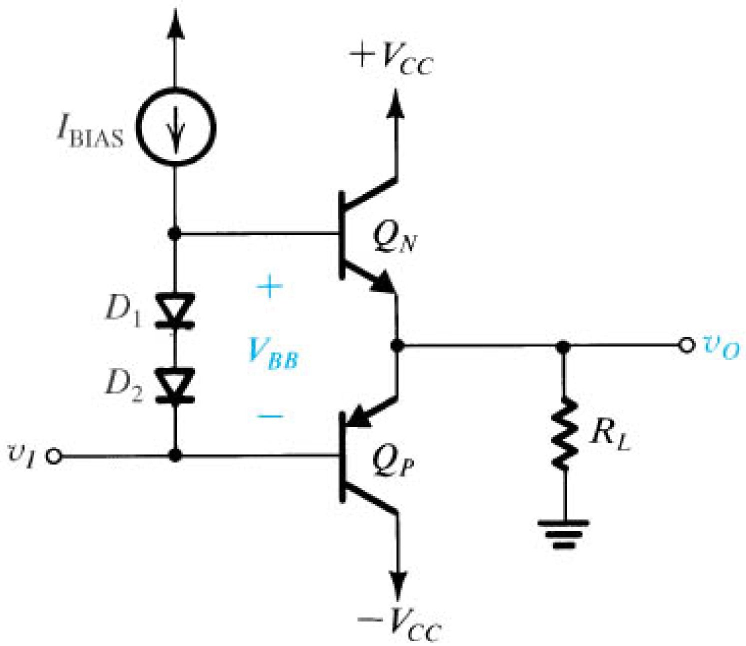
- The quiescent current I_Q, has the following relationship with I_{BIAS}.

  (n denotes the ratio of the emitter-junction area of Q to the junction area of D.)

$$I_Q = nI_{BIAS}$$

- n shouldn't be a large number because I_{BIAS} is drawn into the base of Q_N when its driving a load, thus no current may be left for D.

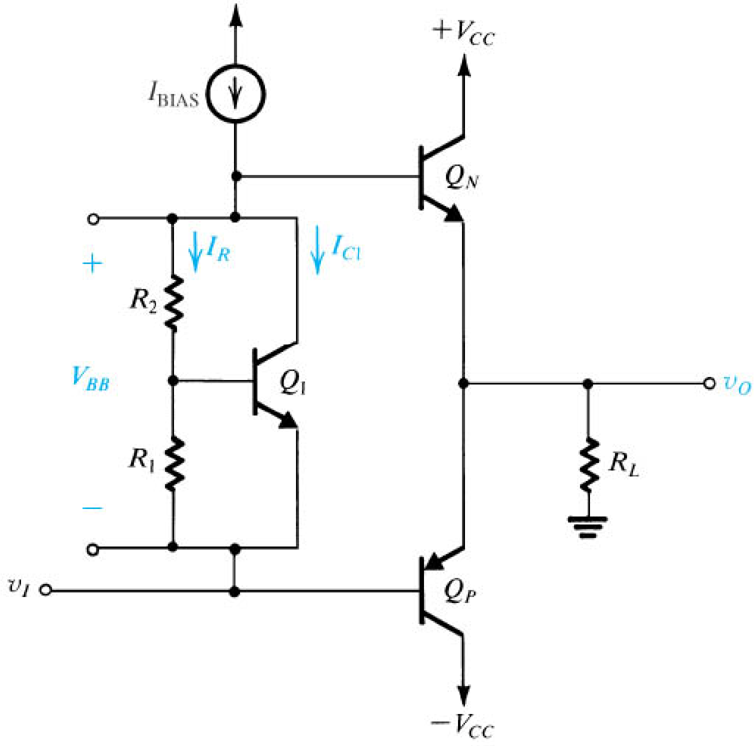
14.5 Biasing The Class AB Circuit - Biasing Using Diodes



- Advantage
  - Protection against thermal runaway
- Disadvantage
  - V_{BB}'s dependence on the load current

(Thermal runaway: a phenomenon that occurs when the power dissipation of the output stage brings temperature rise to the surroundings. The rise in temperature will accommodate more current through BJTs thus forms a positive loop in increasing the quiescent current. It will eventually destroy the BJTs.)

14.5 Biasing The Class AB Circuit - Biasing Using the V_{BE} Multiplier



- (Neglecting base current) R_1 and R_2 will carry the same current I_R, given by

$$I_R = \frac{V_{BE1}}{R_1}$$

- So, the voltage V_{BB} will be

$$V_{BB} = V_{BE1}\left(1 + \frac{R_2}{R_1}\right)$$

where

$$I_{C1} = I_{BIAS} - I_R$$

$$V_{BE1} = V_T \ln \frac{I_{C1}}{I_{S1}}$$