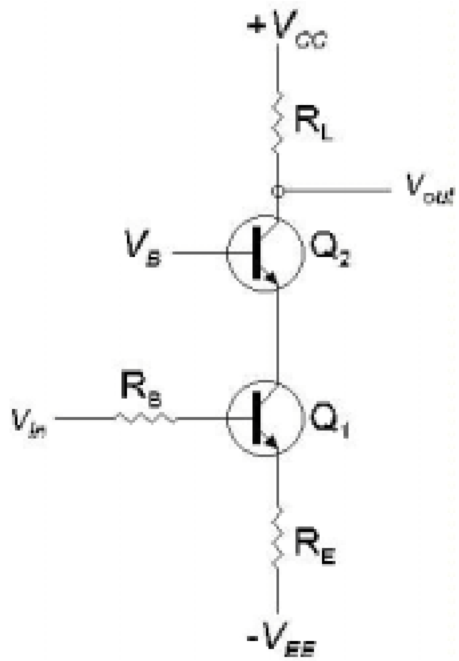
Cascode Amplifiers
by Dennis L. Feucht

Two-transistor combinations, such as the Darlington configuration, provide advantages over single-transistor amplifier stages. Another two-transistor combination in the analog designer's circuit library combines a common-emitter (CE) input configuration with a common-base (CB) output. This article presents the design equations for the basic cascode amplifier and then offers other useful variations. (FETs instead of BJTs can also be used to form cascode amplifiers.) Together, the two transistors overcome some of the performance limitations of either the CE or CB configurations.

Basic Cascode Stage



The basic cascode amplifier consists of an input common-emitter (CE) configuration driving an output common-base (CB), as shown above.

The voltage gain is, by the *transresistance method*, the ratio of the resistance across which the output voltage is developed by the common input-output loop current over the resistance across which the input voltage generates that current, modified by the α current losses in the transistors:

$$A_v = \frac{v_{out}}{v_{in}} = -\alpha_1 \cdot \alpha_2 \cdot \frac{R_L}{R_B/(\beta_1+1)+r_{e1}+R_E}$$

where r_{e1} is Q_1 dynamic emitter resistance. This gain is identical for a CE amplifier except for the additional α_2 loss of Q_2. The advantage of the cascode is that when the output resistance, r_o, of Q_2 is included, the CB incremental output resistance is higher than for the CE. For a bipolar junction transistor (BJT), this may be insignificant at low frequencies. The CB isolates the collector-base capacitance, C_{bc} (or C_μ of the hybrid-π

BJT model), from the input by returning it to a dynamic ground at V_B. At the output, R_L is shunted by C_{bc} only, without a Miller-effect multiplier. The Q_1 collector voltage is also nearly constant and C_{bc} of Q_1 appears from the input with essentially no Miller effect. The C_{bc} of the CE has, in the cascode, been isolated from the output and the Miller effect eliminated. This is its primary advantage and is why it is used in fast amplifiers and RF stages.

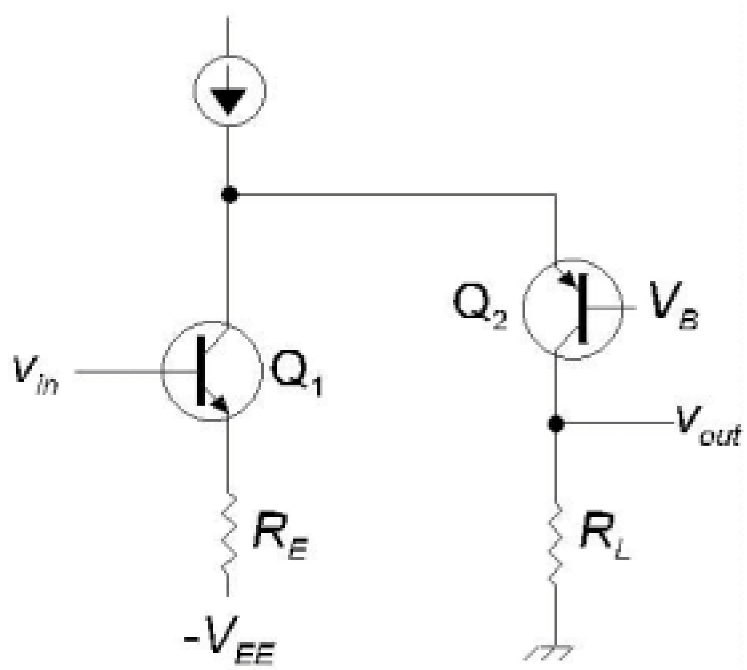
Another advantage of the cascode over a CE is that the right-half-plane zero that causes preshoot in a step response is also eliminated. In the CE configuration alone, C_{bc} provides a parallel, passive path from input to output. When a step is applied as v_{in}, it is coupled to the output node of the CE collector uninverted and precedes the amplified and inverted step as *preshoot*; but not for the cascode. Consequently, the step response of the cascode is not only faster, but "cleaner" than the CE alone.

