Experiment 282: Small Signal Amplifiers

Reference

1. "Transistor Electronics", Gary E.J. Bold, 5$^{\text{th}}$ Edition, 2000.[1]

Aim

We study three common transistor amplifiers. We examine suitable *dc* bias conditions for linear operation and measure performance parameters. Since the relevant theory is no longer covered in stage II courses, the experiment is presented as a teaching tutorial. Each section commences with a theoretical overview, with reference to fuller treatments in the text above. The emphasis is on the aquisition of *understanding*, not mindless measurement.

Before attempting this experiment, it's wise to have completed Experiment 281 "Diodes and Transistors", unless you have prior familiarity with transistor electronics.

Only a general outline of some procedures is given. Devise and carry out whatever measurements you consider appropriate. Consult demonstrators and the reference for help.

Introduction

In *small-signal* amplifiers the amplitude of all signals are assumed to be small enough for all active devices to operate over *linear* regions of their characteristics. In contrast, large-signal amplifiers (studied in a third year experiment) operate beyond the linear regions.

PART A: Discrete Circuits. Biasing Arrangements.

There are two aspects to designing a transistor amplifier.

- The *dc* biasing currents and voltages in and around the transistor are set. This establishes the desired *quiescent operating point*,
- *ac* signal conditions are set to realize the performance desired.

Figure 1 shows a reliable bias circuit which can be adapted for several different configurations. The +15V power supply (V_{cc}) and four resistors establish the operating point voltages and currents.[2]

The voltages V_b, V_c and V_e are measured with the digital multimeter or oscilloscope, with respect to ground. The *dc* bias currents are deduced using

$$\begin{aligned} I_c &= \frac{V_{cc} - V_c}{R_c} \\ I_e &= \frac{V_e}{R_e} \\ I_b &= \frac{V_{cc} - V_b}{R_2} - \frac{V_b}{R_1} \end{aligned}$$

The last equation is inaccurate unless values of R_1 and R_2 are exactly known, since I_b is small (typically 20 - 100 μA), and resistor values are only nominal, typically correct to within ±5%.

[1] Obtainable from the Physics Office, 6$^{\text{th}}$ floor, for $10

[2] Transistor Electronics, pp. 53 – 55

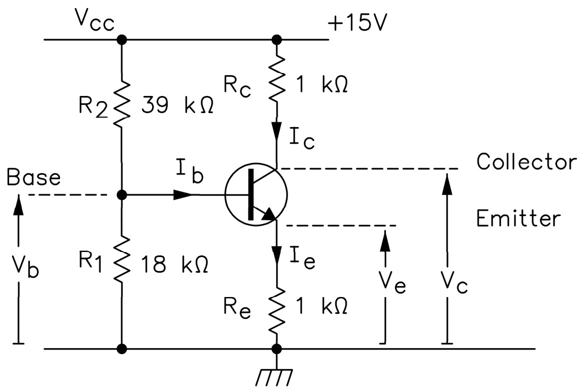

Figure 1: Biasing components for the *npn* transistor.

Connecting one of the three transistor terminals (emitter, base or collector) to ground using large capacitors gives the three basic amplifier configurations: common-emitter, common-base, and common-collector (emitter follower). Since the capacitors "ground" the terminals only for the signal voltages, the *dc* bias conditions remain unchanged.

Common-Emitter Amplifier

figure 2(a) shows the most common transistor amplifier, used in many low-frequency applications (audio amplifiers for example). Conventionally, *dc* and *ac* voltages are designated with upper and lower case letters respectively.

