ANALYSIS AND DESIGN OF ANALOG INTEGRATED CIRCUITS

SECOND EDITION

PAUL R. GRAY

ROBERT G. MEYER

University of California, Berkeley

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EXAMPLE

Calculate the input resistance, transconductance, and output resistance of the cascode circuit of Fig. 3.22. Assume that $I_C = 100\ \mu A$, $\beta_0 = 100$, $r_b = 0$, and $\eta = 2 \times 10^{-4}$.
Solution:

$$R_i = r_{\pi 1} = \frac{\beta_0}{g_{m1}} = 26\ k\Omega$$

$$G_m = g_{m1} = \frac{1}{260\ \Omega}$$

$$R_o = \beta_0 r_{o2} = \frac{\beta_{02}}{\eta_2}\left(\frac{1}{g_{m2}}\right) = \left(\frac{100}{2 \times 10^{-4}}\right)(260) = 130\ M\Omega$$

3.4 EMITTER-COUPLED PAIRS

Emitter and source-coupled pairs are perhaps the most widely used two-transistor subcircuits in monolithic analog circuits. The usefulness of this circuit stems from the facts that cascades of emitter-coupled pairs of bipolar transistors or source-coupled pairs of FETs can be directly coupled to one another without interstage coupling capacitors and that the differential input characteristics provided by the emitter-coupled pair are required in many types of analog circuits.[6,7] In this section we consider the properties of emitter-coupled pairs of bipolar transistors in detail. Source-coupled pairs of junction field-effect transistors are considered in the next section. Source-coupled pairs are a key element of MOS analog circuits as well and are considered in Chapter 12.

The simplest form of emitter-coupled pair is shown in Fig. 3.26. The biasing circuit in the common emitter lead can be either a simple resistor, in which case the equivalent current source will be zero, or a transistor current source, in which case the circuit is the Norton equivalent of the transistor.

3.4.1 dc Transfer Characteristic

The large-signal behavior of the emitter-coupled pair is important both because it illustrates the limited range of input voltages over which the circuit behaves linearly and because it illustrates an important aspect of the circuit behavior, that of nonsaturating limiting of analog waveforms. For simplicity in the analysis we assume that the emitter current source output resistance R_{EE} is infinite, that the base resistance of each transistor is negligible, and that the output resistance of each transistor is infinite. These assumptions do not strongly affect the low-frequency, large-signal behavior of the circuit, although the effect on the small-signal behavior can be significant. We first sum the voltages around the loop

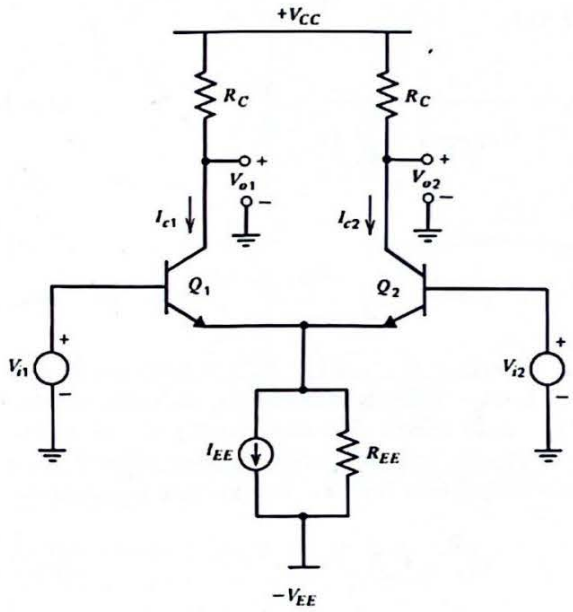

Figure 3.26 Emitter-coupled pair circuit diagram.

consisting of the two voltage sources and the two base-emitter junctions:

$$V_{i1} - V_{be1} + V_{be2} - V_{i2} = 0 \tag{3.57}$$

From the Ebers-Moll equations, assuming $V_{be1}, V_{be2} \gg V_T$,

$$V_{be1} = V_T \ln \frac{I_{c1}}{I_{S1}} \tag{3.58}$$

$$V_{be2} = V_T \ln \frac{I_{c2}}{I_{S2}} \tag{3.59}$$

Combining (3.57), (3.58), and (3.59), and assuming that $I_{S1} = I_{S2}$, we find

$$\frac{I_{c1}}{I_{c2}} = \exp\left(\frac{V_{i1} - V_{i2}}{V_T}\right) = \exp\left(\frac{V_{id}}{V_T}\right) \tag{3.60}$$

