ECE 255, Discrete-Circuit Amplifiers

31 October 2017

In this lecture, we will continue with the study of transistor amplifiers with the presence of biasing circuits and coupling capacitors in place. We will study them as discrete-circuit amplifiers.

1 Discrete-Circuit Amplifiers

Due to history and tradition, most discrete-circuit amplifiers are BJT's. Also, capacitive coupling is often used in discrete-circuit amplifier to simplify the circuits analysis and designs. They act as DC blockers, but can be approximated as short circuits for AC signals.

1.1 A Common-Source (CS) Amplifier

The circuit to be analyzed here is shown in Figiure 1(a). The bias point (or Q point) which is a DC operating point, is determined by Figure 1(b) where all capacitors are open circuited. The AC small signal model is shown in Figure 1(c) where all capacitors are short circuited.

It is noted that the MOSFET source (S) terminal is grounded for the AC signal because of the large coupling capacitor C_S, and hence, it is also called the **signal ground** or **AC ground**. Thus, C_S is also called the **bypass capacitor** as its impedance is much smaller than that of R_S. The presence of R_S is to stabilize the biasing point. Looking at Figure 1(b), if R_S is not there, since V_{GS} is small, hence, V_G has to be small. Thus, all of the fluctuation of V_G will appear across V_{GS}. However, with R_S present, any fluctuation in V_G will be shared by V_{GS} and the voltage drop across R_S, stabilizing it.

Here, C_{C1} is another **coupling capacitor**, which will be acting approximately like a short circuit to AC signals, but is a DC blocker. The second coupling capacitor C_{C2} is also acting like a short circuit to the AC signal, or the small signal. These give the rationale for the small signal model in Figure 1(c).

Using the AC small-signal model, and the hybrid-π model for MOSFET as shown in Figure 1(c), it is seen that

$$R_{\text{in}} = R_{G1} \parallel R_{G2} \tag{1.1}$$

Printed on November 13, 2017 at 00 : 05: W.C. Chew and Z.H. Chen.

Note that R_{in} can be kept high by making R_{G1} and R_{G2} high, usually in the megaohm range. It is seen that the voltage gain proper (terminal voltage gain) is

$$A_v = -g_m(R_D \parallel R_L \parallel r_o) \tag{1.2}$$

and the overall voltage gain is

$$G_v = -\frac{R_{\text{in}}}{R_{\text{in}} + R_{\text{sig}}} g_m(R_D \parallel R_L \parallel r_o) \tag{1.3}$$

