Common-Emitter Amplifier

The circuit diagram of a common-emitter (CE) amplifier is shown in Fig. 1 (a). The capacitor C_B is used to couple the input signal to the input port of the amplifier, and C_C is used to couple the amplifier output to the load resistor R_L. We are interested in the bias currents and voltages, mid-band gain, and input and output resistances of the amplifier.

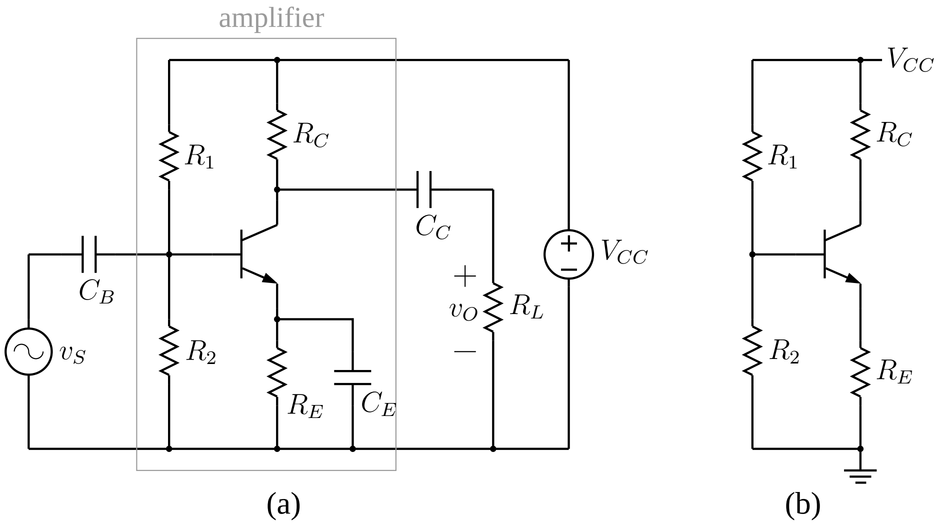

Figure 1: Common-emitter amplifier: (a) circuit diagram, (b) circuit for DC bias calculation.

Bias computation

The term "bias" refers to the DC conditions (currents and voltages) inside the amplifier circuit. The capacitors C_B, C_E, and C_C are replaced with open circuits under DC conditions, and the circuit reduces to that shown in Fig. 1 (b). If the transistor β is assumed to be large ($\beta \rightarrow \infty$), the base current can be neglected, and the R_1-R_2 network is then simply a voltage divider, giving

$$V_B = \frac{R_2}{R_1 + R_2} V_{CC} \,. \tag{1}$$

For the circuit to operate as an amplifier, it is designed such that the BJT operates in its active region, with the B-E junction under forward bias and the B-C junction under reverse bias. The B-E voltage drop ($V_{BE} = V_B - V_E$) is about 0.7 V for a silicon BJT, and that gives us V_E as

$$V_E = V_B - 0.7 = \frac{R_2}{R_1 + R_2} V_{CC} - 0.7 \,. \tag{2}$$

The emitter current I_E is then obtained as $I_E = V_E/R_E$, and $I_C = \dfrac{\beta}{\beta + 1} I_E \approx I_E$ since we have assumed β to be large. The DC collector-emitter voltage is

$$V_{CE} = V_C - V_E = V_{CC} - I_C R_C - I_E R_E \approx V_{CC} - I_C \left(R_C + R_E \right) . \tag{3}$$

The above procedure gives a good estimate of the DC bias quantities. If the base current I_B is to be taken into account in the bias computation, the Thevenin equivalent circuit shown in Fig. 2 can be used. KVL in the B-E loop gives