The cascode incremental output resistance is (with infinite r_o) simply R_L, and the incremental input resistance is, using the *β transform*:

$$r_{in} = R_B + (\beta_1 + 1) \cdot (r_{e1} + R_E)$$

The resistance in the emitter branch of the input circuit is referred to the base as $\beta + 1$ times the emitter-side resistance (the β transform), and adds to the base resistance in series with it.

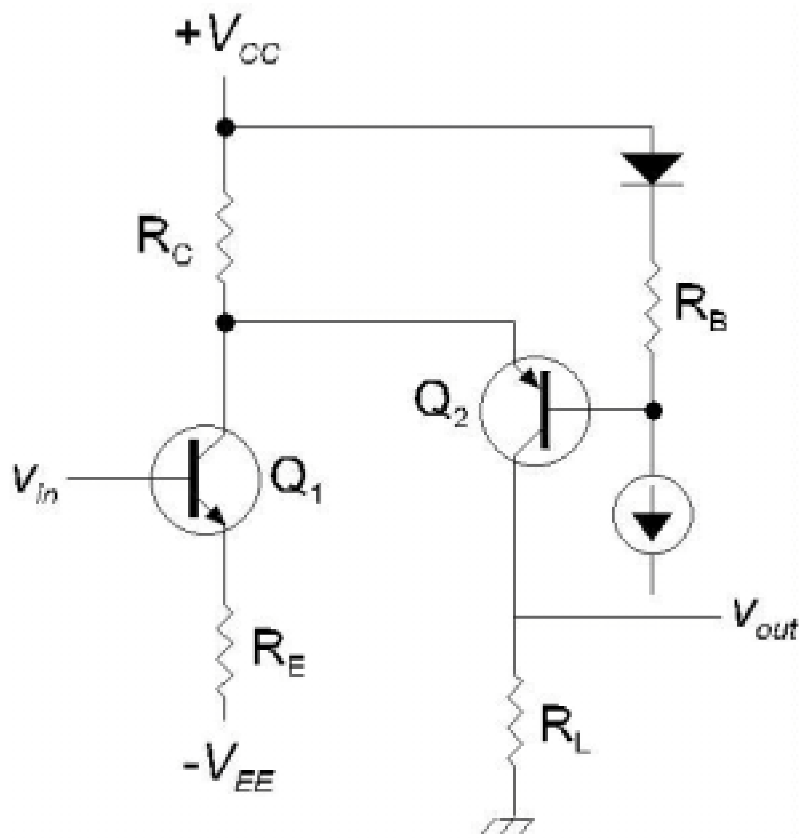
Complementary Cascode Stage



The cascode amplifier also provides voltage translation of the output to a higher static (dc) voltage than the input. This is not always advantageous, however, and can be eliminated by making the CB BJT of opposite polarity to the CE, as shown above.

The output static (dc, quiescent) voltage of the complementary cascode can be the same as the input because the CB BJT inverts the current polarity from the CE. This requires the addition of a bias-current source between the transistors, and the current-source node floats at a junction voltage higher than V_B. Consequently, v_{out} can have the same static voltage as v_{in}, without offset, and the voltage supply used to implement the current source is essentially independent of the rest of the circuit. One implementation is shown below.