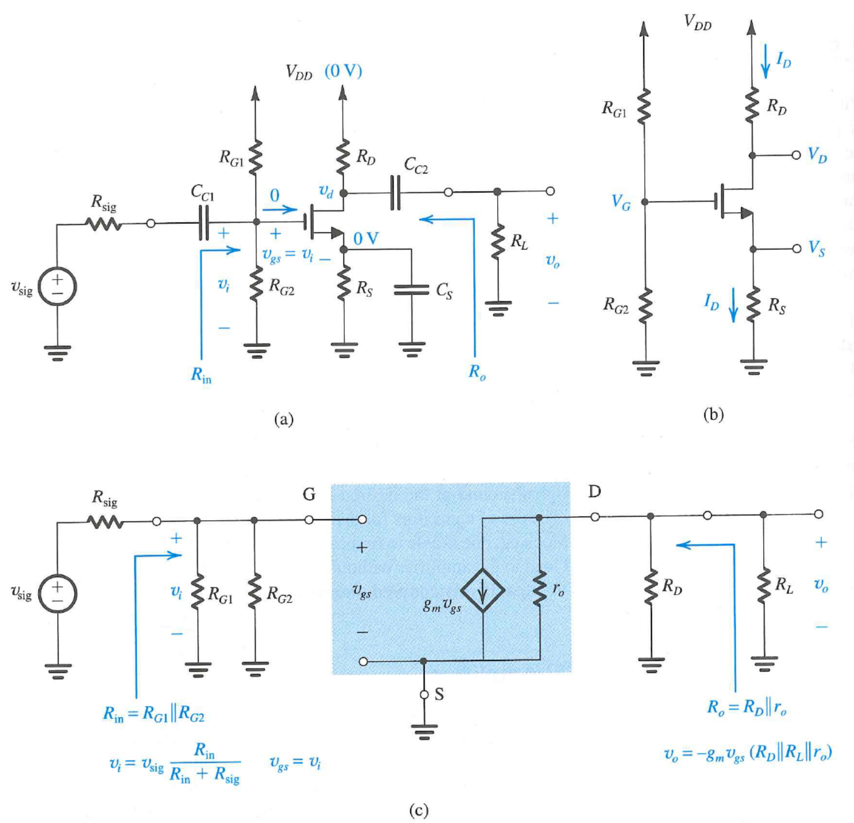

Figure 1: (a) Common-source MOSFET amplifier with the biasing circuit in place. (b) The biasing circuit at DC, where the capacitors are open circuited. (c) AC small-signal equivalent circuit model where the capacitors are assumed to be short circuited (Courtesy of Sedra and Smith).

1.2 A Common-Emitter Amplifier

This is the most commonly used configuration of the BJT amplifiers, as shown in Figure 2(a) with the coupling capacitors C_{C1} and C_{C2}, and the bypass capacitor

C_E in place. These capacitors, to simplify the analysis, are assumed to be open circuited for DC at the bias-point (Q-point) analysis, but are short circuited for the AC small-signal analysis. Again, as in the MOSFET case, R_E is there to stabilize the bias point of the base voltage.

The equivalent small signal model is shown in Figure 2(b). From it, it is seen that

$$R_{\text{in}} = R_{B1} \parallel R_{B2} \parallel r_\pi \tag{1.4}$$

In the above R_{B1} and R_{B2} should be kept large, around tens to hundreds of kilo-ohms, to maintain high input impedance.

The overall voltage gain G_v is then given by

$$G_v = -\frac{R_{\text{in}}}{R_{\text{in}} + R_{\text{sig}}} g_m (R_C \parallel R_L \parallel r_o) \tag{1.5}$$

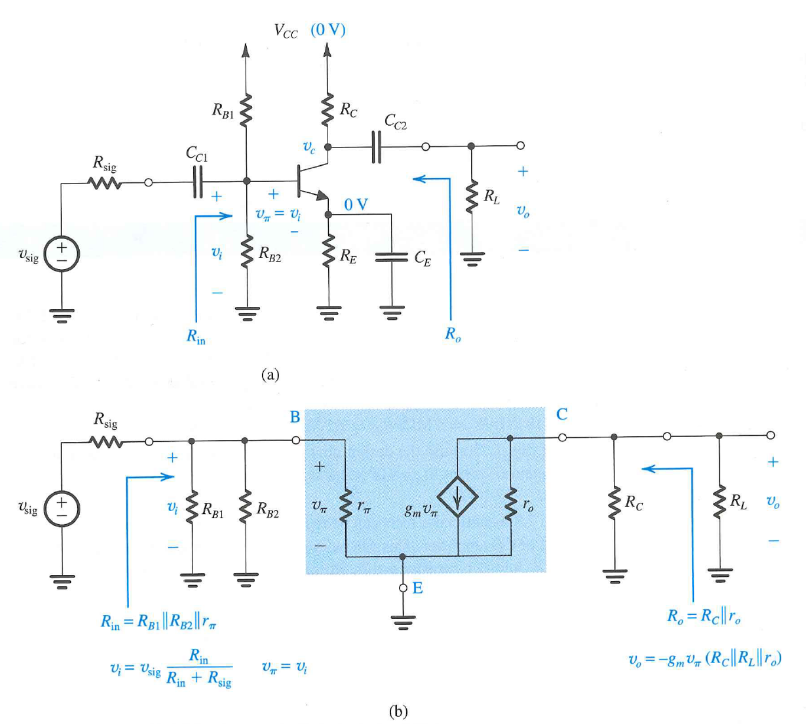

Figure 2: (a) Common-emitter BJT amplifier with the biasing circuit in place. (b) AC small signal equivalent circuit model where the capacitors are assumed to be short circuited (Courtesy of Sedra and Smith).