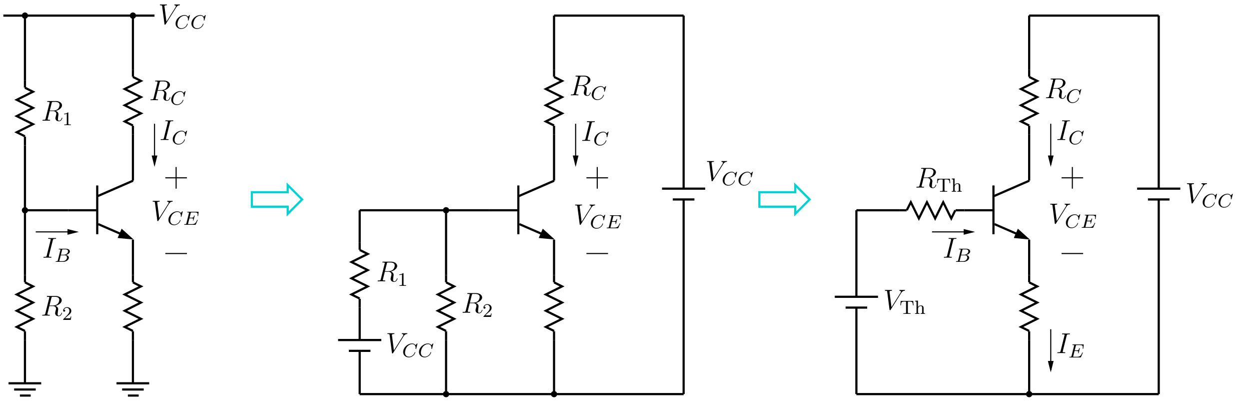

Figure 2: Bias computation for the common-emitter amplifier with finite base current.

$$V_{\text{Th}} = I_B R_{\text{Th}} + V_{BE} + (\beta + 1)\, I_B R_E. \tag{4}$$

The collector current I_C is then given by

$$I_C = \beta I_B = \beta \, \frac{V_{\text{Th}} - V_{BE}}{R_{\text{Th}} + (\beta + 1) R_E} \,, \tag{5}$$

where $R_{\text{Th}} = (R_1 \parallel R_2)$, and $V_{\text{Th}} = \dfrac{R_2}{R_1 + R_2} V_{CC}$.

AC representation of an amplifier

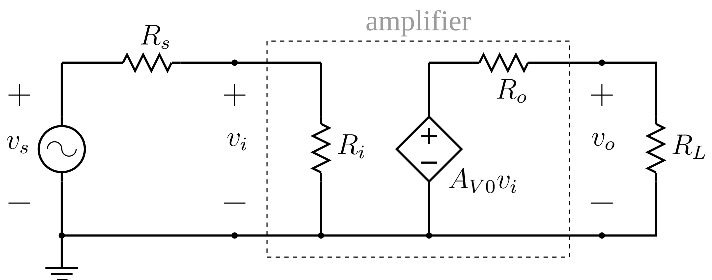

Figure 3: AC representation of an amplifier.

An amplifier can be represented by the AC equivalent circuit enclosed by the box in Fig. 3. Note that the signal source (voltage V_s with a series resistance R_s) and the load resistance R_L are *external* to the amplifier. The coupling capacitors (C_B and C_C) are not shown in the AC circuit since their impedances are negligibly small in the "mid-band" region (see Fig. 4). The amplifier equivalent circuit is characterised by the input resistance R_i (ideally infinite), output resistance R_o (ideally zero), and gain A_{V0}. When $R_L \rightarrow \infty$ (open circuit), the output voltage is $v_o = A_{V0} \times v_i$ (since the current through R_o is zero in that case). With a finite R_L, the gain is lower because of the voltage drop across R_o.

Our goal in this experiment is to measure A_{V0}, R_i, and R_o of the CE amplifier and compare the experimental values with the theoretically expected values given in the following.

Mid-band gain (A_{V0})

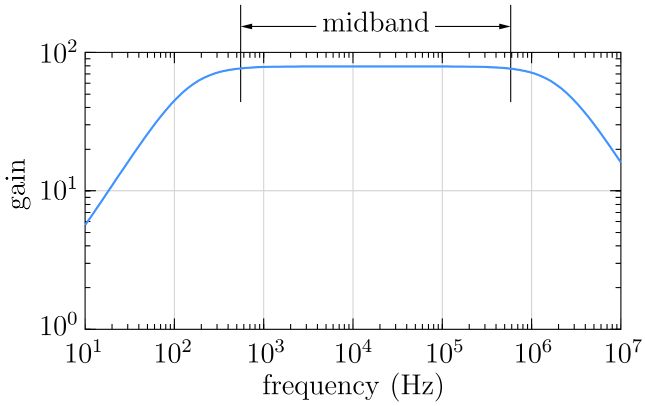

Figure 4: Frequency response of a common-emitter amplifier (representative plot).