By using a current source (consisting of an npn BJT and biasing resistors), a voltage is established across R_B in series with a diode. The diode compensates for the *b-e* junction voltage of Q_2 and tracks it to a first order. Then the voltage drop across R_B is applied by Q_2 to R_C. This establishes the static (bias) current shared by Q_1 and Q_2. For design, the static current of Q_1 is set by V_{IN}, $-V_{EE}$, V_{BE1}, and R_E. Then the bias current of Q_2 is the difference between the Q_1 current and that of R_C. The Q_2 static current also sets the static output voltage across R_L. If v_{out} should be zero volts with no input applied, then a second resistor from the output node must be returned to $-V_{EE}$ so that the Thévenin equivalent of the two resistors results in the desired load resistance and equivalent supply voltage.



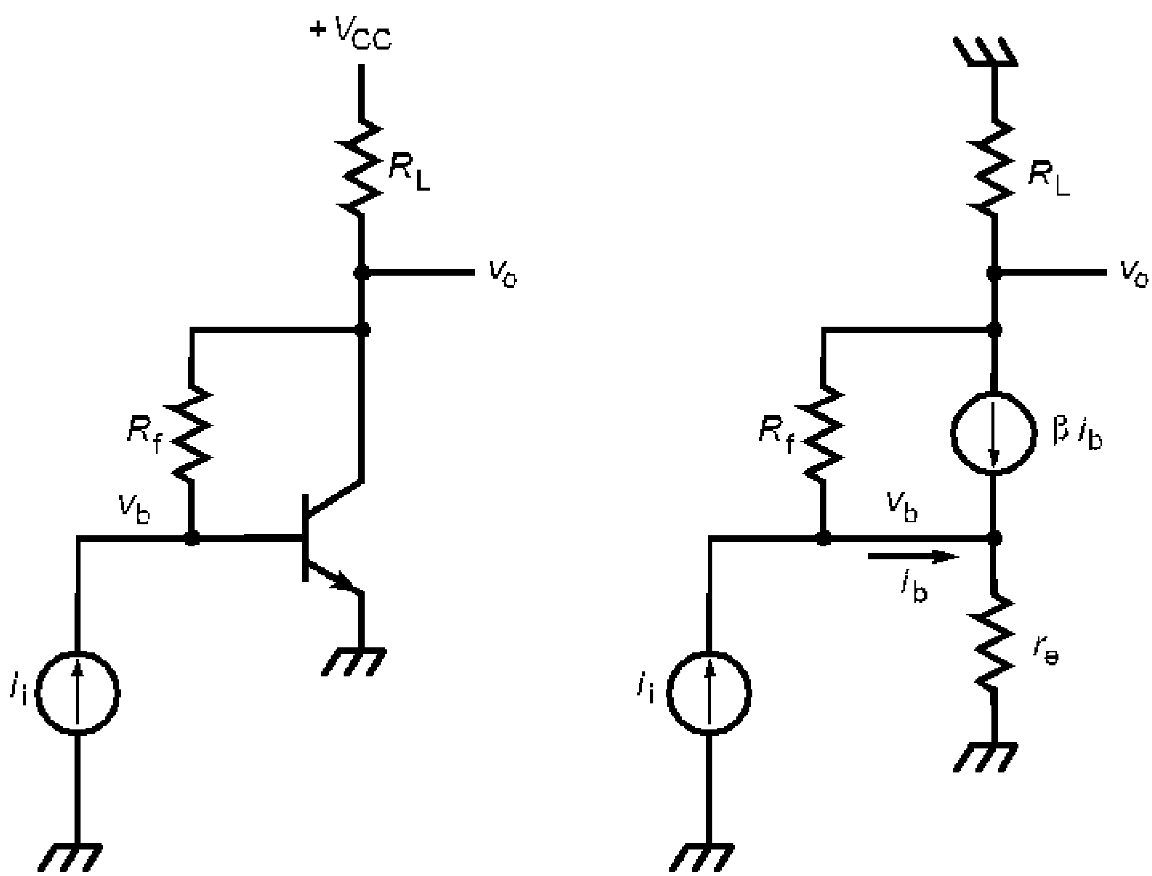
If current biasing is set so that both transistors operate statically at maximum power dissipation then, with a change in input voltage, each will move away from the maximum-power point of operation by approximately the same amount and the resulting thermal distortions will tend to cancel.

