UNIT 4 FREQUENCY RESPONSE AND MULTISTAGE AMPLIFIERS

Frequency Response- Low Frequency response and High Frequency Response equivalent circuit analysis of BJT- Low Frequency response and High Frequency Response equivalent circuit analysis of FET- Miller's Effect - Multistage amplifiers-need for multistage amplifiers-methods of interconnecting multistage amplifiers - Types of Multistage amplifiers - Analysis of RC coupled Amplifiers -Analysis of Direct Coupled Amplifiers-Analysis of Transformer Coupled Amplifiers-cascade amplifier- Cascode amplifier- Darlington Emitter Follower Amplifier

.--

4.1 Frequency Response of Amplifiers

Let us consider an audio frequency amplifier which operates over audio frequency range extending from 20 Hz to 20 kHz. The audio frequency amplifiers are used in everyday life. For example, they are used in radio receivers, to address large public meeting, annual social gathering of college, for various announcements to be made for passengers on railway platforms, etc.

Over the range of frequencies at which it is to be used, an amplifier should ideally provide the same amplification for all frequencies.. The degree to which this is done is usually indicated by a curve, known as **frequency response curve** of the amplifier. This curve is a plot of the voltage gain of an amplifier against the frequency of input signal. A typical frequency response of an RC coupled amplifier is illustrated in Fig. 4.1.

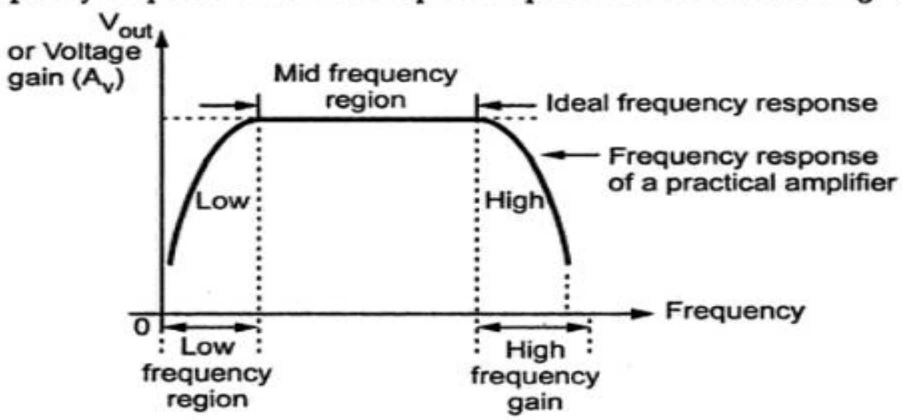


Fig. 4.1 A typical frequency response of an amplifier

To plot this curve, input voltage to the amplifier is kept constant and frequency of input signal is continuously varied. The output voltage at each frequency of input signal is noted; and the gain of the amplifier is calculated. The output voltage or the voltage gain of the amplifier is then plotted against frequency. For an A.F. amplifier, the frequency range of interest is quite large, from 20 Hz to 20 kHz. Hence to show clearly the voltage gain over such a wide frequency range, the frequency of input signal is plotted on x-axis using log scale (instead of usual linear scale). However the output voltage or voltage gain of the amplifier is plotted on y-axis with linear scale.

It is seen from the frequency response curve of an audio frequency amplifier that the gain of the amplifier remains fairly constant in the mid-frequency range, while the gain varies with frequency in low and high frequency regions of the curve. The frequency response is nearly ideal over a wide range of mid-frequency. Only at low and high frequency ends, the gain deviates from ideal characteristics. The decrease in voltage gain with frequency is called **roll-off**.

4.1.1 Definition of cutoff frequencies and Bandwidth

To indicate how constant an amplifiers's gain is with frequency variation, we may specify the range of frequencies over which the gain does not deviate more than 70.7 % of the maximum gain at some reference mid-frequency. This is shown in Fig. 4.2 where these two frequencies are indicated by f_1 and f_2 are called the **lower cut-off** and **upper cut-off** frequencies, respectively.