The term “mid-band” refers to the frequency region in which the amplifier gain is constant (see Fig. 4). In this region, the impedances due to the coupling capacitors (C_B and C_C) and of the bypass capacitor C_E are negligibly small (i.e., they can be replaced with short circuits), and the impedances due to the BJT device capacitances are very large compared to the other components in the circuit (i.e., they can be replaced with open circuits). With these simplifications, the small-signal (AC) equivalent circuit of the CE amplifier shown in Fig. 5 (a) reduces to the circuit of Fig. 5 (b).

The BJT small-signal equivalent circuit (consisting of the resistances r_π and r_o, and the dependent current source) used in Fig. 5 is valid only if the time-varying B-E voltage v_{be} is much smaller than $V_T = kT/q$, the thermal voltage which is about 25 mV at room temperature. The parameters r_π and g_m depend on the bias current I_C as

$$g_m = \frac{I_C}{V_T}\,, \qquad r_\pi = \frac{\beta}{g_m}\,. \tag{6}$$

Since $v_{be} = v_s$ (see Fig. 5 (b)), we get

$$v_o = (R_C \parallel R_L \parallel r_o) \times (-g_m v_{be}) \quad \rightarrow \quad A_{VL} \equiv \frac{v_o}{v_s} = -g_m(R_C \parallel R_L) = -\,\frac{\beta(R_C \parallel R_L)}{r_\pi}\,, \tag{7}$$

if the output resistance r_o of the BJT is large. The open-circuit gain A_{V0} of the amplifier is given by

$$A_{VO} \equiv \left.\frac{v_o}{v_s}\right|_{R_L\rightarrow\infty} = -g_m(R_C \parallel R_L)|_{R_L\rightarrow\infty} = -g_m R_C = -\,\frac{\beta R_C}{r_\pi}\,. \tag{8}$$

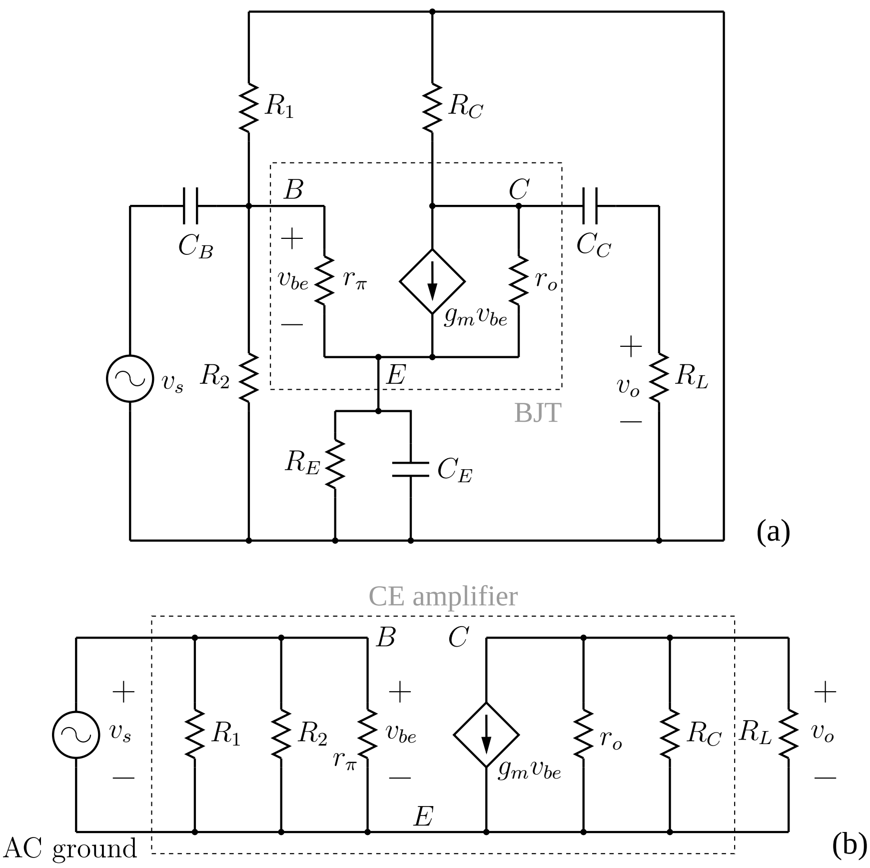

Figure 5: (a) Small-signal equivalent circuit of a CE amplifier, (b) simplified circuit after replacing the coupling and bypass capacitors with short circuits.