A design benefit of the complementary cascode is that the Q_1 collector node can float, along with the base-emitter circuit of Q_2, at some arbitrarily high voltage, as long as the transistors are rated for it. This amplifier allows op amps or other input sources with low supply voltages to drive the complementary cascode as a high-voltage amplifier. In other words, the output voltage range can far exceed the range of v_{in} and is not limited by it. As given, the cascode actively drives in the positive-voltage direction from Q_2. (The "10 A Pulse Amplifier" e-booklet at http://www.innovatia.com presents such an amplifier design in detail.)

A differential complementary cascode amplifier, with common (single-node) load resistance at the output can provide a bipolar voltage range. This approach was taken in design of the Tektronix PG508 pulse generator output amplifier, where the complementary-cascode output drives a bipolar emitter-follower to provide output-current capability.

Shunt-Feedback Cascode Stage

Finally, a variation on the cascode combines it with the shunt-feedback amplifier. The basic shunt-feedback circuit is shown below (left), and with BJT T model (right).



This amplifier will not be explained in detail here. (It is explained in more detail in *Analog Circuit Design*, available from http://www.innovatia.com) It is a transresistance (current in, voltage out) amplifier, with a transresistance of:

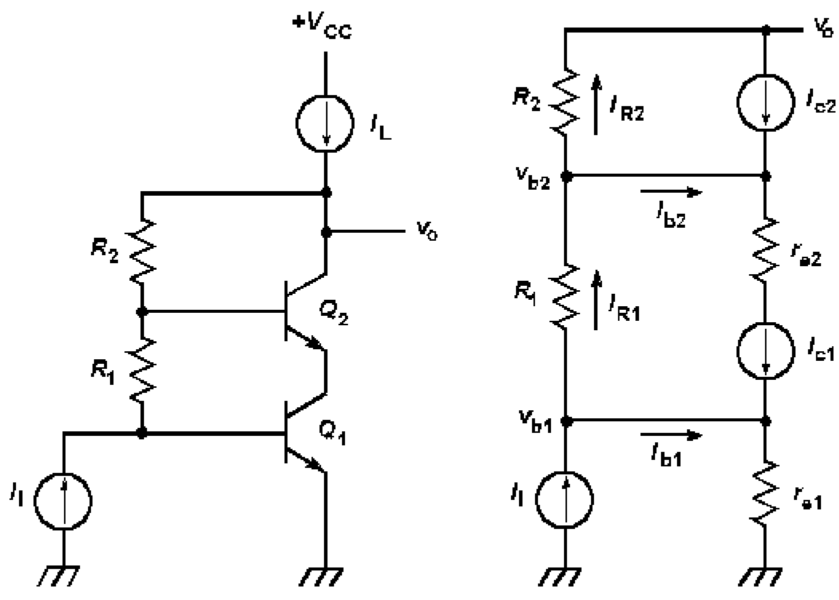
$$\frac{v_o}{i_i} = -\alpha \cdot R_f + r_e \text{ , } R_L \to \infty$$

if R_L approaches being a current source (is large relative to R_f). For R_f>> r_e and α ≈ 1, the transresistance is approximately R_f. The shunt-feedback amplifier can also be used for high-speed applications. (It has an output impedance equivalent to that of an emitter-follower.) When combined with the cascode, the resulting amplifier - the shunt-feedback cascode - is shown below (a) with incremental (small-signal) model (b).

The transresistance of the shunt-feedback cascode amplifier is:

