CHAPTER 6
BJT AMPLIFIERS

6-1 AMPLIFIER OPERATION

- Biasing a transistor is purely DC operation.
- It establishes the Q-point about which the AC voltage and current can change corresponding to an AC input signal.
- These changes in AC voltage and current seen at the output constitute the amplifier operation.
- When the voltages being handled are small then the amplifier is referred to as *small-signal amplifier*.

6.1.1 AC Quantities

- The difference between the symbols used for DC and AC quantities is that subscript of DC quantities have capital letters while the AC quantities have small letters. A summary of DC and AC quantities is listed in Table 1.
- Figure 1 shows the various values that can be attributed to V_{ce}. It can represent rms, average, peak or peak-to-peak value. RMS value is default.

Table 1 Symbol for DC and AC quantities

Description	DC Quantities	AC Quantities
Base-Emitter Voltage	V_{BE}	V_{be}
Collector-Emitter Voltage	V_{CE}	V_{ce}
Base-Collector Voltage	V_{CB}	V_{cb}
Base Current	I_B	I_b
Collector Current	I_C	I_c
Emitter Current	I_E	I_e
External Resistance	R_B, R_C, R_E	R_b, R_c, R_e
Internal Resistance		r'_e, r'_b, r'_c

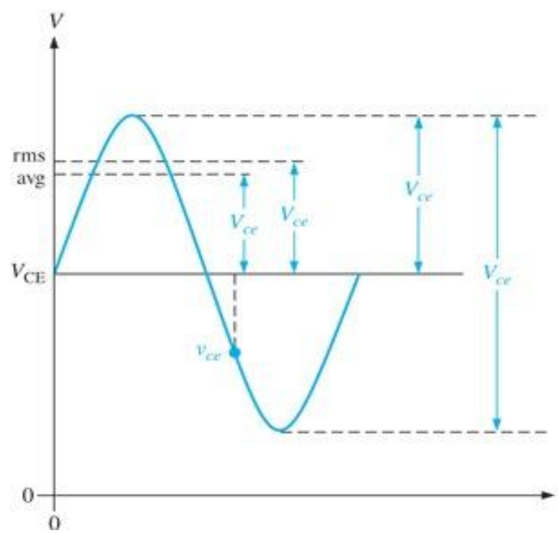


Figure 1 Vce representation

6.1.2 The Linear Amplifier

- Linear amplifier provides amplification of a signal without any distortion (that is there is no clipping from positive or negative half cycles).
- So the output signal of an amplifier has the exact shape and frequency as the input signal.
- A voltage divider biased transistor which acts as an amplifier is shown in Figure 2.

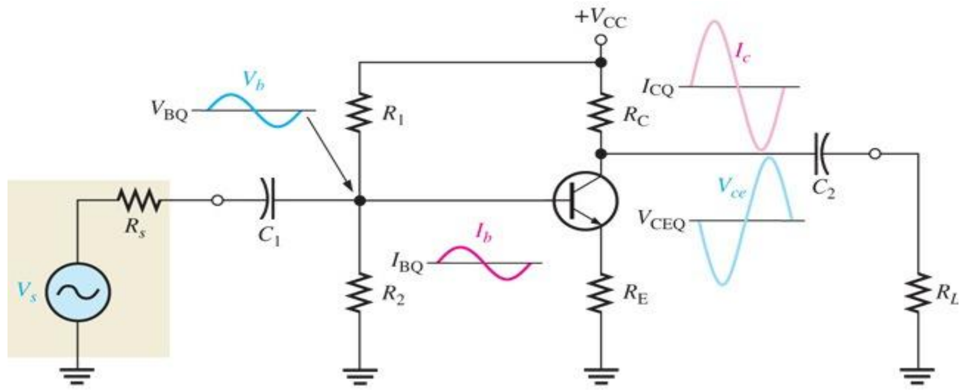


Figure 2 Voltage-divider biased transistor amplifier

- The circuit works in the following manner:
  - The AC input signal V_s changes the DC base voltage above and below its DC level V_{BQ}.
  - This voltage change is shown in Figure 2 as V_b.
  - This changes the DC base current above and below its DC level I_{BQ}.
  - This current change is shown in Figure 2 as I_b.
  - This change in I_{BQ} produces a large change in I_{CQ} because of the transistor current gain β_{DC}.
  - The increase in I_{CQ} decreases the collector voltage V_C which in turns decreases the collector-emitter voltage V_{CEQ}.
  - As shown in Figure 2, increase in the base voltage V_b corresponds to decrease in the collector-emitter voltage V_{ce}. Therefore the output of this amplifier is 180° out of phase with the input voltage.

6-2 TRANSISTOR AC MODELS

- An AC transistor model represents the transistor operation in terms of its internal parameters.
- This section describes these parameters based on resistance and hybrid parameters.
- Following is brief description of the AC parameters discussed.

6.2.1 r Parameters

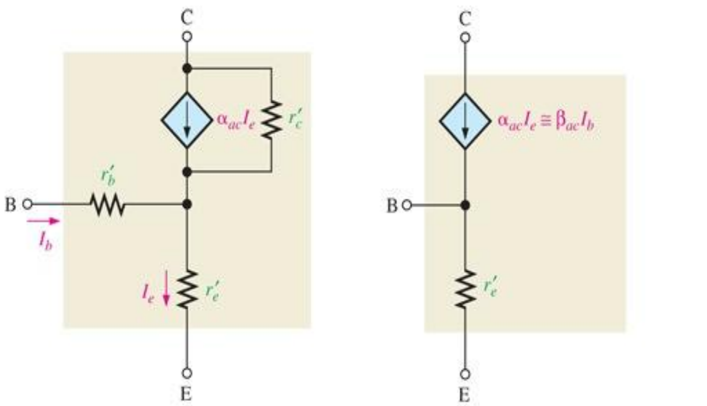
- There are 5 parameters commonly used in BJT listed in Table 2.