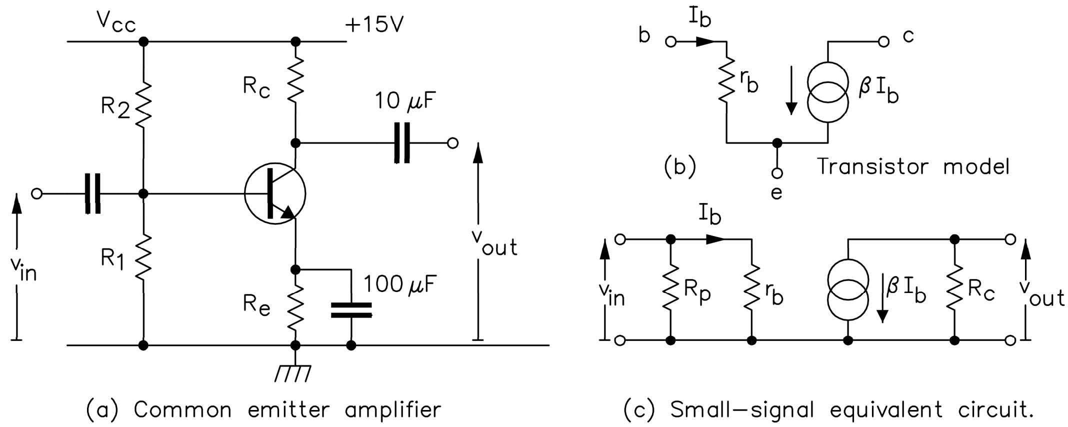

Figure 2: (a) Common emitter amplifier. (b) Transistor small-signal equivalent circuit. (c) Amplifier small-signal *ac* circuit.

A useful expression for the *voltage gain*, $A_v = v_{out}/v_{in}$ results from

- assuming that at *signal* frequencies, all capacitors are short circuits, and the power supply has zero *ac* impedance so that the +15V line can be connected to ground,
- assuming the simplified small-signal transistor equivalent circuit of figure 2(b).

The small-signal circuit of figure 2(c) results, where β is the common-emitter current amplification factor (50 - 600) and r_b is the base-emitter dynamic resistance. We see that

$$
\begin{aligned}
v_{out} &= -\beta i_b R_c = -\beta \frac{v_{in}}{r_b} R_c \\
\text{so } A_v &= \frac{v_{out}}{v_{in}} = -\frac{\beta R_c}{r_b} \\
\text{but } r_b &\approx \frac{\beta}{40 I_c} \qquad \text{at room temperature} \\
A_v &\approx -40 R_c I_c
\end{aligned}
$$

This seems a surprising result, since it doesn't depend on β! The reason is the β dependence of r_b.

The input impedance however, *is* transistor dependent.

$$
\begin{aligned}
r_{in} &= r_b // R_p \approx \frac{\beta}{40 I_c} // R_p \\
\text{where } R_p &= R_1 // R_2
\end{aligned}
$$

The output impedance, $r_{out} = R_c$, since the impedance of an ideal current source is infinite.

Procedure

A schematic of the circuit board provided is shown in Appendix A.

(1) Set up the circuit of figure 2(a). Note that $R_c = R_e = 1\text{k}\Omega$.

(2) Determine and note the bias (dc) voltages and currents V_b, V_c, V_e, I_c and I_e.

(3) Set the signal generator to produce a sine-wave signal at a frequency of 1 kHz. Use $v_{in} \sim 10$ mV to avoid overloading. Determine and note the voltage gain, A_v. Compare this with the theoretical value given above - it should be within $\pm 50\%$. Confirm that the output signal is *inverted*.

(4) Now set the signal generator to produce a triangle-wave signal at a frequency of 1 kHz. This is a better waveform for investigating *linearity* (you can see if the line segments are straight).

- Note that although the input waveform is undistorted, the output waveform is *not*. This is a consequence of the coupling capacitors and the emitter bypass capacitor changing the frequency response of the amplifier.
- Set the signal generator amplitude to give an output waveform amplitude of about 8V peak-to-peak. Sketch and label the input and (distorted) output waveforms.

(5) Return to a 1 kHz sine-wave input signal. Measure and note the input and output ac impedances. See appendix B for methods. Several different values of R_g and R_L are provided. Choose values that give the most accurate estimates. Compare these with the theoretical values given above.

(6) Still using the sine-wave signal, connect, in turn, the 3 capacitors provided (1, 10 and 100 nF) across the output of the amplifier.

