x3

EXTRA TOPICS RELATED TO

Useful Transistor Pairings

This supplement contains material removed from previous editions of the textbook. These topics continue to be relevant and for this reason will be of great value to many instructors and students.

The topics presented here build on and extend the material presented in Chapter 8 of the eighth edition.

The cascode configuration studied in Section 8.5 of Chapter 8 combines CS and CG MOS transistors (CE and CB bipolar transistors) to great advantage. The key to the superior performance of the resulting combination is that the transistor pairing is done in a way that maximizes the advantages and minimizes the shortcomings of each of the two individual configurations. In this supplement we present a number of other such transistor pairings. In each case the transistor pair can be thought of as a compound device; thus the resulting amplifier may be considered as a single stage.

x3.1 The CC–CE, CD–CS, and CD–CE Configurations

Figure x3.1(a) shows an amplifier formed by cascading a common-collector (emitter-follower) transistor Q_1 with a common-emitter transistor Q_2. This circuit has two main advantages over the CE amplifier. First, the emitter follower increases the input resistance by a factor equal to $(\beta_1 + 1)$. As a result, the overall voltage gain is increased, especially if the resistance of the signal source is large. Second, it is shown in Chapter 10 that the CC–CE amplifier can exhibit much wider bandwidth than that obtained with the CE amplifier.

The MOS counterpart of the CC–CE amplifier, namely, the CD–CS configuration, is shown in Fig. x3.1(b). Here, since the CS amplifier alone has an infinite input resistance, the sole purpose for adding the source-follower stage is to increase the amplifier bandwidth, as can be seen in Chapter 10. Finally, Fig. x3.1(c) shows the BiCMOS version of this circuit type. Compared to the bipolar circuit in Fig. x3.1(a), the BiCMOS circuit has an infinite input resistance. Compared to the MOS circuit in Fig. x3.1(b), the BiCMOS circuit typically has a higher g_{m2}.

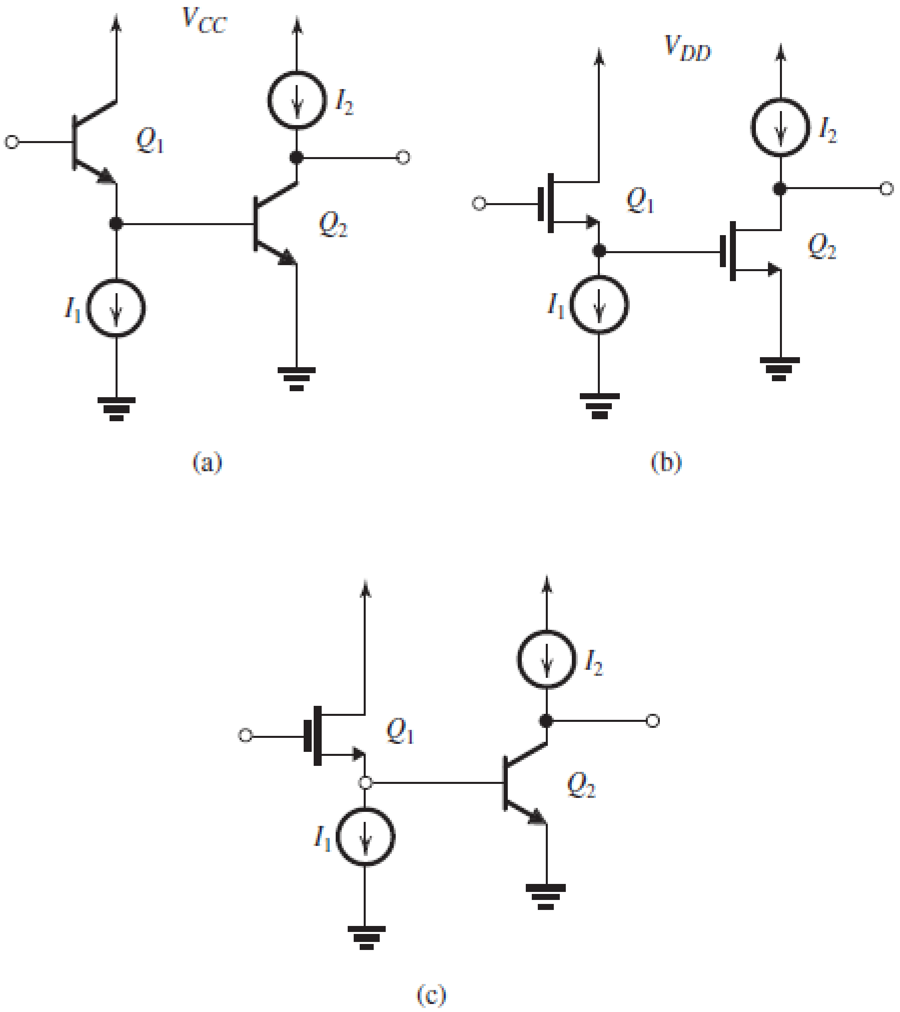


Figure x3.1 (**a**) CC–CE amplifier; (**b**) CD–CS amplifier; (**c**) CD–CE amplifier.