2 A Common-Emitter Amplifier with an Emitter Resistance

It is beneficial to add an emitter resistance as shown in Figure 3(a). The AC small-signal T model is shown in Figure 3(b). The input resistance is simply given by

$$R_{\text{in}} = R_{B1} \parallel R_{B2} \parallel (\beta+1)(r_e + R_e) = R_{B1} \parallel R_{B2} \parallel [r_\pi + (\beta+1)R_e] \tag{2.1}$$

since $(\beta+1)r_e = r_\pi$. The overall voltage gain is then

$$G_v = -\frac{R_{\text{in}}}{R_{\text{in}} + R_{\text{sig}}} \times \alpha \frac{\text{Total resistance in collector}}{\text{Total resistance in emitter}} = -\alpha \frac{R_{\text{in}}}{R_{\text{in}} + R_{\text{sig}}} \frac{R_C \parallel R_L}{r_e + R_e} \tag{2.2}$$

$$\approx -\frac{R_{\text{in}}}{R_{\text{in}} + R_{\text{sig}}} g_m \frac{R_C \parallel R_L}{1 + g_m R_e} \tag{2.3}$$

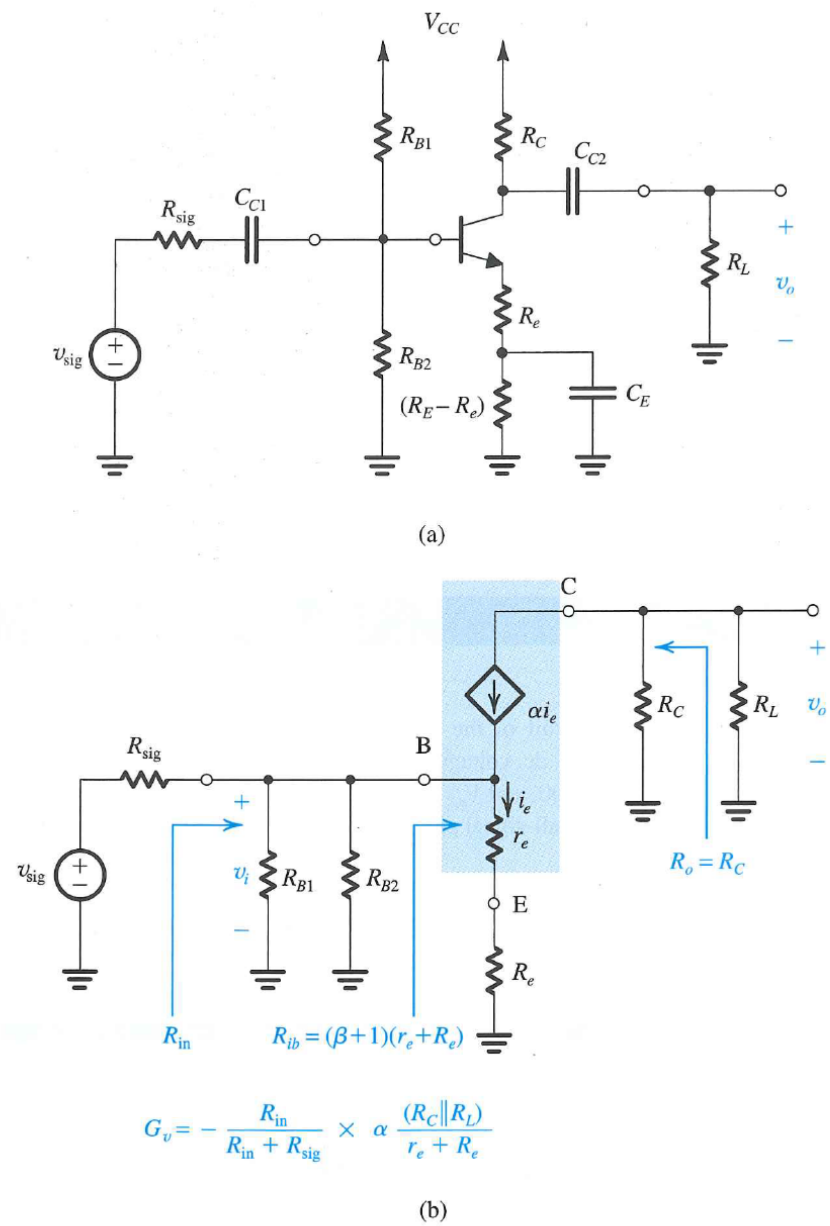

Figure 3: (a) Common-emitter BJT amplifier with emitter resistance, the biasing circuit in place. (b) The AC small-signal equivalent circuit model where the capacitors are assumed to be short circuited (Courtesy of Sedra and Smith).