- Vary the frequency of the signal generator and note the decrease in gain at higher frequencies.
- Determine and note the frequencies at which the gain has decreased by 3 dB from the gain at 1 kHz (the "upper 3dB frequencies"). Compare these with theoretical values. (Hint: Derive expressions for them by considering an RC low-pass transfer function consisting of the output resistance and the capacitor in use. Assume that $\beta = 500$).

(7) Determine and plot the relative frequency response of the amplifier from 10 Hz to 1 MHz, with the 10 nF capacitor across the amplifier output. A reasonable procedure is to:

- Initially, set the output voltage at some convenient value (1 V *peak-to-peak* is fine) with a 1 kHz sine wave input.
- Keep the input signal amplitude constant. Vary its frequency over the range specified. Measure its amplitude as it changes.
- Plot relative gain in dB (vertically) against frequency on 5 cycle log-linear paper. Normalize so that the gain at 1 kHz is 0 dB. This is called a *Bode plot*.

Observe that the response *rolls off* at both low and high frequencies.

- The low-frequency roll-off is caused by the coupling capacitors and the emitter bypass capacitor.
- The high-frequency roll-off is caused by the 10 nF capacitive load.

Since wiring and transistor junction shunt capacitance is unavoidable in practical circuits, *all* such amplifiers show such frequency effects. To operate at higher frequencies, parallel tuned resonant circuits are used in place of R_c[3]. The shunt capacitance can then be incorporated into the resonant circuit.

Common-Collector or Emitter Follower Circuit

See figure 3. Here, the *collector* is the common terminal for both input and output. This is achieved with the 10 μF capacitor across R_c to short-circuit it for *ac* signals. In practice, the collector of the transistor would be connected directly to V_{cc}.

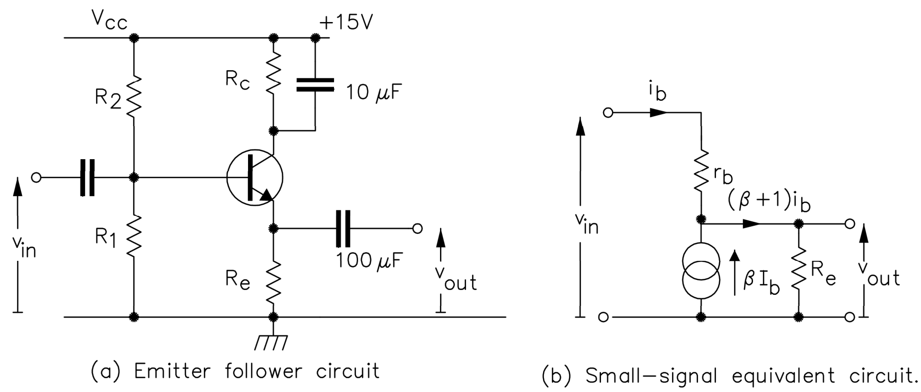

Figure 3: Emitter follower

The base of the transistor is the input and its *emitter* is the output.

Since the base-emitter diode junction is forward-biased, the voltage across it will be almost constant (about 0.7 volt). The emitter voltage thus "follows" the base voltage, hence the name. The voltage gain is therefore, to a good approximaton, unity. In fact, it is very slightly less than unity, since the base-emitter voltage must increase slightly as v_b increases.

Using the small-signal equivalent circuit of figure 3 (b), it can be shown that[4]

$$A_v = \frac{1}{1+\dfrac{r_b}{R_e(\beta+1)}} \qquad \text{(voltage gain)}$$

$$r_{in} = R_1//R_2//(r_b+(\beta+1)\,R_e) \qquad \text{(input impedance, resistive)}$$

$$r_{out} = \frac{r_b}{(\beta+1)}//R_e \qquad \text{(output impedance, resistive)}$$

$$r_{out} \approx \frac{1}{40I_c}$$

[3]Transistor Electronics, pp. 92 – 97
[4]*Transistor Electronics*, pp. 61 – 63

An "amplifier" having a voltage gain less than one might not seem useful. However, it is *very* useful, as a *buffer* or *isolating* stage, since its input impedance is much *higher* than that of a common-emitter amplifier, and its output impedance is much *lower*.