Example x3.1

For the CC–CE amplifier in Fig. x3.1(a) let $I_1 = I_2 = 1$ mA and assume identical transistors with $\beta = 100$. Find the input resistance R_{in} and the overall voltage gain obtained when the amplifier is fed with a signal source having $R_{\text{sig}} = 4$ kΩ and loaded with a resistance $R_L = 4$ kΩ. Compare the results with those obtained with a common-emitter amplifier operating under the same conditions. Ignore r_o.

Solution

At an emitter current of 1 mA, Q_1 and Q_2 have

$$g_m = 40 \text{ mA/V}$$
$$r_e = 25\ \Omega$$
$$r_\pi = \frac{\beta}{g_m} = \frac{100}{40} = 2.5 \text{ k}\Omega$$

Referring to Fig. x3.2 we can find

$$\begin{aligned}
R_{\text{in2}} &= r_{\pi 2} = 2.5 \text{ k}\Omega \\
R_{\text{in}} &= (\beta_1 + 1)(r_{e1} + R_{\text{in2}}) \\
&= 101(0.025 + 2.5) = 225 \text{ k}\Omega \\
\frac{v_{b1}}{v_{\text{sig}}} &= \frac{R_{\text{in}}}{R_{\text{in}} + R_{\text{sig}}} = \frac{255}{255 + 4} = 0.98 \text{ V/V} \\
\frac{v_{b2}}{v_{b1}} &= \frac{R_{\text{in2}}}{R_{\text{in2}} + R_{e1}} = \frac{2.5}{2.5 + 0.025} = 0.99 \text{ V/V} \\
\frac{v_o}{v_{b2}} &= g_{m2} R_L = -40 \times 4 = -160 \text{ V/V}
\end{aligned}$$

Thus,

$$G_v = \frac{v_o}{v_{\text{sig}}} = -160 \times 0.99 \times 0.98 = -155 \text{ V/V}$$

For comparison, a CE amplifier operating under the same conditions will have

$$\begin{aligned}
R_{\text{in}} &= r_\pi = 2.5 \text{ k}\Omega \\
G_v &= \frac{R_{\text{in}}}{R_{\text{in}} + R_{\text{sig}}}(-g_m R_L) \\
&= \frac{2.5}{2.5 + 4}(-40 \times 4) \\
&= -61.5 \text{ V/V}
\end{aligned}$$

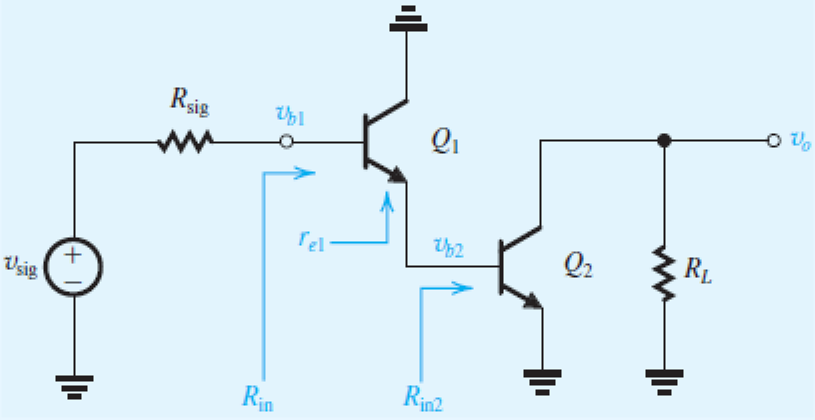


Figure x3.2 Circuit for Example x3.1.