To measure A_{VL} and A_{V0}, we apply a sinusoidal input voltage[1] (v_s in Fig. 1 (a)) and measure v_o with R_L in place and with $R_L \rightarrow \infty$ (i.e., open circuit), respectively.

Input resistance R_i

The input resistance of an amplifier can be found by applying a voltage v_s and measuring by some means the current[2] $i_{\rm in}$ shown in Fig. 6 (a) to obtain $R_i = v_s/i_{\rm in}$. From the AC equivalent circuit of Fig. 5 (b), we can see that the input resistance is

$$R_i = (R_1 \parallel R_2 \parallel r_\pi), \quad \text{where} \quad r_\pi = \frac{\beta}{g_m} = \frac{\beta V_T}{I_C}\,, \tag{9}$$

with I_C being the bias (DC) value of the collector current.

A simple way for experimental measurement of R_i is shown in Fig. 6 (b). We connect the input voltage source to the amplifier[3] through a variable resistance (pot) R_s. Keeping

[1] v_s must be sufficiently small to ensure that the output voltage is purely sinusoidal.

[2] Note that v_s and $i_{\rm in}$ are AC quantities.

[3] The coupling capacitor C_B is not shown explicitly in Fig. 6 (b), but it must be connected so that the bias

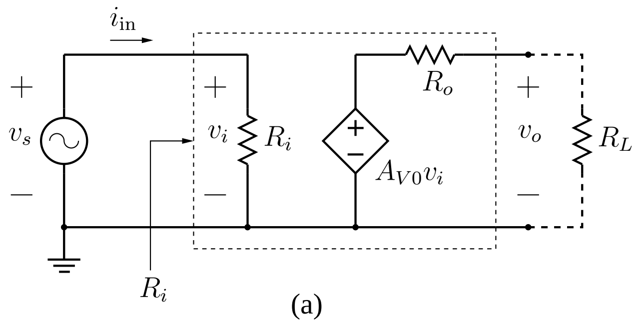

Figure 6: (a) Theoretical interpretation of R_i, (b) practical technique to measure R_i.

v_s constant, we then vary R_s and measure v_o. If v_o' corresponds to $R_s = 0\,\Omega$, then the input resistance R_i is equal to the value of R_s which gives $v_o = v_o'/2$.

Output resistance R_o

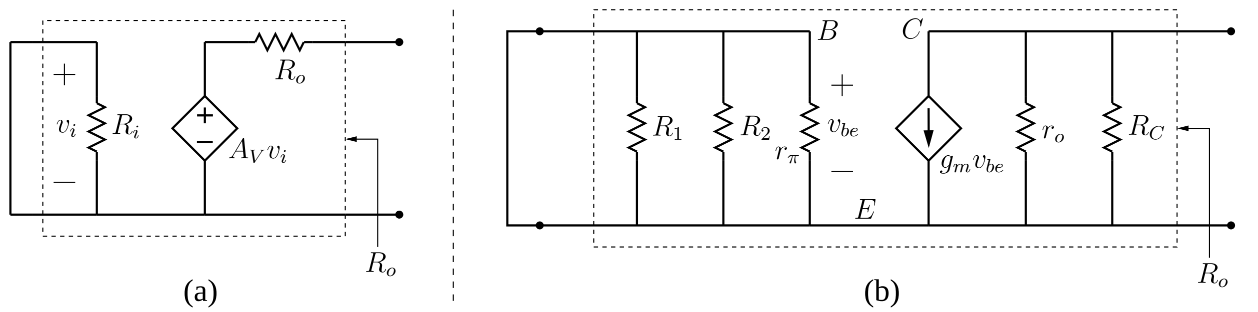

Figure 7: (a) AC equivalent circuit of an amplifier with $v_s = 0$, (b) AC equivalent circuit of the CE amplifier with $v_s = 0$.