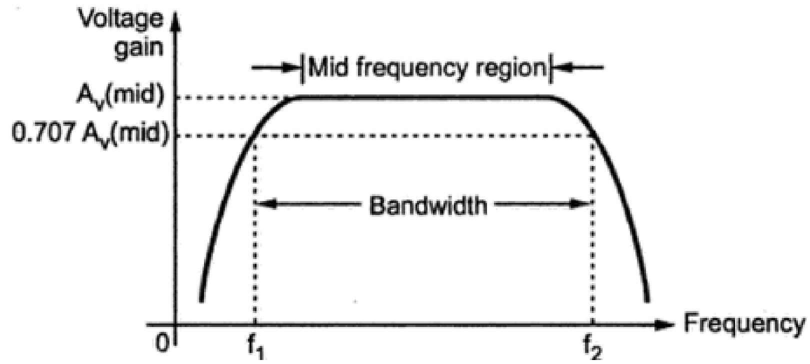


Fig. 4.2 Frequency response, half power frequencies and bandwidth of an RC coupled amplifier

Bandwidth of the amplifier is defined as the difference between f_2 and f_1; i.e. Bandwidth of the amplifier = $f_2 - f_1$. The frequency f_2 lies in high frequency region, while the frequency f_1 lies in low frequency region. These two frequencies are also referred to as half-power frequencies since gain or output voltage drops to 70.7 % of maximum value and this represents a power level of one-half the power at the reference frequency in mid-frequency region. Although this drop from maximum value to 70.7 % may seem to be large drop, the change is not easily noticeable to the listener, so that an amplifier may be considered to have a flat response from f_1 to f_2.

4.2 Low Frequency analysis of BJT

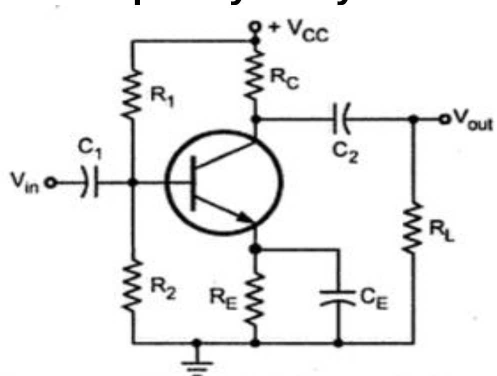


Fig. 4.3 Typical RC coupled common emitter amplifier

Let us consider a typical common emitter amplifier as shown in Fig. 4.3.

The amplifier shown in Fig. 4.3 has three RC networks that affect its gain as the frequency is reduced below midrange. These are :

1) RC network formed by the input coupling capacitor C_1 and the input impedance of the amplifier.
2) RC network formed by the output coupling capacitor C_2, the resistance looking in at the collector, and the load resistance.
3) RC network formed by the emitter bypass capacitor C_E and the resistance looking in at the emitter.

Input RC Network

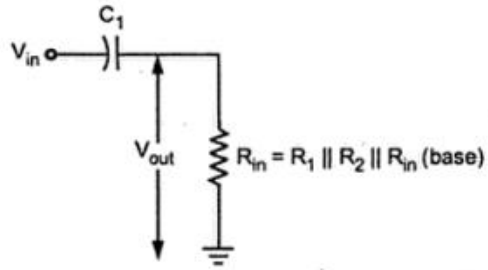


Fig. 4.4

Fig. 4.4 shows input RC network formed by C_1 and the input impedance of the amplifier. Note that V_{out} shown in the Fig. 4.4 is the output voltage of the network.

Applying voltage divider theorem we can write

$$V_{out} = \left(\frac{R_{in}}{\sqrt{R_{in}^2 + X_{C1}^2}} \right) V_{in}$$

We know that a critical point in the amplifier response is generally accepted to occur when the output voltage is 70.7 percent of the input ($V_{out} = 0.707\ V_{in}$). Thus we can write, at critical point

$$\frac{R_{in}}{\sqrt{R_{in}^2 + X_{C1}^2}} = 0.707 = \frac{1}{\sqrt{2}}$$

$\therefore$ At this condition $R_{in} = X_{C1}$.