EXERCISE

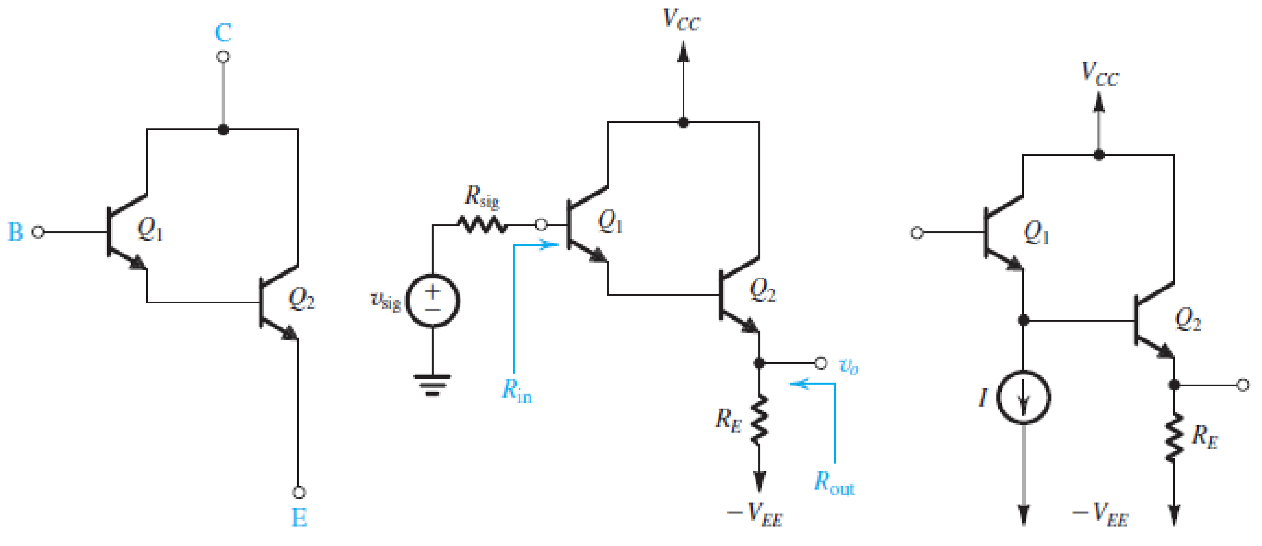
x3.1 Repeat Example x3.1 for the CD–CE configuration of Fig. x3.1(c). Let $I_1 = I_2 = 1$ mA, $\beta_2 = 100$, $R_L = 4$ kΩ, and $k_{n1} = 8$ mA/V^2; neglect the body effect in Q_1 and r_o of both transistors. Find R_{in} and G_v when $R_{\text{sig}} = 4$ kΩ (as in Example x3.1) and $R_{\text{sig}} = 400$ kΩ. What would G_v of the CC–CE amplifier in Example x3.1 become for $R_{\text{sig}} = 400$ kΩ?

Ans. $R_{\text{in}} = \infty$; $G_v = -145.5$ V/V, independent of R_{sig}; -61.7 V/V

x3.2 The Darlington Configuration

Figure x3.3(a) shows a popular BJT circuit known as the **Darlington configuration**. It can be thought of as a variation of the CC–CE circuit with the collector of Q_1 connected to that of Q_2. Alternatively, the **Darlington pair** can be thought of as a composite transistor with $\beta = \beta_1\beta_2$. It can therefore be used to implement a high-performance voltage follower, as illustrated in Fig. x3.3(b). Note that in this application the circuit can be considered as the cascade connection of two common-collector transistors (i.e., a CC–CC configuration).

Since the transistor β depends on the dc bias current, it is possible that Q_1 will be operating at a very low β, rendering the β-multiplication effect of the Darlington pair rather ineffective. A simple solution to this problem is to provide a bias current for Q_1, as shown in Fig. x3.3(c).



(a) (b) (c)

Figure x3.3 **(a)** The Darlington configuration; **(b)** voltage follower using the Darlington configuration; **(c)** the Darlington follower with a bias current I supplied to Q_1 to ensure that its β remains high.