If we apply $v_s = 0$ to the generic amplifier shown in Fig. 3, we obtain the circuit shown in Fig. 7 (a). Since $v_i = 0$, the dependent voltage source gets replaced by a short circuit, and looking at the circuit from the output port, we only see R_o. If we do that for the AC equivalent circuit of the CE amplifier (Fig. 7 (b)), we get

$$R_o = r_o \parallel R_C \approx R_C\,, \tag{10}$$

since r_o of a BJT is typically much larger than R_C.

To experimentally measure R_o of the CE amplifier, we can use a procedure similar to that discussed for R_i. We connect a variable load resistance R_L (through a suitably large coupling capacitor) as shown in Fig. 8. Keeping v_s constant, we first measure $v_o \equiv v_o'$ with $R_L \to \infty$ (open circuit). R_o is given by the value of R_L which gives $v_o = v_o'/2$.

values are not disturbed.

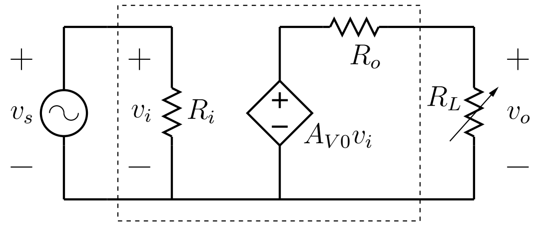

Figure 8: Circuit for experimental measurement of R_o.

Distortion

An amplifier is expected to produce a faithful or undistorted version of the input voltage (except for the amplification factor) at the output. For the CE amplifier, an undistorted output voltage is obtained as long as the small-signal condition $v_{be} \ll V_T$ is satisfied. This is because the BJT small-signal model is valid if the nonlinear terms (degree 2 and higher) are negligibly small compared to the linear term in

$$\exp\left(\frac{v_{be}}{V_T}\right) = 1 + \frac{v_{be}}{V_T} + \frac{1}{2}\left(\frac{v_{be}}{V_T}\right)^2 + \cdots \qquad (11)$$

Since the signal voltage v_s is the same as v_{be} in the CE amplifier (see Fig. 5), we must have $v_s \ll V_T$ to avoid distortion in the output voltage. With $V_T \approx 25\,\text{mV}$ at room temperature, the amplitude of v_s should therefore be restricted to about $5\,\text{mV}$.