r Parameter	Description	Importance
α_{ac}	AC alpha (I_c/I_e)	
β_{ac}	AC beta (I_c/I_b)	IMPORTANT
r_e'	AC emitter resistance	$r_e' = \frac{25mV}{I_E}$ (MOST IMPORTANT)
r_b'	AC base resistance	Small enough to be ignored
r_c'	AC emitter resistance	Large enough to be taken as open circuit

Table 2 r Parameters

6.2.2 r-Parameter Transistor Model

- There are 2 parameters transistor models.
  - Generalized r-parameter model – All r-parameter are shown as in Figure 3(a).
  - Simplified r-parameter model –$r_b{}'$ is ignored and $r_c{}'$ is open circuit to get as shown in Figure 3(b).
  - Figure 4 shows the relation of r-parameter to the transistor symbol.



(a) Generalized r-parameter model for a BJT (b) Simplified r-parameter model for a BJT

Figure 3 r-parameter transistor model

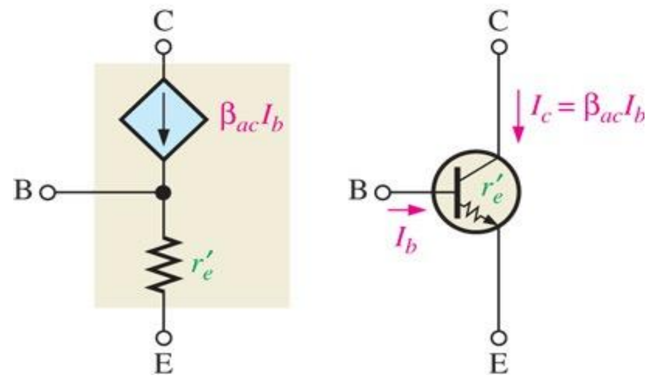
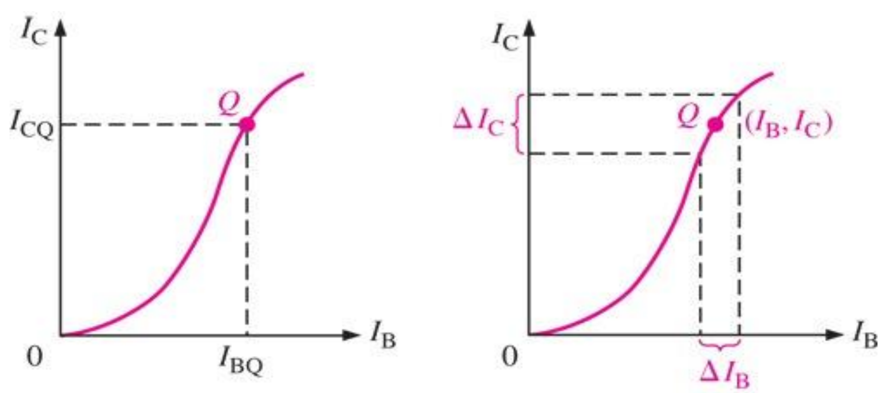


Figure 4 Relation of transistor symbol to r-parameter

6.2.3 Comparison of β_{ac} to β_{DC}

- The graph of I_C vs. I_B is nonlinear (curve, not line) as shown in Figure 5.
- If the base current changes by amount ΔI_B, then the collector current will change by amount ΔI_C.
- The ratio of these two quantities $\beta_{ac} = \Delta I_C/\Delta I_B$ is different at every point on the curve due to the nonlinear curve and may differ from the ratio $\beta_{DC} = I_C/I_B$ at the Q-point.



(a) $\beta_{DC} = I_C/I_B$ at Q-point (b) $\beta_{ac} = \Delta I_C/\Delta I_B$

Figure 5 I_C vs. I_B curve to show difference between β_{ac} and β_{DC}

6.2.4 h Parameter and its relation with r parameter

- The manufacturer's datasheet typically specifies h (hybrid) parameters.
- The most commonly used parameters are
  - $h_{fe} = \beta_{ac}$ - Common Emitter Forward Current Gain
  - $h_{fb} = \alpha_{ac}$ - Common Base Forward Current Gain

6-3 THE COMMON-EMITTER AMPLIFIER

- There are 3 amplifier configurations:
  - Common-Emitter (CE) Amplifier
  - Common-Collector (CC) Amplifier
  - Common-Base (CB) Amplifier
- The CE configuration shows high voltage gain and high current gain.
- Figure 6 shows a CE amplifier with a voltage divider bias.
- The AC input signal V_{in} is applied to the base of the transistor while the AC output signal V_{out} is taken from the collector.
- The emitter is connected to ground or is common between base and collector, hence the name common-emitter amplifier.
- The output voltage is 180° out-of-phase with the input voltage.
- C_1 and C_3 are called coupling capacitor while C_2 is called a bypass capacitor.