At this condition the overall gain is reduced due to the attenuation provided by the input RC network. The reduction in overall gain is given by

$$A_v = 20 \log \left(\frac{V_{out}}{V_{in}} \right) = 20 \log (0.707) = -3\text{dB}$$

The frequency f_c at this condition is called lower critical frequency and is given by

$$f_c = \frac{1}{2\pi R_{in} C_1}$$

where $R_{in} = R_1 || R_2 || h_{ie}$

$$\therefore \quad f_c = \frac{1}{2\pi (R_1 || R_2 || h_{ie}) C_1}$$

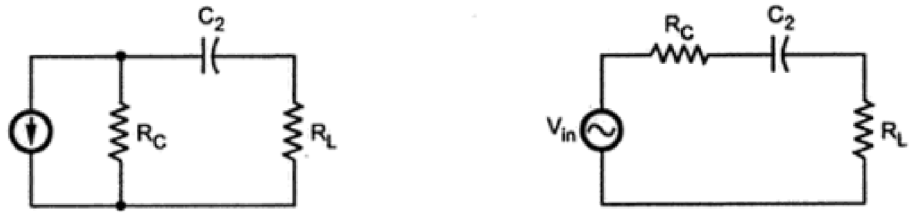
If the resistance of input source is taken into account the above equation becomes

$$f_c = \frac{1}{2\pi (R_s + R_{in}) C_1}$$

The phase angle in an input RC circuit is expressed as $\theta = \tan^{-1}\left(\frac{X_{C1}}{R_{in}}\right)$.

Output RC Network

Fig. 4.5 shows output RC network formed by C_2, resistance looking in at the collector and the load resistance.



(a) Current source (b) Current source replaced by voltage source

Fig. 4.5

The critical frequency for this RC network is given by,

$$f_c = \frac{1}{2\pi(R_C + R_L)C_2}$$

The phase angle in the output RC circuit is expressed as $\theta = \tan^{-1}\left(\frac{X_{C2}}{R_C + R_L}\right)$.

Bypass Network

Fig. 4.6 (b) shows RC network formed by the emitter bypass capacitor C_E and the resistance looking in at the emitter.

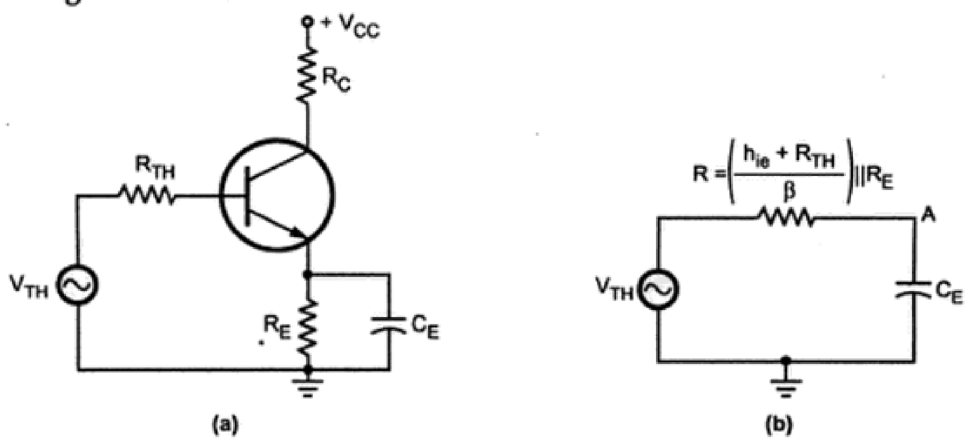


Fig. 4.6 Bypass RC network

Here, $\frac{h_{ie} + R_{TH}}{\beta}$ is the resistance looking in at the emitter. It is derived as follows

$$R = \frac{V_e}{I_e} + \frac{h_{ie}}{\beta} \cong \frac{V_b}{\beta I_b} + \frac{h_{ie}}{\beta} = \frac{I_b R_{TH}}{\beta I_b} + \frac{h_{ie}}{\beta} = \frac{R_{TH} + h_{ie}}{\beta}$$

where $R_{TH} = R_1 || R_2 || R_s$. It is the thevenin's equivalent resistance looking from the base of the transistor towards the input as shown in the Fig. 4.6 (a)