Procedure

Where theoretical calculations are required, assume that $\beta = 500$, and estimate r_b using $r_b = \frac{\beta}{40 I_c}$.

(8) Set up the circuit of figure 3(a). Use $R_c = R_e = 1\text{k}\Omega$.

(9) Determine and note the bias (dc) voltages and currents V_b, V_e and I_e.

(10) Set the signal generator to produce a triangular-wave signal at a frequency of 1 kHz. Determine and note

- the voltage gain, A_v. Compare this with the theoretical value given above.
- The range of input and output signal amplitudes over which operation is linear.
- The input and output impedances, r_{in} and r_{out}. Compare these with the theoretical values given above.

(11) Connect, in turn the three capacitors provided across the amplifier output. Determine and note *where possible* the upper 3-dB roll-off frequencies. Note that these are *much higher* than for the common-emitter amplifier. We have traded *gain* for *bandwidth*.

Split-Load Amplifier

This can be considered as a combination of common-emitter and emitter follower stages.[5] See figure 4.

Two outputs are available, from the collector and the emitter.

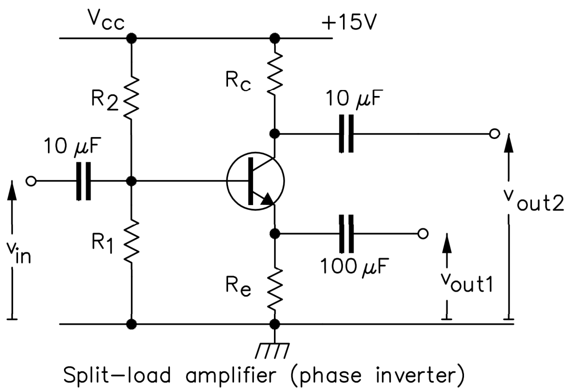

Figure 4: Split load amplifier

This amplifier behaves, to a first approximation, like an emitter-follower with a second load resistance in the collector circuit. The input impedance is *high*, similar to an emitter follower. The collector output impedance is approximately R_c, as for the common-emitter stage. The emitter output impedance is *low*, approximately that of an emitter follower.

Almost exactly the same current flows through both R_c and R_e. It is readily shown that the voltage gains at emitter and collector outputs, A_{ve} and A_{vc} respectively, are

[5] *Transistor Electronics*, pp. 63 - 64

$$
\begin{aligned}
A_{ve} &\approx 1 \\
A_{vc} &\approx -\frac{R_c}{R_e}
\end{aligned}
$$

If $R_c = R_e$, as here, the two outputs are both nearly equal in amplitude to the input amplitude, and in *antiphase*. This circuit was almost invariably used to drive *push-pull* power amplifiers in former times. With the advent of modern *totem-pole* output stages[6], it has become rarer.

Procedure

(12) Using a triangular 1 kHz waveform, observe both output voltages simultaneously, and sketch their form on the same graph.

(13) Measure and note A_{ve} and A_{vc}.

(14) Make appropriate measurements to convince yourself that the output impedances, and frequency responses at emitter and collector are about what you would expect. Briefly describe what you did, and what you observed.

List of Equipment

1. 1 x Hitachi Oscilloscope Model V212 or V552
2. 1 x Wavetek VCG Generator Model 131A
3. 1 x Fluke Model 77 Digital Multimeter
4. 2 x Circuit boards
5. 1 x Circuit-board holder
6. 3 x Coax leads with BNC connectors
7. 2 x Twisted-wire leads with banana plugs.

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[6] Transistor Electronics, pp. 90 – 91

APPENDIX A

Layout of Circuit Board

The discrete amplifier circuit board (5), has two sets of resistors. The left-hand set is used as series input resistances, the right-hand set as load resistances. In addition a selection of load capacitors (1 nF, 10 nF, 100 nF) is provided for determining the effect of load capacitance upon the voltage gain.