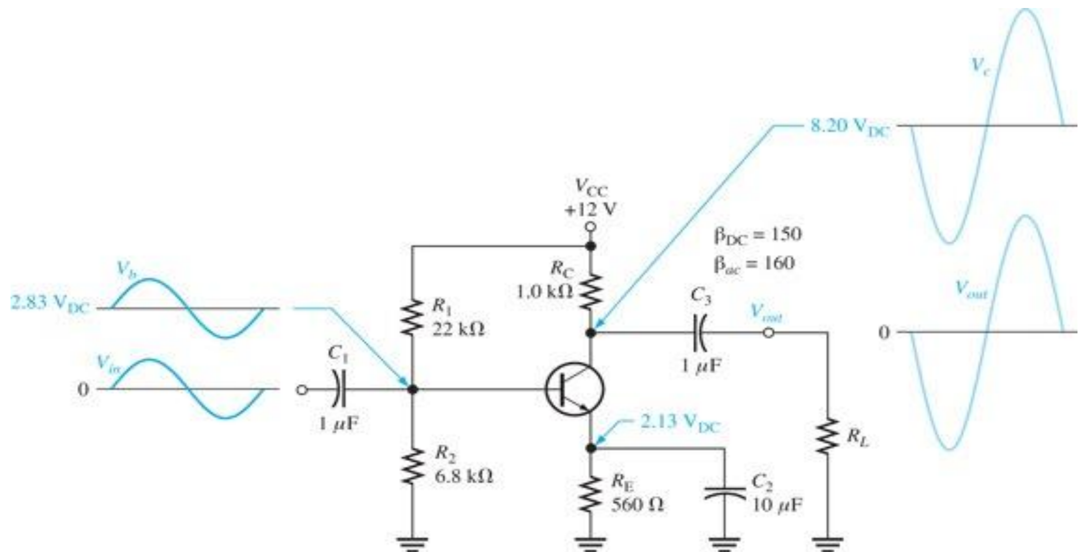


Figure 6 CE amplifier with voltage divider bias

6.3.1 DC Analysis

- To analyze the amplifier in Figure 6, we have to do 2 types of analyses.
  - DC analysis to establish the DC bias i.e. Q-point. We have covered this in Chapter 4 and 5.
  - AC analysis to establish the voltage gain, input resistance and output resistance.
- DC analysis starts by developing the DC equivalent circuit of the amplifier in Figure 6.
- This is done by removing all components that depend on AC signal like capacitor (as they act as open circuit in DC).
- The DC equivalent circuit of Figure 6 is shown in Figure 7.
- Notice all capacitors are removed along with R_L (C3 is open).
- This results in the same circuit that has been analyzed in Chapter 5.
- All the DC values like V_B, V_C, V_E and I_E can be found through the equations in Chapter 4 and 5.
- Figure 6 shows these DC values.

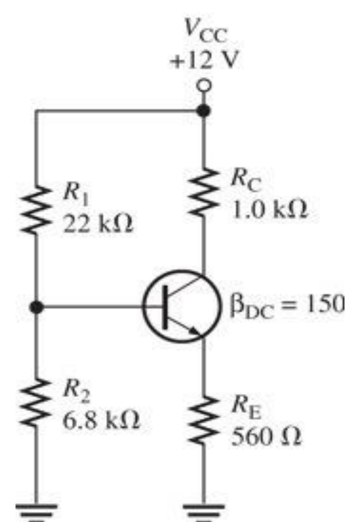


Figure 7 DC equivalent circuit

6.3.2 AC Analysis

- AC analysis also requires the development of AC equivalent circuit.
- This is done by:
    - The capacitors C_1, C_2 and C_3 are replaced by short circuit.
    - DC source is replaced by 0V.
- Figure 8 shows the AC equivalent circuit.
- Note that R_E is also removed as it is bypassed through capacitor C_2.

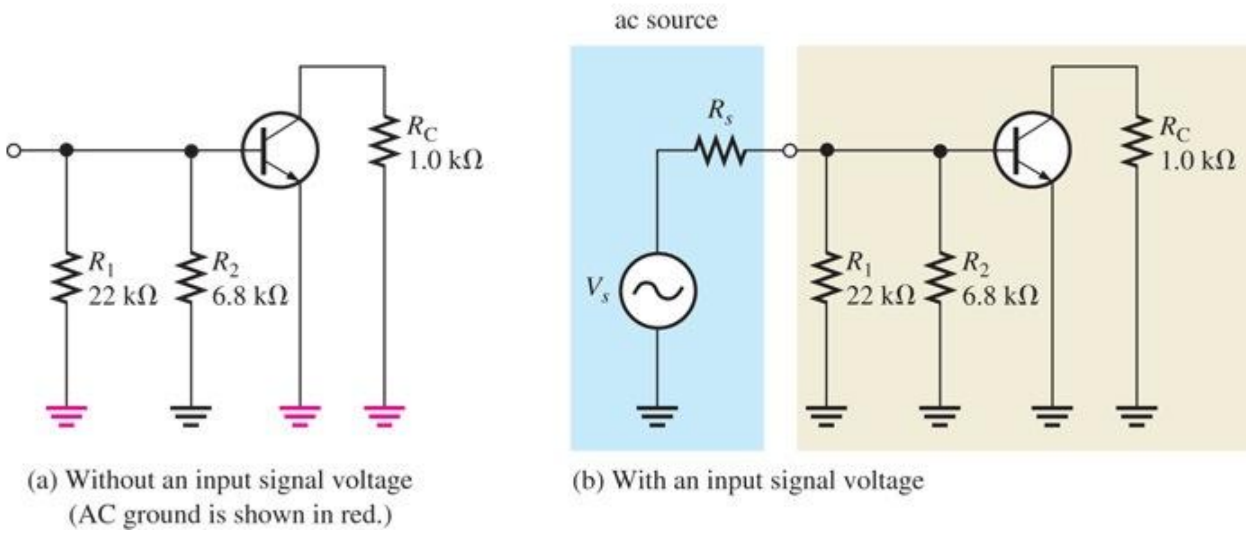


Figure 8 AC equivalent circuit

6.3.2.1 AC Signal Voltage at the Base

- The AC signal source is given by V_S in Figure 8(b).
- In order to determine the AC voltage at the base, there can be 2 scenarios.
    - V_S has no internal resistance so $R_S = 0\Omega$. In this case $V_b = V_s$.
    - If V_S has an internal resistance then, 3 resistances need to considered: *source internal resistance* R_S, *bias resistances* (R_1, R_2) and *AC input resistance* at the base of the transistor ($R_{in(base)}$). These are shown in Figure 9(a).
    - These resistances appear in parallel. So the total AC input resistance can be determined by