EXERCISE

x3.2 For the Darlington voltage follower in Fig. x3.3(b), show that:

$$R_{\text{in}} = (\beta_{1+1})[r_{e1} + (\beta_2 + 1)(r_{e2} + R_E)]$$

$$R_{\text{out}} = R_E \| \left[r_{e2} + \frac{r_{e1} + [R_{\text{sig}}/(\beta_1 + 1)]}{\beta_2 + 1} \right]$$

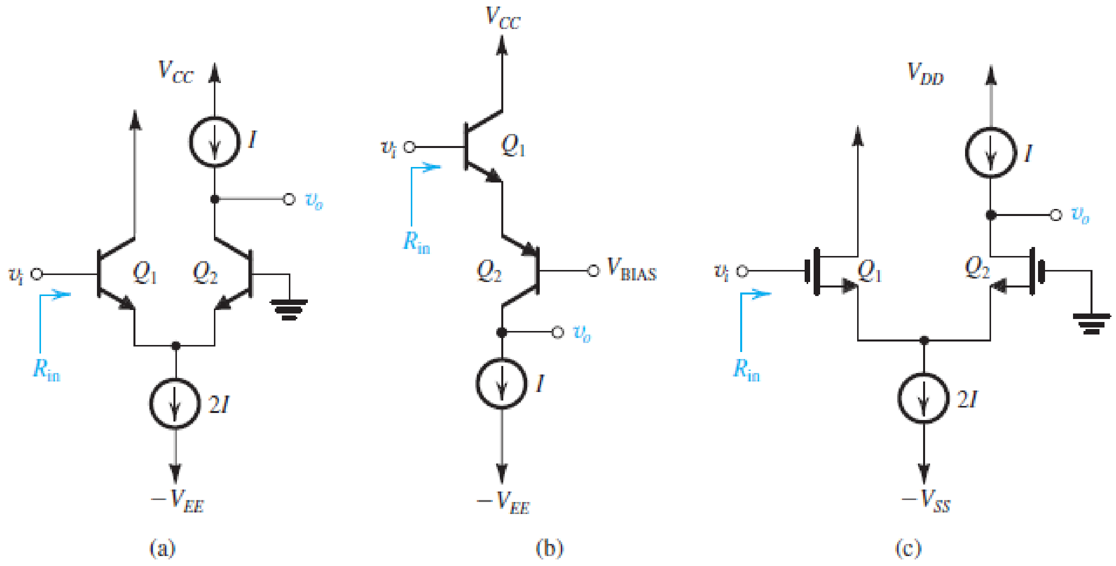
$$\frac{v_o}{v_{\text{sig}}} = \frac{R_E}{R_E + r_{e2} + [r_{e1} + R_{\text{sig}}/(\beta_1 + 1)]/(\beta_2 + 1)}$$

Evaluate R_{in}, R_{out} , and v_o/v_{sig} for the case I_{E2} = 5mA, $\beta_1 = \beta_2 = 100$, R_E = 1 kΩ, and R_{sig} = 100 kΩ.

Ans. 10.3 MΩ; 20 Ω; 0.98 V/V

x3.3 The CC–CB and CD–CG Configurations

Cascading an emitter follower with a common-base amplifier, as shown in Fig. x3.4(a), results in a circuit with a low-frequency gain approximately equal to that of the CB but with the problem of the low input resistance of the CB solved by the buffering action of the CC stage. It will be shown in Chapter 10 that this circuit exhibits wider bandwidth than that obtained with a CE amplifier of the same gain. Note that the biasing current sources shown in Fig. x3.4(a) ensure that each of Q_1 and Q_2 is operating at a bias current I. We are not showing, however, how the dc voltage at the base of Q_1 is set, nor do we



(a) (b) (c)

Figure x3.4 **(a)** A CC–CB amplifier. **(b)** Another version of the CC–CB circuit with Q_2 implemented using a pnp transistor. **(c)** The MOSFET version of the circuit in (a).

show the circuit that determines the dc voltage at the collector of Q_2. Both issues are usually looked after in the larger circuit of which the CC–CB amplifier is a part.

An interesting version of the CC–CB configuration is shown in Fig. x3.4(b). Here the CB stage is implemented with a *pnp* transistor. Although only one current source is now needed, observe that we also need to establish an appropriate bias voltage at the base of Q_2. This circuit is part of the internal circuit of the popular 741 op amp and is studied in Section 13.3.4 of the eighth edition of the textbook and in much greater detail in Supplement x5 of the bonus topics. The MOSFET version of the circuit in Fig. x3.4(a) is the CD–CG amplifier shown in Fig. x3.4(c).

Example x3.2

For the CC–CB amplifiers in Fig. x3.4(a) and (b), find R_{in}, v_o/v_i, and v_o/v_{sig} when each amplifier is fed with a signal source having a resistance R_{sig}, and a load resistance R_L is connected at the output. For simplicity, neglect r_o.

