MULTISTAGE AMPLIFIERS

To achieve the desired voltage or current gain and the necessary response \( \Rightarrow \) stages of amplification may be require.

Cascading

\( \Rightarrow \) In cascade \( \Rightarrow \) the output of one stage connected to the input of the next stage.

In midfrequency

\[ R_L = r_\pi \]

BJT

\( \Rightarrow \) The mid-frequency per stage \( \Rightarrow \) voltage gain

\[ A_{VO} = \frac{V_o}{V_{be}} = \frac{-g_m V_{be} R_o}{V_{be}} = -g_m R_o \]
The mid-frequency per stage \( \Rightarrow \) current gain

\[
A_{IO} = \frac{I_o}{I_b} = \frac{V_o/r_{\pi}}{V_{be}/r_{\pi}} = \frac{V_o}{V_{be}} = -g_mR_o = -\frac{\beta}{r_{\pi}}R_o
\]

\( R_o < r_{\pi} \) ** determined in part by \( \Rightarrow r_{\pi} \)

The current gain per stage \( \Rightarrow A_{Io} < \beta \)

In the following Fig.

![Block diagram of amplifiers in cascade.](image)

**Figure 14.18** Block diagram of amplifiers in cascade.

The overall voltage gain \( \downarrow \)

\[
A = \frac{V_4}{V_1} = \frac{V_2}{V_1} \frac{V_3}{V_2} \frac{V_4}{V_3} = A_a A_b A_c
\]

or

\[
\frac{A}{\theta} = A_a A_b A_c / \theta_a + \theta_b + \theta_c
\]

**A \( \neq \theta \) function of frequency**

Similar statement \( \Rightarrow \) the overall current gain
Ch(6) Small-Signal Amplifiers

**Gain in Decibels**

\[
\text{Gain in decibels} = \text{dB} = 10 \log \frac{P_2}{P_1} \quad (14-41)
\]

Since for a given resistance, power is proportional to the square of the voltage,

\[
\text{Gain in decibels} = 10 \log \frac{V_2^2}{V_1^2} = 20 \log \frac{V_2}{V_1} \quad (14-42)
\]

**Ex: 14-7 cancelled**

- The advantage of ⇒ dB ⇒ when response ⇒ plotted in ⇒ dB ⇒ the overall response curves of a multistage amplifier ⇒ obtained by adding the individual response curves

- The response curves of ⇒ two stages \(a\) and \(b\) ⇒ plotted in dB in the following Fig.

![Graph showing frequency response in decibels](image)

**Figure 14.19** Frequency response expressed in decibels.
\[
\frac{A_L}{A_0} = \frac{1}{1 - j\omega_{11}/\omega} \cdot \frac{1}{1 - j\omega_{12}/\omega}
\]
\[
\frac{A_H}{A_0} = \frac{1}{1 + j\omega/\omega_{21}} \cdot \frac{1}{1 + j\omega/\omega_{22}}
\]

From these Eqns.:

for \( f << f_1 \)
\[
\frac{A_L}{A_0} \propto f
\]

for \( f >> f_2 \)
\[
\frac{A_H}{A_0} \propto \frac{1}{f}
\]

In the region where

\[
A = A_0 \left(\frac{f}{f_1}\right)^{\pm 1}
\]

The gain in \( \text{dB} \):

\[
20 \log A = 20 \log A_0 \pm 20 \log \left(\frac{f}{f_1}\right)
\]

OR

10:1 change in frequency (a "decade")
results in a 20-dB change in gain.
These relations with frequency on a log scale ⇒ straight lines with slopes ⇒ 20 dB per decade

The response of ⇒ RC – coupled amplifier ⇒ can be ⇒ approximated by curve \( A_a \)

Second amplifier with better L-F ⇒ approximated by curve \( A_b \)

The overall gain ⇒ of the combination ⇒ the sum of the two curves ⇒ the straight-line approximation ⇒ easily drawn

For single-stage amplifier with two high-frequency breakpoints ⇒ the frequency response ⇒ curve A ⇒ Fig. 14-19

Gain-Bandwidth Product

The bandwidth of any ⇒ amplifier ⇒ is useful design criterion

Audio amplifier needs ⇒ bandwidth of 20 kHz

Video amplifier needs ⇒ bandwidth of 4 MHz
The bandwidth for an untuned amplifier

\[ BW = \omega_2 - \omega_1 \approx \omega_2 \text{ since } \omega_1 \text{ is small compared to } \omega_2 \]

For a single FET stage in Fig. 14-20, the gain

\[ A = \frac{V_o}{V_{gs}} = \frac{g_m}{1 + j\omega R_o C_{eq}} = A_0 \frac{g_m R_o}{1 + j\omega R_o C_{eq}} \]  \hspace{1cm} (14-43)

\[ \omega_2 = \frac{1}{R_o C_{eq}} \]

Decreasing \( R_o \) increases bandwidth but decreases the mid-frequency gain.