$$R_{in(tot)} = R_1||R_2||R_{in(base)}$$

    - Therefore the AC base voltage V_b is given by

$$V_b = \left(\frac{R_{in(tot)}}{R_s + R_{in(tot)}}\right)V_s$$

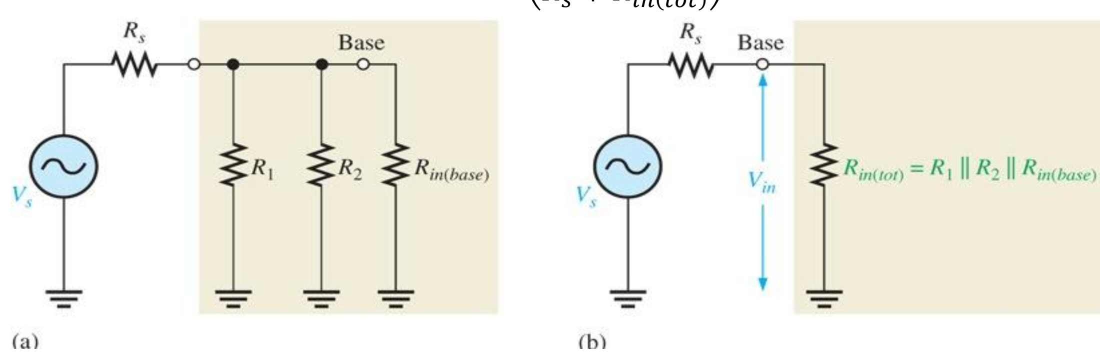


Figure 9 AC equivalent circuit

6.3.2.2 Input Resistance and Output Resistance

- The AC input resistance at the base is given by

$$R_{in(base)} = \beta_{ac} r_e'$$

- It is recommended to have high input resistance.
- The AC output resistance at the collector is given by

$$R_{out} \approx R_C$$

- It is recommended to have low output resistance.

6.3.3 Voltage Gain

- The voltage gain of any amplifier is given by the general formula

$$A_v = \frac{V_{out}}{V_{in}}$$

- In terms of the circuit of Figure 6, $V_{in} = V_b$ and $V_{out} = V_c$, so the voltage gain becomes

$$A_v = \frac{V_c}{V_b}$$

- After doing some mathematical manipulations, the voltage gain for a CE amplifier comes out to be

$$A_v = \frac{R_C}{r_e'}$$

6.3.3.1 Attenuation

- Attenuation is the reduction in signal voltage as it passes through a circuit whose gain is less than 1.
- For example if a signal voltage is reduced by half this means that the attenuation is 2. This corresponds to a gain of 0.5 because gain is the inverse of attenuation.
- This occurs in CE amplifier if the internal resistance R_S of AC source voltage is not zero.
- In this case the attenuation is given by

$$Attenuation = \frac{V_s}{V_b} = \frac{R_s + R_{in(tot)}}{R_{in(tot)}}$$

- Therefore the overall voltage gain of an amplifier, A_v' is voltage gain from base to collector, A_v, times the reciprocal of the attenuation.

$$A_v' = \left(\frac{V_b}{V_s}\right)\left(\frac{V_c}{V_b}\right) = \left(\frac{V_b}{V_s}\right) A_v = \left(\frac{V_c}{V_s}\right)$$

- Attenuation, voltage gain from base to collector and overall voltage gain are shown in Figure 10.

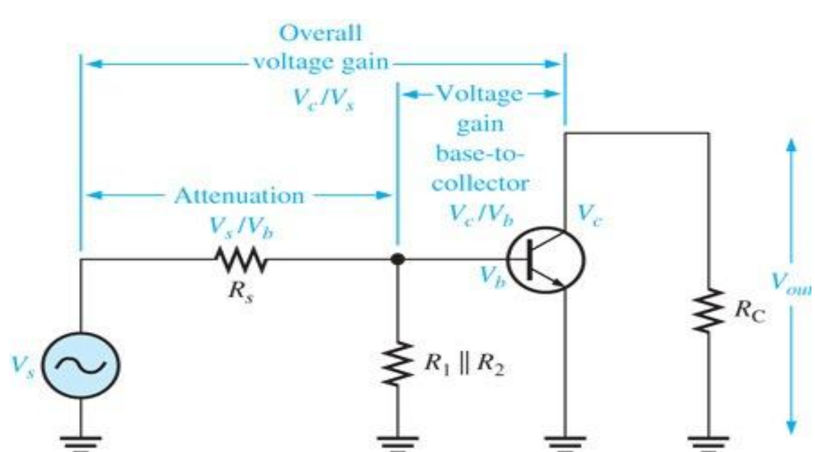


Figure 10 Base circuit with overall gain

NOTE: REFER EXAMPLE 6-3 PAGE 266

6.3.3.2 Effect of Emitter Bypass Capacitor on Voltage Gain

- The emitter bypass capacitor C_2 shorts the emitter resistor R_E. Therefore it does not appear in the AC equivalent model.
- This results in the maximum voltage gain.

$$A_v = \frac{R_C}{r_e'}$$

6.3.3.3 Voltage Gain without Bypass Capacitor

- If the bypass capacitor is removed then RE will not be shorted out of the AC equivalent circuit.
- This results in the voltage gain to change as

$$A_v = \frac{R_C}{r_e' + R_E}$$

- This reduces the voltage gain of the amplifier.