3 A Common-Base (CB) Amplifier

Figure 4(a) shows a CB amplifier with biasing circuits in place and two DC power supply V_{CC} and $-V_{EE}$. Its AC small-signal equivalent circuit is shown in Figure 4(b).

From the circuit, it is seen that

$$R_{\text{in}} = r_e \parallel R_E \approx r_e \approx 1/g_m \tag{3.1}$$

which is small. The output voltage can be found to be

$$v_o = -\alpha i_e \left(R_C \parallel R_L\right) \tag{3.2}$$

Using the fact that

$$i_e = -\frac{v_i}{r_e} \tag{3.3}$$

the voltage gain proper (terminal voltage gain) is

$$A_v = \frac{v_o}{v_i} = \alpha \frac{R_C \parallel R_L}{r_e} = g_m(R_C \parallel R_L) \tag{3.4}$$

Now using the fact that

$$v_i = v_{\text{sig}} \frac{R_{\text{in}}}{R_{\text{in}} + R_{\text{sig}}} \tag{3.5}$$

then the overall voltage gain is

$$G_v = \alpha \frac{R_{\text{in}}}{R_{\text{in}} + R_{\text{sig}}} \frac{R_C \parallel R_L}{r_e} = \frac{R_{\text{in}}}{R_{\text{in}} + R_{\text{sig}}} g_m(R_C \parallel R_L) \tag{3.6}$$

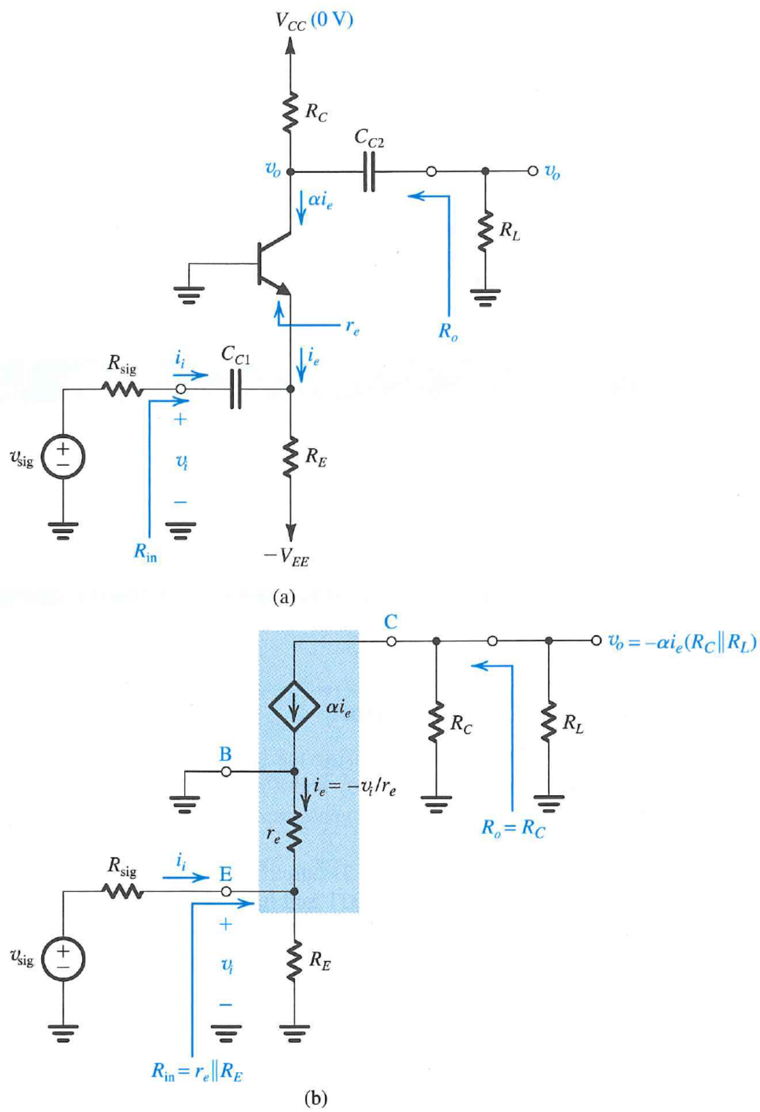

Figure 4: (a) Common-base BJT amplifier with the biasing circuit in place. (b) The AC small signal equivalent circuit model where the capacitors are assumed to be short circuited (Courtesy of Sedra and Smith).