The critical frequency for the bypass network is

$$f_c = \frac{1}{2\pi R C_E}$$

or $$f_c = \frac{1}{2\pi\left[\left(\frac{h_{ie}+R_{TH}}{\beta}\right) || R_E\right] C_E}$$

We have seen that each network has a critical frequency. It is not necessary that all these frequencies should be equal. The network which has higher critical frequency than other two networks is called dominant network. The dominant network determines the frequency at which the overall gain of the amplifier begin to drop at –20dB/decade. This is illustrated in the following example.

Example : *Determine the low frequency response of the amplifier circuit shown in Fig.*

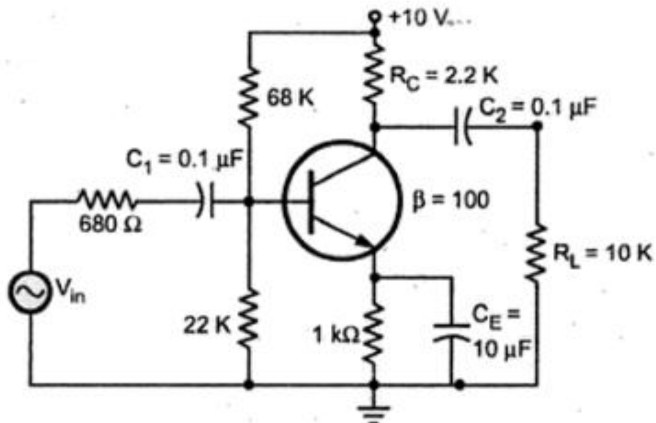


Fig.

Solution : It is necessary to analyze each network to determine the critical frequency of the amplifier

a) Input RC network

$$f_c\text{ (input)} = \frac{1}{2\pi[R_s + (R_1 || R_2 || h_{ie})] C_1}$$

$$= \frac{1}{2\pi[680 + (68\text{ K} || 22\text{ K} || 1.1\text{ K})] \times 0.1 \times 10^{-6}}$$

$$= \frac{1}{2\pi[680 + 1031.7] \times 0.1 \times 10^{-6}} = 929.8\text{ Hz}$$

b) Output RC network

$$f_{c\,(output)} = \frac{1}{2\pi(R_C + R_L) C_2} = \frac{1}{2\pi(2.2\text{ K}+10\text{ K}) \times 0.1 \times 10^{-6}} = 130.45\text{ Hz}$$

c) Bypass RC network

$$f_{c\,(bypass)} = \frac{1}{2\pi\left[\left(\frac{R_{TH} + h_{ie}}{\beta}\right) || R_E\right] C_E}$$

$$R_{TH} = R_1 \,||\, R_2 \,||\, R_s = 68\text{ K} \,||\, 22\text{ K} \,||\, 680 = 653.28\ \Omega$$

$$f_{c\,(bypass)} = \frac{1}{2\pi\left[\left(\frac{653.28+1100}{100}\right)||\,1\text{ K}\right]\times 10\times 10^{-6}} = \frac{1}{2\pi\,(17.23)\times 10\times 10^{-6}} = 923.7$$

We have calculated all the three critical frequencies :

a) f_c (input) = 929.8 Hz b) f_c (output) = 130.45 Hz c) f_c (bypass) = 923.7 Hz

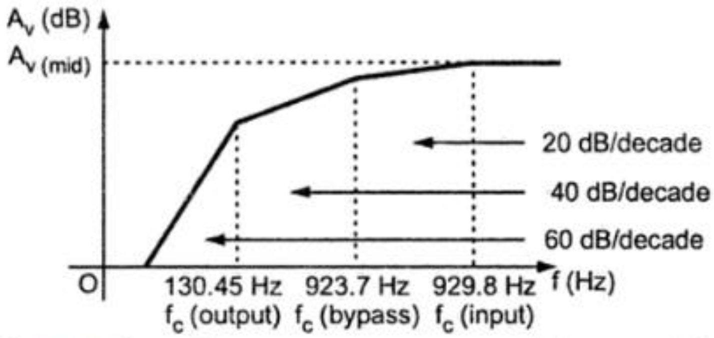


Fig. 4.7 Low frequency response of the amplifier

The above analysis shows that the input network produces the dominant lower critical frequency. Fig. 4.7 shows low frequency response of the given amplifier.