NOTE: REFER EXAMPLE 6-5 PAGE 269

6.3.3.4 Effect of Load on the Voltage Gain

- A **load** is the amount of current drawn from the output of an amplifier through a load resistance.
- Connecting a load resistor R_L through a coupling capacitor C_3 puts the load resistor in parallel with the collector resistor R_C as shown in the Figure 11.
- This changes the total AC collector voltage and is given by

$$R_c = R_C || R_L = \frac{R_C R_L}{R_C + R_L}$$

- So the voltage gain will change to

$$A_v = \frac{R_c}{r_e'}$$

- If $R_c < R_C$ then the voltage gain is reduced because R_L is small.
- If $R_L \gg R_C$ then there is very little effect on the voltage gain.

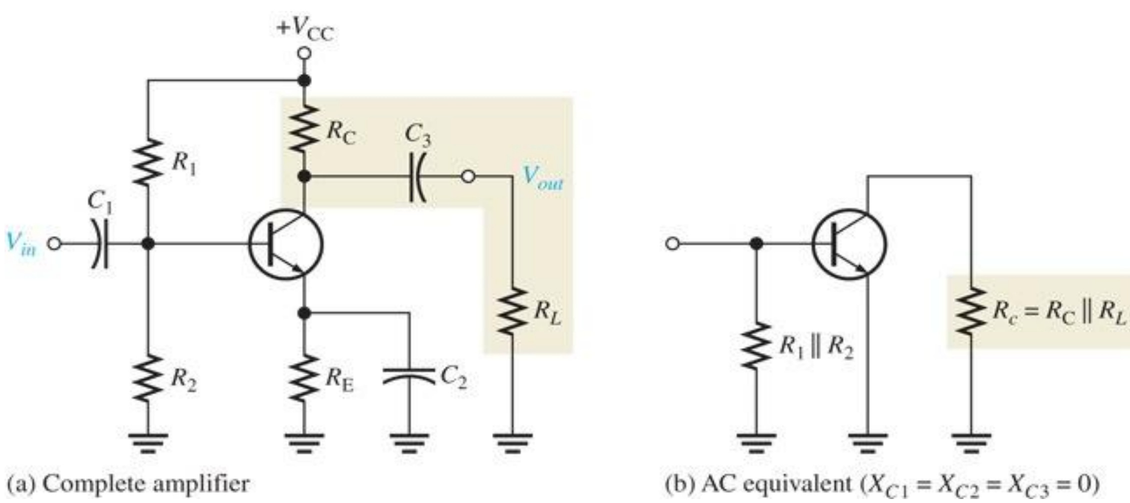


Figure 11 CE amplifier with load

NOTE: REFER EXAMPLE 6-6 PAGE 270

6.3.4 Stability of Voltage Gain

- Stability is a measure of how well an amplifier maintains its design values over changes in temperature or a transistor with different β.
- Bypassing R_E does produce the maximum voltage gain but then the voltage gain depends upon r_e' ($A_v = R_c/r_e'$).
- r_e' depends upon I_E ($r_e' = 25mV/I_E$) which can change with temperature and β.
- This leads to an unstable CE amplifier.
- Without bypassing the RE the voltage gain becomes $A_v = \frac{R_c}{r_e'+R_E}$.
- If $R_E \gg r_e'$, then the voltage gain would be independent of r_e' and can be expressed as

$$A_v \approx \frac{R_C}{R_E}$$

- But this reduces the voltage gain to its minimum value. The solution to the problem is **Swamping**.

6.3.4.1 Swamping r_e' to Stabilize the Voltage Gain

- **Swamping** is a method used to minimize the effect of r_e' without reducing the voltage gain of the amplifier.
- In a swamped amplifier, R_E is partially bypassed so that reasonable gain can be achieved and effect of r_e' is greatly reduced.
- The R_E is split into 2 resistors such that $R_E = R_{E1} + R_{E2}$ as shown in Figure 12.
- One of the resistors R_{E2} is bypassed and the other one R_{E1} is not.
- Both resistors $R_{E1} + R_{E2}$ effects the DC bias while only R_{E1} effects the AC voltage gain i.e.

$$A_v = \frac{R_C}{r_e'+R_{E1}}$$

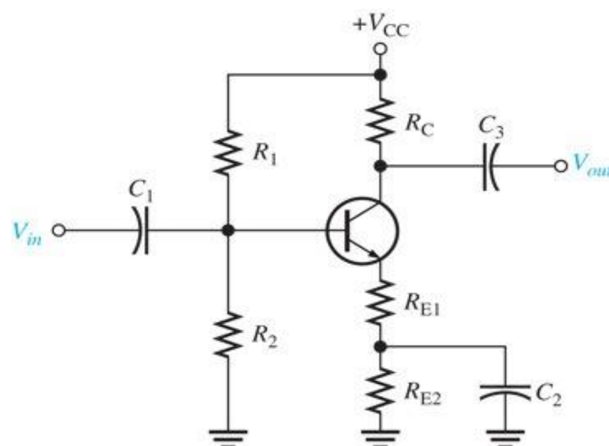


Figure 12 Swamped amplifier with partial R_E bypass

- If R_{E1} is at least ten times larger than r_e' then the effect of is greatly reduced and the voltage gain for the swamped amplifier is

$$A_v \approx \frac{R_C}{R_{E1}}$$

6.3.4.2 Effect of Swamping on Amplifier's Input Resistance

- If R_E is completely bypassed then the input resistance at the base of an amplifiers is given by $R_{in(base)} = \beta_{ac} r_e'$.
- With partial bypass in swamped amplifier, the input resistance at the base is given by

$$R_{in(base)} = \beta_{ac}(r_e' + R_{E1})$$

NOTE: REFER EXAMPLE 6-7 & 6-8 PAGE 272

6.3.4 Current Gain & Power Gain

- The current gain from base to collector is I_c/I_b or β_{ac}.
- However the overall current gain of a CE amplifier is

$$A_i = \frac{I_c}{I_s}$$

- I_s is the total signal input current produced by the source and is given by

$$I_s = \frac{V_s}{R_s + R_{in(tot)}}$$

- The overall power gain is the product of overall voltage gain, A'_v, and the overall current gain, A_i

$$A_p = A'_v A_i$$

6-4 THE COMMON-COLLECTOR AMPLIFIER

- The common-collector (CC) amplifier is usually referred to as an emitter-follower (EF).
- The ac input voltage is applied to the base and output is taken from the emitter.
- Its voltage gain is approximately equal to 1.
- The phase of input voltage and output voltage is the same i.e. phase difference is 0.
- Its main advantage is high input resistance and high current gain.
- The emitter-follower circuit with voltage divider bias is shown in Figure 13.