4 An Emitter Follower

The emitter follower, also known as the common-collector (CC) amplifier, is shown in Figure 5(a) with its biasing circuit in place, with two DC voltage source V_{CC} and $-V_{EE}$. The AC small-signal equivalent circuit is shown in Figure 5(b). The DC emitter current I_E is given by

$$I_E = \frac{V_{EE} - V_{BE}}{R_E + R_B/(\beta + 1)} \tag{4.1}$$

The base resistance R_B should be made as large as possible to increase the input impedance of the amplifier, but yet not too large so that I_E is too dependent on β.

The input resistance of the emitter follower is seen to be

$$R_{\text{in}} = R_B \parallel R_{ib} \tag{4.2}$$

where R_{ib}, the input resistance looking into the base, using the resistance-reflection rule, is given by

$$R_{ib} = (\beta + 1) \left[r_e + (R_E \parallel r_o \parallel R_L) \right] \tag{4.3}$$

The voltage gain proper is seen to be

$$A_v = \frac{v_o}{v_i} = \frac{R_E \parallel r_o \parallel R_L}{r_e + (R_E \parallel r_o \parallel R_L)} \approx g_m \frac{R_E \parallel r_o \parallel R_L}{1 + g_m \left(R_E \parallel r_o \parallel R_L \right)} \tag{4.4}$$

Using that

$$\frac{v_i}{v_{\text{sig}}} = \frac{R_{\text{in}}}{R_{\text{in}} + R_{\text{sig}}} \tag{4.5}$$

then the overall voltage gain is

$$G_v = \frac{v_o}{v_{\text{sig}}} = \frac{R_{\text{in}}}{R_{\text{in}} + R_{\text{sig}}} \frac{R_E \parallel r_o \parallel R_L}{r_e + (R_E \parallel r_o \parallel R_L)} = \frac{R_{\text{in}}}{R_{\text{in}} + R_{\text{sig}}} g_m \frac{R_E \parallel r_o \parallel R_L}{1 + g_m \left(R_E \parallel r_o \parallel R_L \right)} \tag{4.6}$$

The output resistance is the Thévenin equivalent resistor when the amplifier is replaced with the Thévenin equivalent circuit. The Thévenin resistance can be found by the test current method by setting $v_{\text{sig}} = 0$,[1]

$$R_{\text{out}} = r_o \parallel R_E \parallel \left[r_e + \frac{R_B \parallel R_{\text{sig}}}{\beta + 1} \right] \tag{4.7}$$

In the above, the inverse reflection formula has been used by dividing the total resistance of the base ($R_B \parallel R_{\text{sig}}$) by $\beta + 1$.

[1] The textbook defines R_{out} to be the Thévenin equivalence for the voltage source v_{sig}, while R_{o} to be the case when the voltage source is v_i.