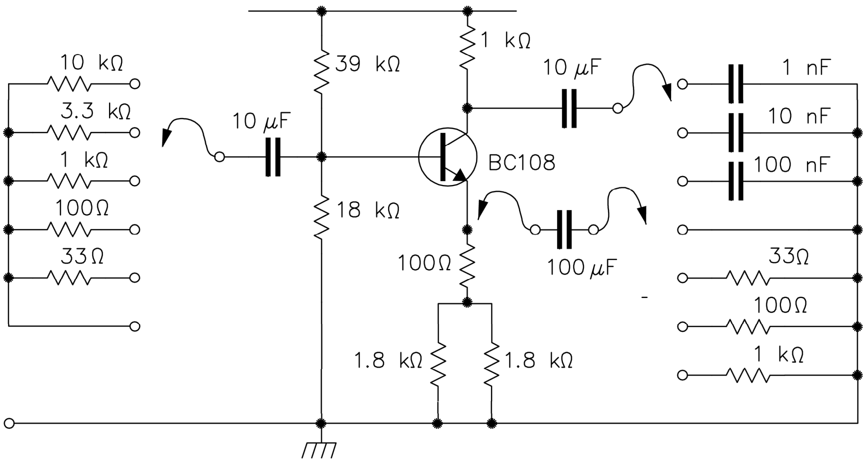


Figure 5: Transistor Amplifier Circuit board

APPENDIX B

Voltage Gain and Impedance Measurements

Any three-terminal, small-signal linear amplifier may be represented by the equivalent circuit of Figure 6.

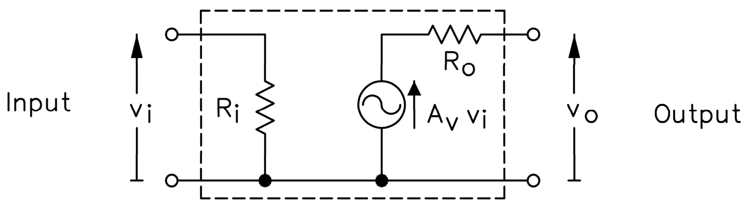
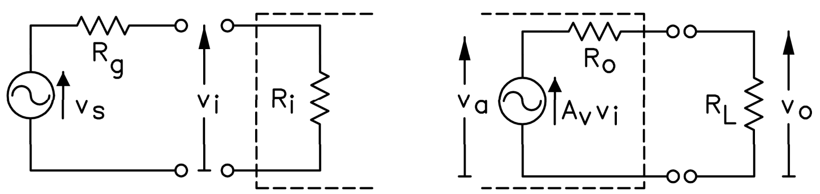


Figure 6: Equivalent circuit of a linear amplifier



(a) Input impedance (b) Output impedance

Figure 7: Measuring input and output impedance

$$\begin{aligned} A_v &= \text{the open-circuit voltage gain} \\ R_i &= \text{the input impedance} \\ R_o &= \text{the output impedance} \end{aligned}$$

Here, R_i and R_o are shown as resistive, although this may not be the case at high frequencies. R_i is measured as in fig. 7 (a), where a signal source having a series impedance R_g is connected to the input and adjusted so that operation is in the linear range. Then

$$\begin{aligned} v_i &= v_s \frac{R_i}{R_i + R_g} \\ \text{whence } R_i &= \frac{R_g}{\dfrac{v_s}{v_i} - 1} \end{aligned}$$

The most accurate estimat of R_i results when $R_g \approx R_i$, when $v_i \approx v_s/2$.

The output impedance is measured as in figure 7(b). A suitable input voltage is applied to give an output voltage $A_v v_i = v_a$ say. A load resistance R_L is then connected and the (lower) output voltage v_o is measured. Then

$$\begin{aligned} v_o &= v_a \frac{R_L}{R_L + R_o} \\ \text{whence } R_o &= R_L \left(\frac{v_a}{v_o} - 1 \right) \end{aligned}$$

Again, the most accurate estimate results when $v_o \approx v_a/2$.