4.3 Low Frequency analysis of FET

Let us consider a typical common source amplifier as shown in Fig. 4.8.

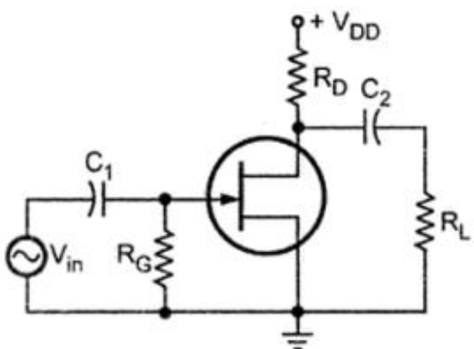


Fig. 4.8 Typical RC coupled common source amplifier

The amplifier shown in Fig. 4.8 has two RC networks that affect its gain as the frequency is reduced below midrange. These are :

1) RC network formed by the input coupling capacitor C_1 and the input impedance and
2) RC network formed by the output coupling capacitor and the output impedance looking in at the drain.

Input RC Network

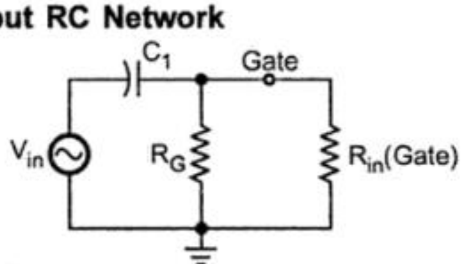


Fig. 4.9 Input RC network

Fig. 4.9 shows the input RC network formed by C_1 and the input impedance of the amplifier.

The lower critical frequency of this network can be given as,

$$f_c = \frac{1}{2\pi R_{in} C_1}$$

where $R_{in} = R_G \,||\, R_{in\,(gate)}$

The value of $R_{in\,(gate)}$ can be determined from the data sheet as follows :

$$R_{in\,(gate)} = \left|\frac{V_{GS}}{I_{GSS}}\right|$$

where I_{GSS} is the gate reverse current.

The phase shift in the low frequency input RC circuit is $\theta = \tan^{-1}\left(\frac{X_{C1}}{R_{in}}\right)$.

Output RC Network

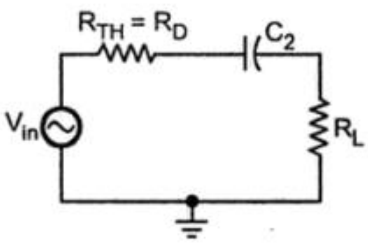


Fig. 4.10 Output RC network

Fig. 4.10 shows the output RC network formed by C_2 and the output impedance looking in at the drain.

The lower critical frequency for this network can be given as,

$$f_c = \frac{1}{2\pi(R_D + R_L)C_2}$$

The FET amplifier circuit shown in Fig. 4.8 has two critical frequencies for two networks, and network having higher critical frequency is called **dominant network.**

The phase shift in low frequency output RC circuit is $\theta = \tan^{-1}\left(\frac{X_{C2}}{R_D + R_L}\right)$.

Example : *Determine the low frequency response of the amplifier circuit shown in* Fig.

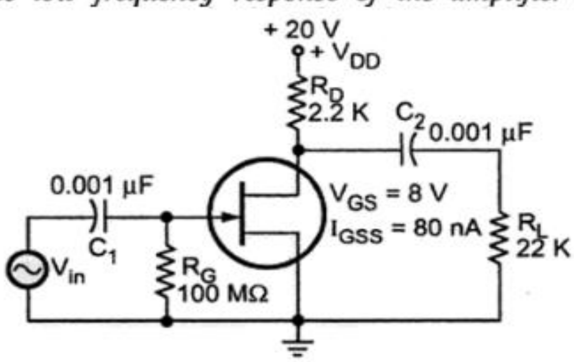


Fig.