Common-emitter amplifier with partial bypass

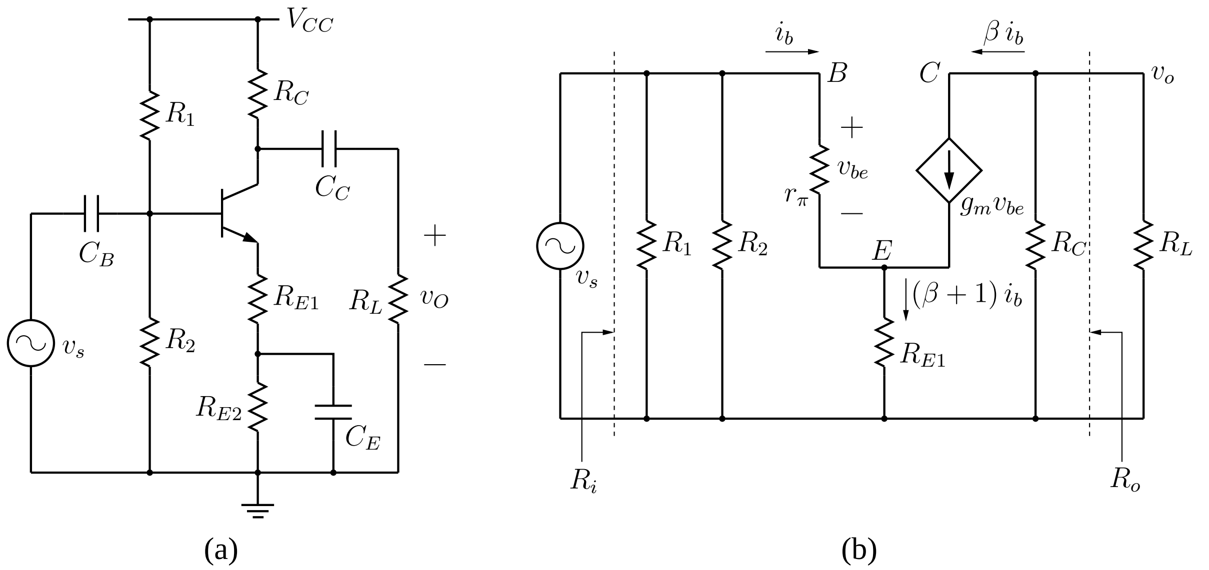

Figure 9: (a) CE amplifier with partially bypassed emitter resistance, (b) AC equivalent circuit.

A CE amplifier with partially bypassed emitter resistance is shown in Fig. 9 (a). The bias point computation of the CE amplifier (Fig. 1) is valid for the partial bypass case if we replace

R_E with $(R_{E1} + R_{E2})$. For computing the AC quantities of interest (gain, R_i, R_o), we use the circuit shown in Fig. 9 (b). Since $i_e = (\beta + 1)\, i_b$, the resistance R_{E1} appears as $(\beta + 1)R_{E1}$ as seen from the base, and we can write

$$v_s = i_b \left[r_\pi + (\beta + 1) R_{E1} \right]. \tag{12}$$

The output voltage is

$$v_o = -\beta\, i_b \times (R_C \parallel R_L), \tag{13}$$

and the gain with load A_{VL} is therefore

$$A_{VL} = \frac{v_o}{v_s} = -\, \frac{\beta\,(R_C \parallel R_L)}{r_\pi + (\beta + 1) R_{E1}}\,. \tag{14}$$

If $(\beta+1)R_{E1} \gg r_\pi$, $A_{VL} \rightarrow -\,\dfrac{(R_C \parallel R_L)}{R_{E1}}$, and the open-circuit gain $A_{V0} = A_{VL}|_{R_L \rightarrow \infty} = -\,\dfrac{R_C}{R_{E1}}$.

Note that the gain of the CE amplifier with partial bypass is less than that of the CE amplifier (compare Eqs. 7 and 14) as we would expect from an amplifier with negative feedback[4].

The input resistance, by inspection of Fig. 9 (b) is

$$R_i = r_\pi + (\beta + 1) R_{E1}, \tag{15}$$

and the output resistance is $R_o \approx R_C$, assuming r_o of the BJT to be large.

An important point to note is that the base-emitter small-signal voltage v_{be} in this case is much smaller than v_s (see Fig. 9 (b)):

$$\frac{v_{be}}{v_s} = \frac{r_\pi i_b}{r_\pi i_b + (\beta + 1) R_{E1} i_b} = \frac{r_\pi}{r_\pi + (\beta + 1) R_{E1}}\,. \tag{16}$$

As a result, the small-signal condition $v_{be} \ll V_T$ means that $v_s \dfrac{r_\pi}{r_\pi + (\beta + 1) R_{E1}} \ll V_T$ or $v_s \ll V_T \left(1 + \dfrac{(\beta + 1) R_{E1}}{r_\pi} \right)$, i.e., a larger v_s can be applied (as compared to the CE amplifier) without causing distortion in the output voltage.

References

1. A.S. Sedra and K.C. Smith and A.N. Chandorkar, *Microelectronic Circuits Theory and Applications*. New Delhi: Oxford University Press, 2009.

2. P.R. Gray and R.G Meyer, *Analysis and Design of Analog Integrated Circuits*. Singapore: John Wiley and Sons, 1995.

3. M.B. Patil, *Basic Electronic Devices and Circuits*. Prentice-Hall India: Delhi, 2013.

[4] The feedback involved in the CE amplifier with partial bypass is of the series-series type. On the output side, the output current i_c causes a voltage drop $R_{E1} i_e \approx R_{E1} i_c$ across R_{E1}, and this voltage drop gets subtracted from the input voltage v_s.