Here we have defined V_{id} as the difference between V_{i1} and V_{i2}. Summing currents at the emitters of the transistors,

$$-(I_{e1} + I_{e2}) = I_{EE} = \frac{1}{\alpha_F}(I_{c1} + I_{c2}) \tag{3.61}$$

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Combining Equations 3.60 and 3.61:

$$I_{c1} = \frac{\alpha_F I_{EE}}{1 + \exp\left(-\frac{V_{id}}{V_T}\right)} \tag{3.62}$$

$$I_{c2} = \frac{\alpha_F I_{EE}}{1 + \exp\left(\frac{V_{id}}{V_T}\right)} \tag{3.63}$$

These two currents are shown as a function of V_{id} in Fig. 3.27. Note that for input voltage differences of greater than several hundred millivolts, the collector currents become independent of V_{id}, since all the current is flowing in one of the transistors. Only for difference voltages less than approximately 50 mV does the circuit behave in an approximately linear fashion. We can now compute the output voltages, since

$$V_{o1} = V_{CC} - I_{c1}R_C \tag{3.64}$$

$$V_{o2} = V_{CC} - I_{c2}R_C \tag{3.65}$$

The output signal of interest is often the difference between V_{o1} and V_{o2}, which we term V_{od}.

$$V_{od} = V_{o1} - V_{o2} = \alpha_F I_{EE} R_C \tanh\left(\frac{-V_{id}}{2V_T}\right) \tag{3.66}$$

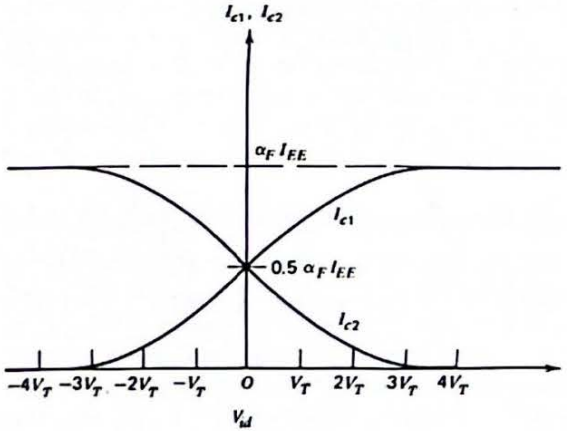

Figure 3.27 Emitter-coupled pair collector currents as a function of differential input voltage.

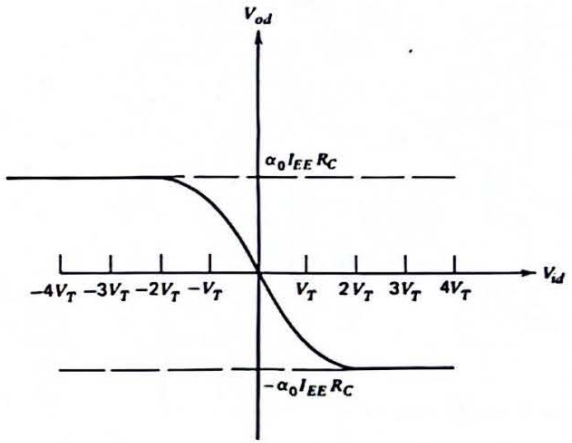

Figure 3.28 Emitter-coupled pair, differential output voltage as a function of differential input voltage.

This function is plotted in Fig. 3.28. Here a significant advantage of differential amplifiers is apparent: When V_{id} is zero, V_{od} is zero, which allows direct coupling of cascaded stages without introducing dc offsets.

3.4.2 Emitter Degeneration

In order to increase the range of input voltage over which the emitter coupled pair behaves approximately as a linear amplifier, emitter-degeneration resistors are frequently included in series with the emitters of the transistors as shown in Fig. 3.29. The analysis of this circuit proceeds in the same manner as before, except the voltage drop across these resistors must be included in the voltage summation corresponding to (3.57). A closed form result like that of (3.66) does not result from the analysis, but the effect of the resistors may be understood intuitively from the examples plotted on Fig. 3.29. For large values of emitter degeneration, the linear range of operation is extended by an amount approximately equal to $I_{EE}R_E$. The voltage gain is reduced by approximately the same factor that the input range is increased. The emitter resistor actually introduces local feedback in the pair and is discussed further in Chapter 8.

3.4.3 Small-Signal Analysis

In many cases, the features of interest in the performance of the emitter-coupled pair are the small-signal properties of the circuit for dc differential input voltages near zero volts. In the following analysis we assume that the dc differential input voltage is zero and calculate the small-signal gain and input resistance for signals that are small enough that they do not violate the assumption of linear operation. We also assume that the Norton equivalent resistance of the emitter biasing

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