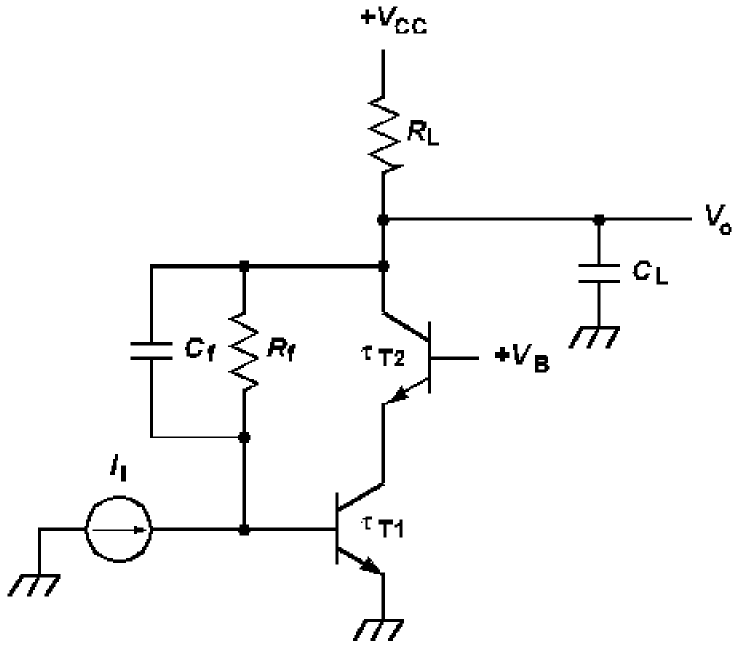
$$\frac{v_{out}}{i_{in}} = -\alpha_1 \cdot R_1 - \alpha_1 \cdot \alpha_2 \cdot R_2 + r_{e1}$$

R_1 in series with R_2 is basically R_f. Because the current through R_2 loses both base currents before being returned to the input node, both α_1 and α_2 appear in the second gain term. Unlike the simple shunt-feedback stage, C_{bc} of either BJT does not shunt R_f, and is divided between transistors. The voltage at the base of Q_2 varies, as the midpoint of an R_1, R_2 voltage divider, and Q_2 is not a purely CB configuration. The two feedback resistor values can be chosen to adjust the extent of the Miller effect across the *b-c* junctions of the transistors.

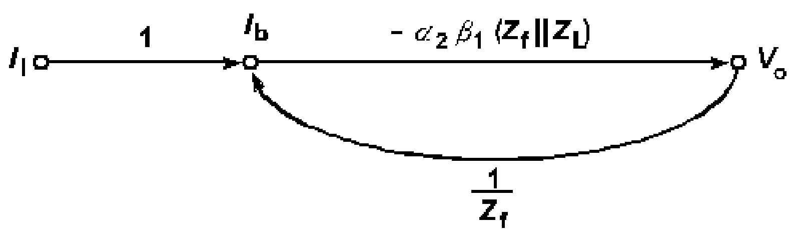


(a) (b)

If speed is not the driving parameter, but voltage is, then this amplifier provides the advantage of dividing the collector voltage across two series BJTs. If $R_1 = R_2$, then each BJT need have only about half the breakdown voltage of a single-BJT amplifier. Again, the cascode shows an advantage for high-voltage applications.



(a)



(b)

Finally, another shunt-feedback cascode variant uses a single feedback resistor, as shown above in (a), along with a flow graph (for feedback analysis) of the dynamic model of the circuit (b). (Z_f is R_f in parallel with C_f and Z_L is R_L in parallel with C_L.) C_f is added to provide an additional parameter for adjusting dynamic response. The transistor gain-bandwidth time constant, ω_T, is related to f_T by:

$$\tau_T = \frac{1}{\omega_T} = \frac{1}{2 \cdot \pi \cdot f_T}$$

For $R_f C_f >> \tau_{T1}, \tau_{T2}$, then the poles of the amplifier response follow a circular *s*-plane locus as τ_{T2} is varied. As Q_2 is made a slower transistor, the closed-loop poles converge, then split off the real axis and follow a circular path to the origin. Variation of τ_{T1}, C_f or C_L follows a vertical locus. As any one of them increases in value, the poles move vertically toward the real axis, then split along the axis, heading for the origin and negative infinity.

The dynamic input impedance of this amplifier is interesting. For infinite R_f and β_1, the input resistance should appear to be infinite but it is not. The *static* input resistance is infinite, but not the *dynamic* resistance. This unusual phenomenon will be the subject of a future article. (Hint: apply a 1-V step to the input and trace through the effects. As the collector node responds to the input step (but not as a step, because of capacitance), then what is the current through C_f? If it is constant, then what impedance does a constant current due to a constant input voltage appear as at the input node?)

Closure

The cascode amplifier, with its variants, is a basic entry in the circuit designer's library of useful circuits. It has advantages for increasing speed and for high-voltage amplifier applications. For more details on it and other circuits that should be in that library, refer to my 4-volume CD-book, *Analog Circuit Design*, available at http://www.innovatia.com

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