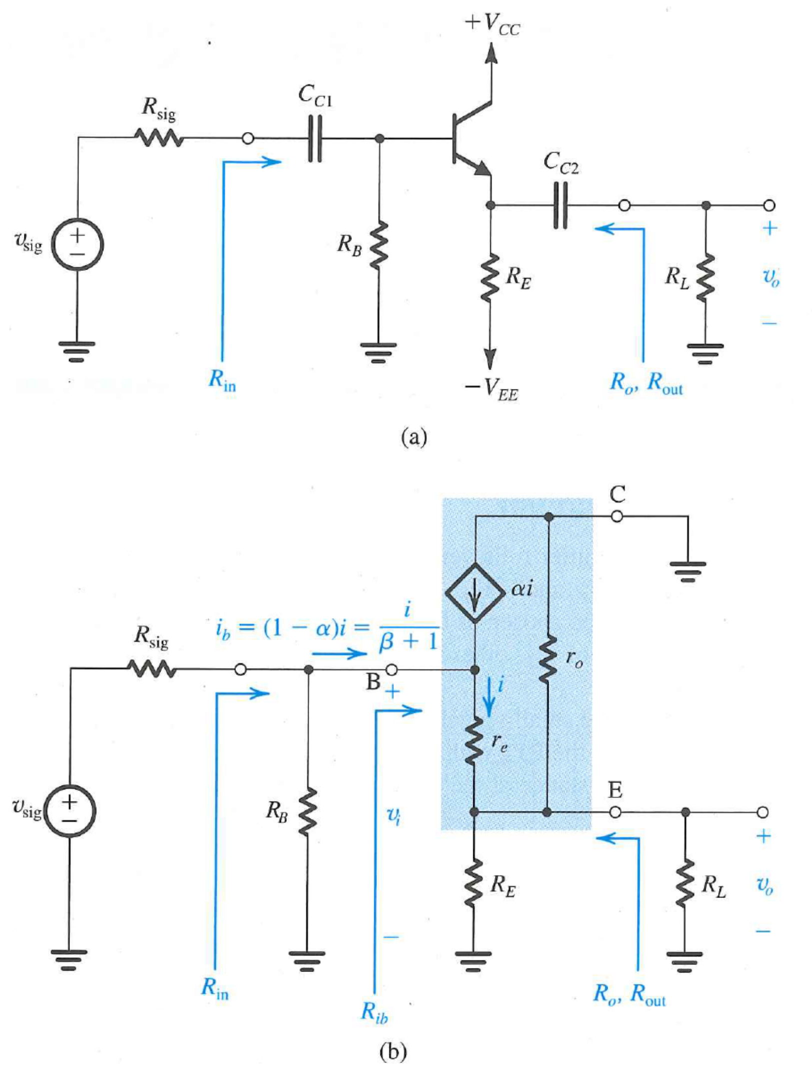

Figure 5: (a) Common-collector BJT amplifier with the biasing circuit in place. (b) Small signal equivalent circuit model for AC signals where the capacitors are assumed to be short circuited (Courtesy of Sedra and Smith).

5 The Amplifier Frequency Response

We have assumed that the gain of the transistor amplifier is a constant, which is not true. Because of the use of the coupling capacitors for simplifying the analysis and designs, these capacitors are not short circuits anymore at a lower frequency. Their non-zero impedances impede the performance of the amplifiers at lower frequencies.

At higher frequencies, two pieces of metal placed close together has parasitic charge coupling giving rise to parasitic capacitances. These parasitic capacitances correspond to charges that store energy in the electric field. A piece of wire carrying a current produces a magnetic field. This gives rise to a parasitic inductor, corresponding to energy stored in the magnetic field.

Hence, at high frequencies, these parasitic effects will cause the equivalent circuit to be invalid. The parasitic capacitances will act like bypass capacitors at high frequencies, while a parasitic inductor will act like a high frequency choke. Therefore, the performance of the amplifier is greatly impeded at high frequencies. Hence, the frequency response of a typical transistor amplifier is as shown in Figure 6. Nevertheless, there is a mid-frequency regime over which the gain of the transistor amplifier is essentially a constant where our approximate analysis is valid.

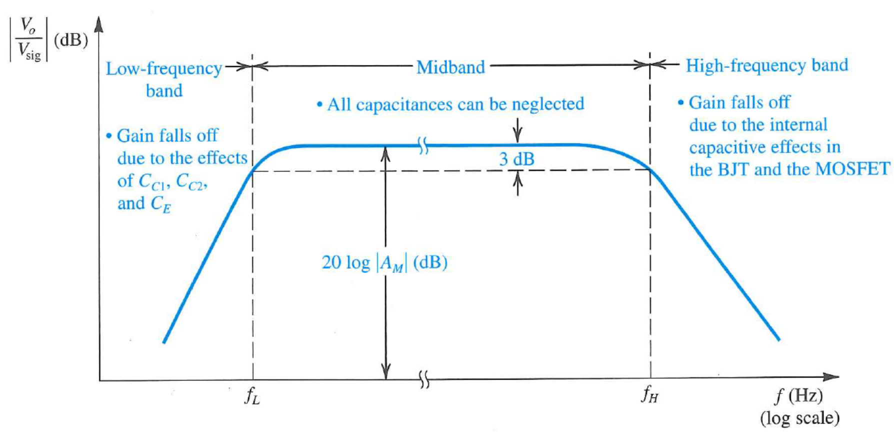

Figure 6: The frequency response of a typical transistor amplifier (Courtesy of Sedra and Smith).

The 3-dB bandwidth of an amplifier is defined as

$$BW = f_H - f_L \tag{5.1}$$

where f_H and f_L are the frequencies at which the gain of the amplifier has dropped below the peak by 3 dB.

A figure of merit for an amplifier is the **gain-bandwidth product** defined as

$$GB = |A_M| BW \tag{5.2}$$

where $|A_M|$ is the magnitude of the gain at midband.