Solution : It is necessary to analyze each network to determine the critical frequency of the amplifier.

a) Input RC Network

$$f_c = \frac{1}{2\pi R_{in} C_1}$$

where $R_{in} = R_G \,||\, R_{in\,(gate)} = R_G \,||\left|\frac{V_{GS}}{I_{GSS}}\right|$

$$= 100\,M\Omega || \frac{8}{80 \times 10^{-9}} = 100\ M\Omega\ ||\ 100\ M\Omega = 50\ M\Omega$$

$$\therefore \quad f_c = \frac{1}{2\pi \times 50 \times 10^6 \times 0.001 \times 10^{-6}} = 3.18\ Hz$$

b) Output RC Network

$$f_c = \frac{1}{2\pi(R_D + R_L)C_2} = \frac{1}{2\pi(2.2\,K + 22\,K)1 \times 10^{-6}} = 6.577\ Hz$$

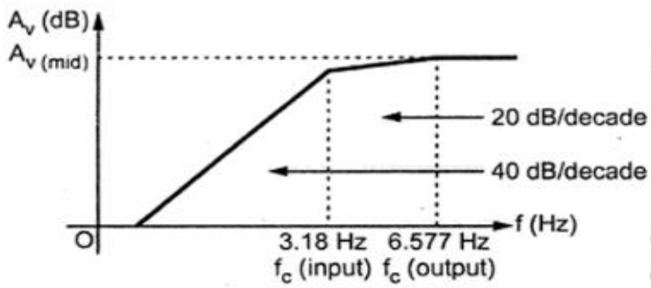


Fig. 4.11 Low frequency response of the FET amplifier

We have calculated two critical frequencies

a) f_c (input) = 3.18 Hz

b) f_c (output) = 6.577 Hz

The above analysis shows that the output network produces dominant lower critical frequency. Fig. 4.11 shows the frequency response of the given amplifier.

4.4 High Frequency analysis of BJT

Let us consider a typical common emitter amplifier as shown in Fig. 4.12.

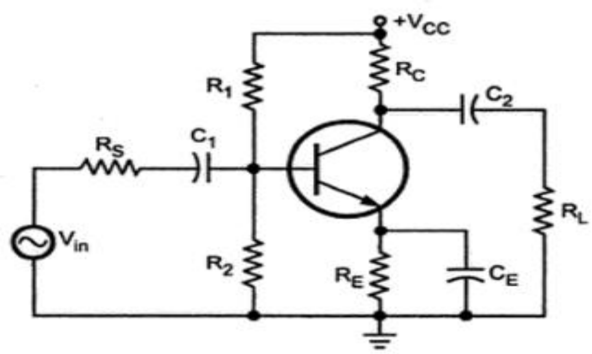


Fig. 4.12 Typical RC coupled common emitter amplifier

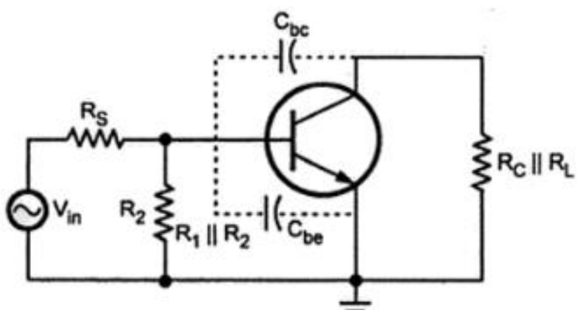


Fig. 4.13 High frequency equivalent circuit

As mentioned earlier, at high frequencies, the coupling and bypass capacitors act as a short circuit and do not affect the amplifier frequency response. However, at higher frequencies the internal capacitances do come into play. Fig. 4.13 shows the high frequency equivalent circuit for the given amplifier circuit.