Solution

The analysis of both circuits is illustrated in Fig. x3.5. Observe that both amplifiers have the same R_{in} and v_o/v_i. The overall voltage gain v_o/v_{sig} can be found as

$$\frac{v_o}{v_{sig}} = \frac{R_{in}}{R_{in} + R_{sig}} \frac{\alpha_2 R_L}{2r_e}$$

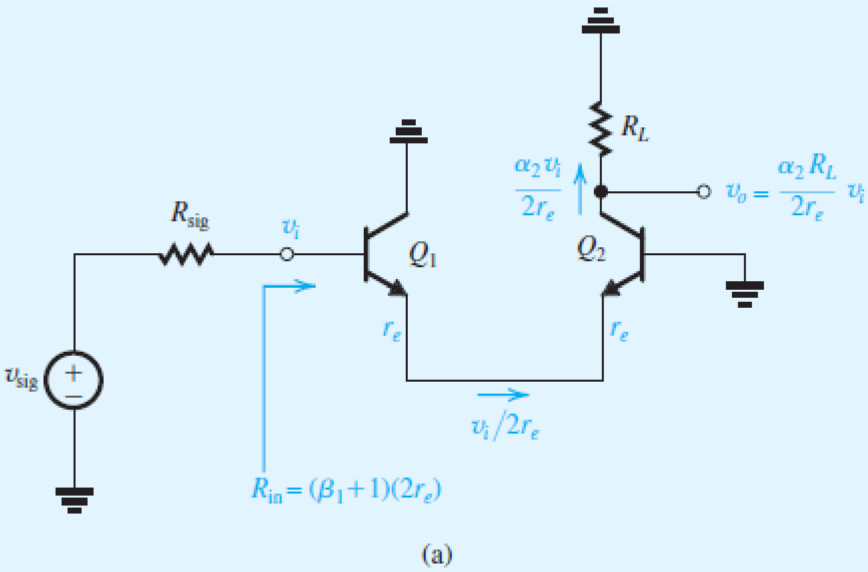


Figure x3.5 **(a)** Circuit for Example x3.2.

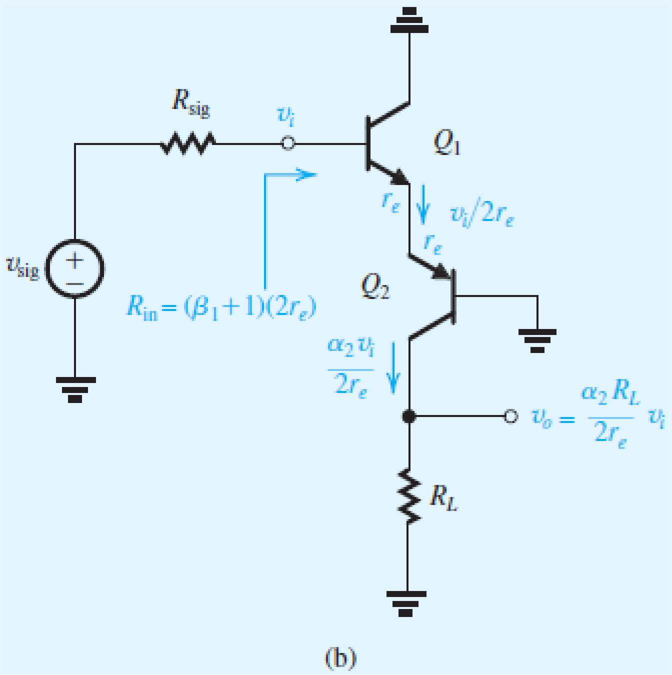


Figure x3.5 **(b)** Circuit for Example x3.2.

EXERCISES

x3.3 For the amplifiers in Example x3.2 find R_{in}, v_o/v_i, and v_o/v_{sig} for the case $I = 1$ mA, $\beta = 100$. $R_L = R_{\text{sig}} = 5$ kΩ.

Ans. 5.05 kΩ; 100 V/V; 50 V/V

xD3.4 (a) Neglecting r_{o1} and the body effect, show that the voltage gain v_o/v_i of the CD–CG amplifier shown earlier in Fig. x3.4(c) is given by

$$\frac{v_o}{v_i} = \frac{IR_L}{V_{OV}}$$

where R_L is a load resistance connected at the output and V_{OV} is the overdrive voltage at which each of Q_1 and Q_2 is operating.

(b) For $I = 0.1$ mA and $R_L = 20$ kΩ, find W/L for each of Q_1 and Q_2 to obtain a gain of 10 V/V. Assume $k'_n = 200\ \mu\text{A/V}_2$.

Ans. (b) $W/L = 25$