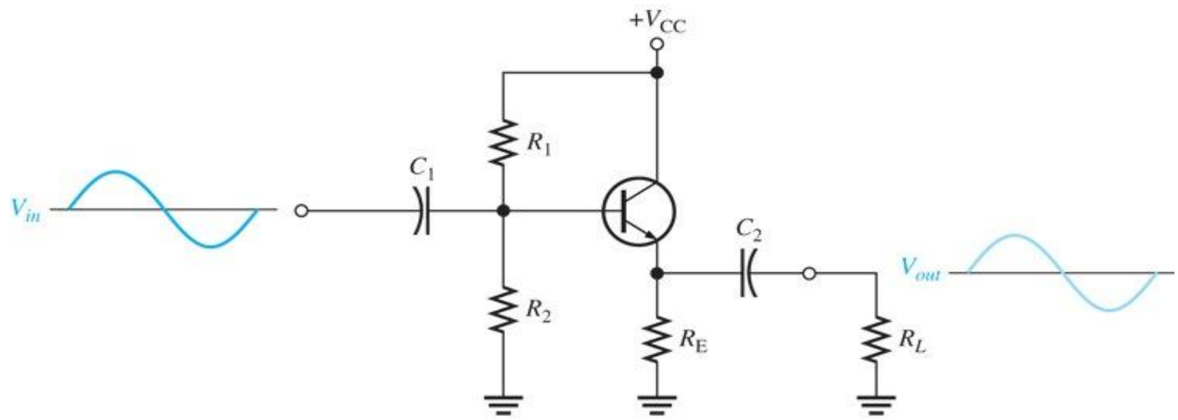


Figure 13 Emitter-follower with voltage divider bias

6.4.1 Voltage Gain

- Due to the circuit configuration (AC equivalent shown in Figure 14), the voltage gain of EF amplifier is given as

$$A_v = \frac{V_{out}}{V_{in}} = \frac{V_e}{V_b} \approx 1$$

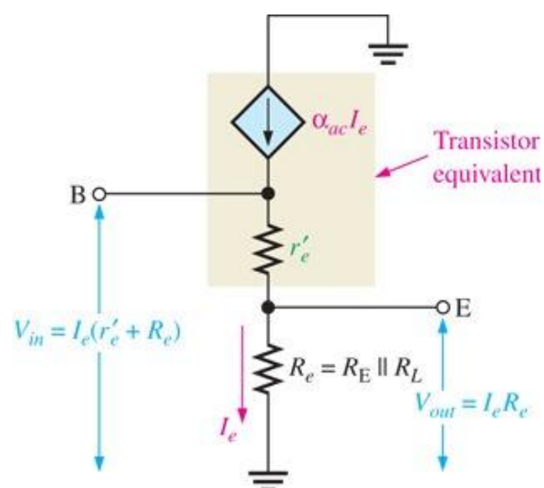


Figure 14 EF AC equivalent circuit

6.4.2 Input Resistance

- One of the advantages of EF circuit is that it provides high input resistance.
- In the case of EF amplifier the R_E is never bypassed as the output is taken across $R_e = R_E||R_L$.
- Therefore the AC input resistance to the base of the amplifier is given as

$$R_{in(base)} \approx \beta_{ac}(r'_e + R_e)$$

- If $R_e \gg r'_e$, then the input resistance at the base is simplified to

$$R_{in(base)} \approx \beta_{ac} R_e$$

- As R_1, R_2 and $R_{in(base)}$ all appear in parallel therefore the total input resistance is given by

$$R_{in(base)} = R_1||R_2||R_{in(base)}$$

6.4.3 Output Resistance

- The output resistance of the EF amplifier is given as

$$R_{out} \approx \left(\frac{R_s}{\beta_{ac}}\right) || R_E$$

6.4.4 Current Gain and Power Gain

- The current gain of the EF amplifier is given as

$$A_i = \frac{I_e}{I_{in}}$$

where $I_{in} = V_{in}/R_{in(tot)}$.

- The power gain is the product of voltage gain and current gain i.e.

$$A_p = A_v A_i$$

- As the voltage gain is approximately equal to 1 therefore power gain becomes

$$A_p \approx A_i$$

NOTE: REFER EXAMPLE 6-9 PAGE 279

6-5 THE COMMON-BASE AMPLIFIER

- Common-base (CB) amplifier provides high voltage gain with a maximum current gain of 1.
- Its input resistance is low so it's not good for certain applications.
- A common-base amplifier is shown in Figure 15.