The product of gain magnitude and bandwidth

\[ A_0 \omega_2 = \frac{g_m R_o}{R_o C_{eq}} = \frac{g_m}{C_{eq}} \leq \frac{g_m}{C_{gs}} \]  \hspace{1cm} (14-44)

since \( C_{eq} \approx C_{gs} \) if the Miller effect is not large. Because \( g_m \) and \( C_{gs} \) are device parameters:

The gain-bandwidth product is a constant for a specific FET.
For the FET of Example 5, \( g_m/C_{gs} = 2 \times 10^{-3}/20 \times 10^{-12} \approx 15 \text{ MHz} \). With this FET a gain of 5 permits a bandwidth of less than 3 MHz (2.9 MHz in Example 5 where \( R_s = 1 \text{ k}\Omega \)); if a bandwidth of 5 MHz is required, the maximum possible gain is \( 15/5 = 3 \).

- **BJT** ⇒ has ⇒ similar figure ⇒ usually expressed in different way
- If the high-frequency response ⇒ limited by ⇒ \( \beta_{co} \)
- The bandwidth ⇒ approximately ⇒ \( f_\beta \) ⇒ the gain bandwidth product \( \Downarrow \)

\[
A_0f_2 \leq \beta f_\beta = f_T \quad (14-45)
\]

The frequency \( f_T \) at which \( \beta_f = 1 \) typically ranges from 100 kHz for alloy junction power transistors to 10 GHz for high-frequency transistors.
\( f_\beta = \text{beta cutoff frequency} \)

\( \beta_f = \text{high-frequency current gain} \)

\( f_T = \text{total frequency} \)

**Example 8**

The specifications for a certain silicon transistor indicate a minimum \( h_{ie} \) of 40 and a typical \( f_T \) of 8 MHz. Is this transistor suitable as a radiofrequency amplifier at 1 MHz?

By Eq. 14-35 at \( f = 1 \text{ MHz} \),

\[
\beta_f = \frac{\beta f_\beta}{f} = \frac{f_T}{f} = \frac{8}{1} = 8
\]

By Eq. 14-45,

\[
f_\beta = \frac{f_T}{\beta} = \frac{f_T}{h_{ie}} = \frac{8 \text{ MHz}}{40} = 0.2 \text{ MHz}
\]

Although some current gain is possible at 1 MHz, the beta cutoff is only 0.2 MHz and another transistor should be selected.
**Example 9**

Design a single-stage amplifier with a voltage gain of 34 dB, flat within 3 dB from 46 Hz to 200 KHz. Source and load resistances are $R_s = 2 \, \text{k}\Omega$ and $R_L = 10 \, \text{k}\Omega$.

Use a 2N3114 with $h_{fe} = \beta = 50$ (1 kHz) and $h_{ie} = 1.5 \, \text{k}\Omega = r_o + r_e \approx r_e$ at $I_C = 1 \, \text{mA}$ and $V_{CE} = 5 \, \text{V}$; $C_{ob} = C_{jc} = 6 \, \text{pF}$ and $f_t = 54 \, \text{MHz}$.

Replace the circuit diagram by the small-signal model of Fig. 14.21b, assuming $R_B \gg r_e$.

At midfrequencies,

$$A_{VO} = \left| \frac{V_o}{V_i} \right| = \frac{\beta I_b (R_C / R_L)}{I_b (R_s + r_e)} = 10^{4b/20} \approx 50$$

Solving,

$$R_o = R_C / R_L = \frac{(R_s + r_e)A_{VO}}{\beta} = \frac{(2 + 1.5)50}{50} = 3.5 \, \text{k}\Omega$$

Hence

$$R_C = \frac{1}{(1/R_o) - (1/R_L)} = \frac{10^3}{0.286 - 0.1} = 5.38 \, \text{k}\Omega$$

Assuming high-frequency response is limited by $C_{eq}$ with $C_e = 98 \, \text{pF}$ from Example 6,

$$C_{eq} = C_e + (1 + \beta R_o / r_e) C_j c$$

$$= 98 + (1 + 50 \times 3.5 / 1.5) 6 = 804 \, \text{pF}$$

$$f_2 = \frac{1}{2\pi C_{eq} (R_s / r_e)} = \frac{1}{2\pi \times 804 \times 10^{-12} \times 860} = 230 \, \text{kHz}$$

Therefore, the high-frequency response is acceptable.

Assuming bias is not critical (Fig. 14.21c), let

$$R_E = \frac{3}{I_E} \approx \frac{3}{I_C} = \frac{3}{0.001} = 3 \, \text{k}\Omega$$

$$R_B = \frac{\beta R_E}{10} = \frac{50 \times 3}{10} = 15 \, \text{k}\Omega$$

Then

$$V_{CC} = V_E + V_{CE} + I_C R_C = 3 + 5 + 1(5.38) \approx 13 \, \text{V}$$

$$V_{BB} = R_B I_C / \beta + V_{BE} + V_E = 15 \times 1 / 50 + 0.7 + 3 = 4 \, \text{V}$$

$$R_2 = R_B V_{CC} / V_{BB} = 15 \times 13 / 4 = 48.8 \rightarrow 47 \, \text{k}\Omega$$

$$R_1 = R_B R_3 / (R_2 - R_B) = 15 \times 47 / 32 = 22.03 \rightarrow 22 \, \text{k}\Omega$$

For low-frequency response, use the results of Example 4 where $C_E = 50 \, \mu\text{F}$, $C_{CI} = 5 \, \mu\text{F}$, and $C_{C2} = 1 \, \mu\text{F}$. 

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**Figure 14.21** BJT amplifier design.