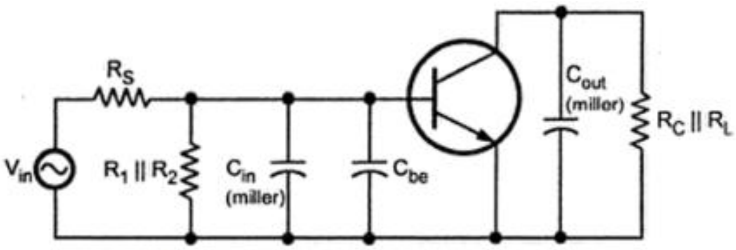


Fig. 4.14 Simplified high frequency equivalent circuit

Using Miller theorem this high frequency equivalent circuit can be further simplified as follows.

The internal capacitance C_{bc} can be splitted into $C_{in\,(miller)}$ and $C_{out\,(miller)}$ as shown in the Fig. 4.14.

where $$C_{in\,(miller)} = C_{bc}(A_v + 1)$$

and $$C_{out\,(miller)} = C_{bc}\left(\frac{A_v + 1}{A_v}\right) \approx C_{bc}$$

Fig. 4.14 shows that there are two RC networks which affect the high frequency response of the amplifier. These are :

1) Input RC Network and
2) Output RC Network

Input RC Network

Fig. 4.15 shows input RC network.

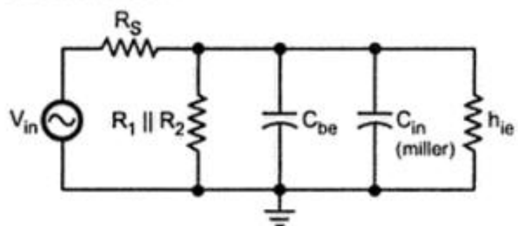


Fig. 4.15 Input RC network

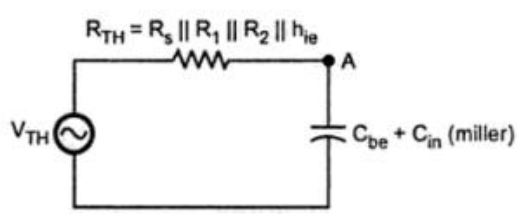


Fig. 4.16 Reduces input RC network

This network is further reduced as shown in the Fig. 4.16. At high frequencies capacitive reactance becomes smaller. If we apply voltage divider theorem, voltage at point A in Fig. 4.16 reduces as capacitive reactance reduces with increase in frequency above midrange. This reduces the signal voltage applied to the base, reducing the circuit gain and hence the output voltage.

The critical frequency can be calculated at condition capacitive reactance is equal to the resistance, i.e. $X_{C1} = R_s \,||\, R_1 \,||\, R_2 \,||\, h_{ie}$.

It is given as,

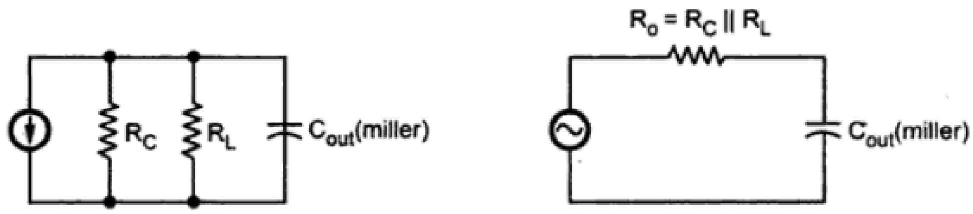
$$f_c\,(\text{input}) = \frac{1}{2\pi(R_s \,||\, R_1 \,||\, R_2 \,||\, h_{ie})C_T}$$

where $C_T = C_{bc} + C_{in\,(Miller)}$

The phase shift in high frequency input RC circuit is $\theta = \tan^{-1}\left(\frac{R_s||R_1||R_2||h_{ie}}{X_{CT}}\right)$

Output RC Network

Fig. 4.17 shows the output RC network.