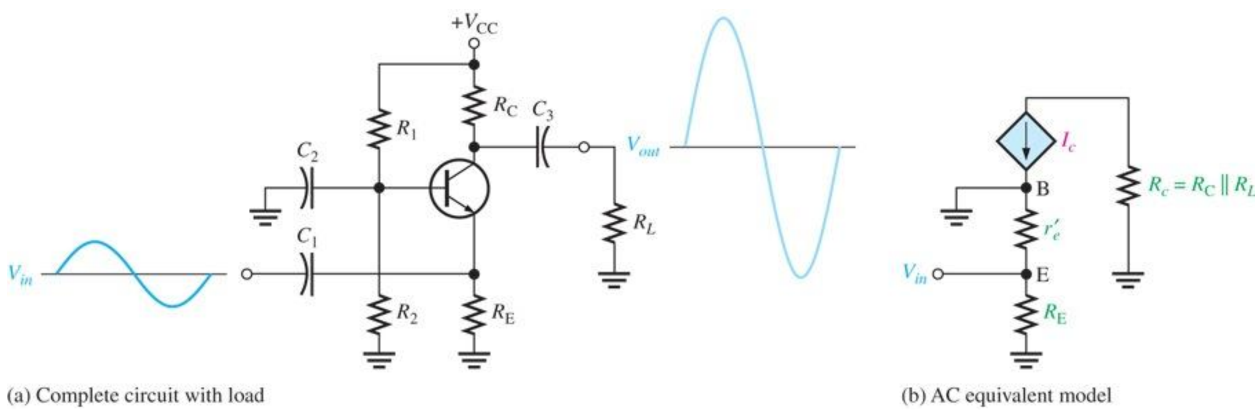


Figure 15 Common-base (CB) amplifier

- In CB amplifier, base is the common terminal.
- The input voltage is applied to the emitter while output is taken through the collector terminal.
- There is no phase difference between the input voltage and output voltage signals.

6.5.1 Voltage Gain

- The voltage gain of a CB amplifier is given by (if $R_E \gg r_e'$)

$$A_v = \frac{V_{out}}{V_{in}} = \frac{V_e}{V_c} = \frac{R_c}{r_e'}$$

Where $R_c = R_C || R_L$.

6.5.2 Input Resistance

- As the input terminal is emitter, we are going to find out $\mathrm{R}_{\mathrm{in(emitter)}}$ which is given by

$$R_{in(emitter)} \approx r_e'$$

- As r_e' is usually small therefore the input resistance of CB amplifier is low.

6.5.3 Output Resistance

- The output resistance of a CB amplifier is give by

$$R_{out} \approx R_C$$

6.5.4 Current Gain and Power Gain

- The current gain of the CB amplifier is approximately equal to 1.
- As $I_{in} = I_e$ and $I_{out} = I_c$ and we know that $I_c \approx I_e$, so

$$A_i = \frac{I_e}{I_c} \approx 1$$

- Since current gain of CB is approximately equal to 1, the power gain of the CB is then given by

$$A_p \approx A_v$$

NOTE: REFER EXAMPLE 6-11 PAGE 285

6-6 MULTISTAGE AMPLIFIERS

- Two or more amplifiers can be connected in a **cascaded** arrangement.
- The output of the first becomes the input of the second.
- Each amplifier is known as a **stage**.
- The main function of multistage amplifiers is to increase the overall voltage gain.

6.6.1 Multistage Voltage Gain

- The overall voltage gain of cascaded amplifiers is the product of the individual voltage gains.

$$A_v' = A_{v1}A_{v2}A_{v3} \dots A_{vn}$$

Where n is the number of stages.

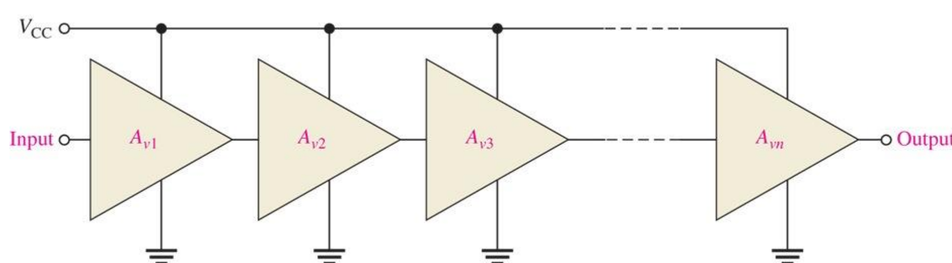


Figure 16 Cascaded amplifiers

- Amplifier voltage gain is often expressed in **decibels** (dB) as

$$A_{v(dB)} = 20 \log A_v$$

6.6.2 Capacitively-Coupled Multistage Amplifier

- Each stage in capacitively-coupled multistage amplifier is connected with a coupling capacitor.
- Figure 17 shows a 2-stage amplifier where both stages are connected through coupling capacitor C_3.

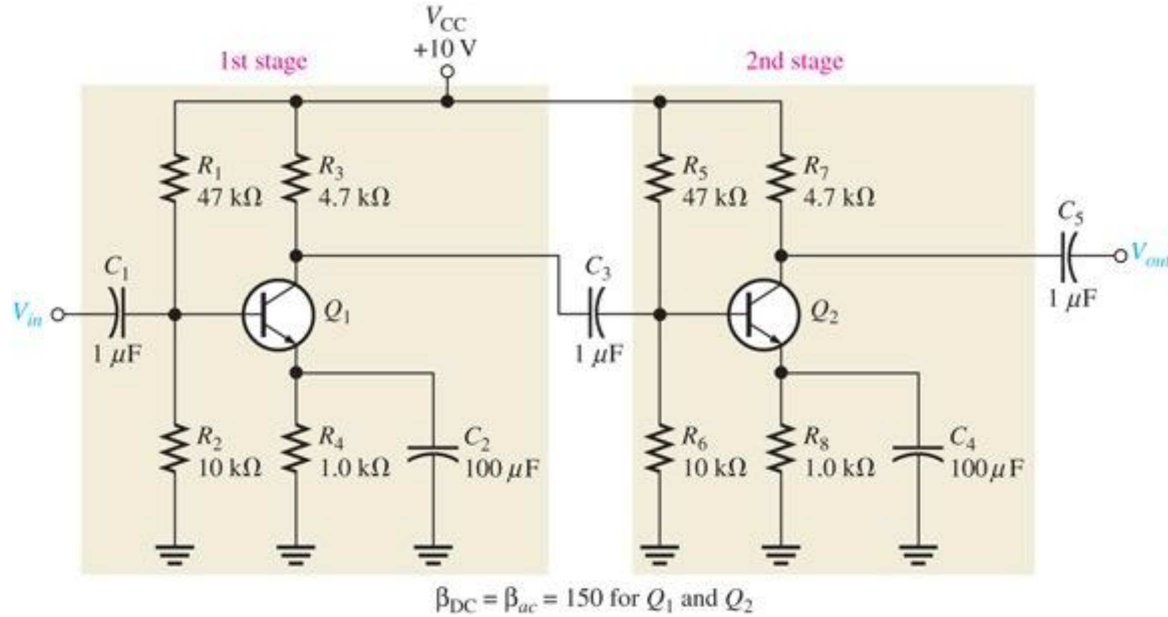


Figure 17 Two-stage common-emitter amplifier

6.6.2.1 Voltage gain of the First Stage

- To determine the voltage gain of the first stage, we need to understand that the bias resistors of the second stage R_5 and R_6 appear as load to the first stage.
- Also the input resistance to the base of Q_2, $R_{in(base2)}$ will also be considered as load to the first stage.
- This creates a loading effect for the amplifier of the first stage (therefore will reduce gain of first stage).
- Q1 of the first stage sees R_3, R_5, R_6 and $R_{in(base2)}$ all in parallel as shown in Figure 18.
- So the ac collector resistance of the first stage is

$$R_{c1} = R_3||R_5||R_6||R_{in(base2)}$$

- The voltage gain of first stage is therefore given as

$$A_{v1} = \frac{R_{c1}}{r_e'}$$

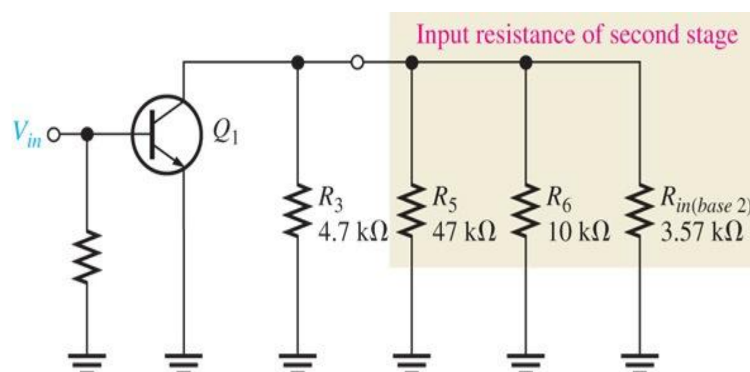


Figure 18 AC equivalent of first stage

6.6.2.2 Voltage gain of the Second Stage

- As the second stage has no load resistance so the gain is

$$A_{v2} = \frac{R_7}{r_e'}$$

6.6.2.3 Overall Voltage Gain

- The overall voltage gain the amplifier in Figure 17 will be $A_v' = A_{v1}A_{v2}$.

KEY FORMULAS OF THE CHAPTER

Quantity	Configuration		
	Common Emitter	**Common Collector**	**Common Base**
AC emitter resistance	$r'_e = \frac{25mV}{I_E}$	$r'_e = \frac{25mV}{I_E}$	$r'_e = \frac{25mV}{I_E}$
AC voltage at the base	With internal source resistance: $V_b = \left(\frac{R_{in(total)}}{R_s + R_{in(total)}}\right)V_s$ Without internal source resistance: $V_b = V_s$	With internal source resistance: $V_b = \left(\frac{R_{in(total)}}{R_s + R_{in(total)}}\right)V_s$ Without internal source resistance: $V_b = V_s$	
AC voltage at the collector	$V_c = A'_v V_s$		$V_c = A'_v V_s$
Input Resistance	$R_{in(base)} \approx \beta_{ac} r'_e$ Swamped Amplifier: $R_{in(base)} \approx \beta_{ac}(r'_e + R_{E1})$	$R_{in(base)} \approx \beta_{ac}(r'_e + R_e)$ **If $R_e \gg r'_e$** $R_{in(base)} \approx \beta_{ac} R_e$ Where $R_e = R_E \Vert R_L$	$R_{in(emitter)} \approx r'_e$
Output Resistance	$R_{out} \approx R_C$	$R_{out} \approx \left(\frac{R_s}{\beta_{ac}}\right) \Vert R_E$	$R_{out} \approx R_C$
Voltage Gain	Without Load: $A_v = \frac{V_c}{V_b} = \frac{R_C}{r'_e}$ With Load: $A_v = \frac{R_C \Vert R_L}{r'_e} = \frac{R_c}{r'_e}$ Without Bypass Capacitor: $A_v = \frac{R_C}{r'_e + R_E}$ Swamped Amplifier: $A_v = \frac{R_C}{r'_e + R_{E1}}$ **If $R_{E1} > 10r'_e$:** $A_v \approx \frac{R_C}{R_{E1}}$ Attenuation: $Attenuation = \frac{V_s}{V_b} = \frac{R_s + R_{in(tot)}}{R_{in(tot)}}$ Overall Voltage Gain: $A'_v = \left(\frac{V_b}{V_s}\right)\left(\frac{V_c}{V_b}\right) = \left(\frac{V_b}{V_s}\right)A_v = \frac{V_c}{V_s}$	$A_v \approx 1$	$A_v = \frac{V_c}{V_e} = \frac{R_c}{r'_e}$ Where $R_c = R_C \Vert R_L$
Current Gain	$A_i = \frac{I_c}{I_s}$ Where $I_s = \frac{V_s}{R_s + R_{in(tot)}}$	$A_i = \frac{I_e}{I_{in}}$	$A_i = \frac{I_c}{I_e} \approx 1$
Power Gain	$A_p = A'_v A_i$	$A_p \approx A_i$	$A_p \approx A_v$