(a) Output network with current source (b) Output network with voltage source

Fig. 4.17

The critical frequency can be given as

$$f_c\,(\text{output}) = \frac{1}{2\pi R_o\, C_{out\,(miller)}} \approx \frac{1}{2\pi(R_C \,||\, R_L)\,C_{bc}}$$

We have seen that both the networks have critical frequencies. It is not necessary that these frequencies should be equal. The network which has lower critical frequency than other network is called **dominant network.**

The phase shift in high frequency output RC network is $\theta = \tan^{-1}\left(\frac{R_o}{X_{C\,out(Miller)}}\right)$

Example *Determine the high frequency response of the amplifier circuit shown in Fig.*

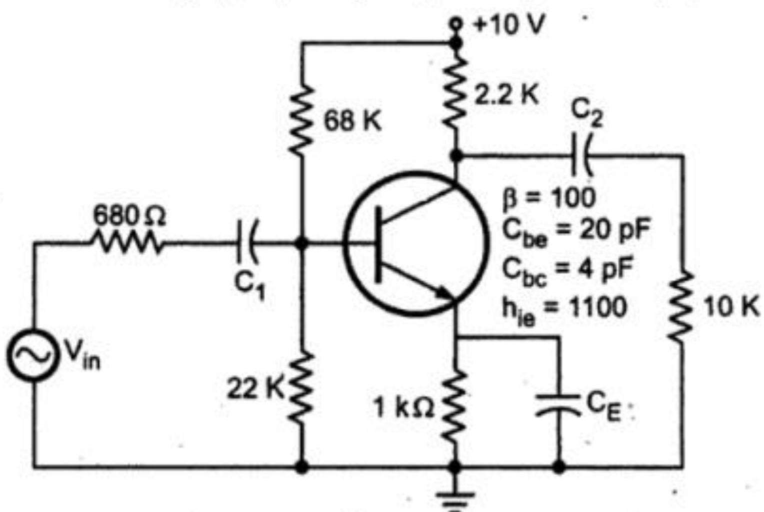


Fig.

Solution : Before calculating critical frequencies it is necessary to calculate mid frequency gain of the given amplifier circuit. This is required to calculate $C_{in\,(miller)}$ and $C_{out\,(miller)}$.

$$A_v = \frac{-h_{fe} R_o}{R_i}$$

where $R_i = h_{ie} \,||\, R_1 \,||\, R_2$

and $R_o = R_C \,||\, R_L$

$$\therefore \quad A_v = \frac{-h_{fe}(R_C \,||\, R_L)}{h_{ie} \,||\, R_1 \,||\, R_2} = \frac{-100\,(2.2\,K \,||\, 10\,K)}{1100 \,||\, 68\,K \,||\, 22\,K}$$

$$= \frac{-100\,(1.8\,K)}{1.032\,K} = -174.4$$

Negative sign indicates 180° phase shift between input and output.

$$C_{in\,(miller)} = C_{bc}(A_v + 1) = 4pF\,(174.4 + 1) = 0.7016\ nF$$

$$C_{out\,(miller)} = \frac{C_{bc}(A_v + 1)}{(A_v)} = \frac{4\,pF\,(174.4 + 1)}{(174.4)} = 4\ pF$$

We now analyze input and output network for critical frequency.

$$f_c\,(input) = \frac{1}{2\pi(R_s \,||\, R_1 \,||\, R_2 \,||\, h_{ie})(C_{bc} + C_{in\,(miller)})}$$

$$= \frac{1}{2\pi(680 \,||\, 68\,K) \,||\, 22\,K \,||\, 1100)(20\,pF + .7016\,nF)}$$

$$= \frac{1}{2\pi(410)(0.7216 \times 10^{-9})} = 537947\ Hz = \mathbf{537.947\ kHz}$$

$$f_c\,(output) = \frac{1}{2\pi(R_C \,||\, R_L)\,C_{out\,(miller)}} = \frac{1}{2\pi(2.2\,K \,||\, 10\,K) \times 4\,pF}$$

$$= \mathbf{22.1\ MHz}$$

We have calculated both the critical frequencies :

a) f_c (input) = **537.947 kHz**

b) f_c (output) = **22.1 MHz**

The above analysis shows that the input network produces the dominant higher critical frequency. Fig. 4.18 shows high frequency response of the given amplifier.

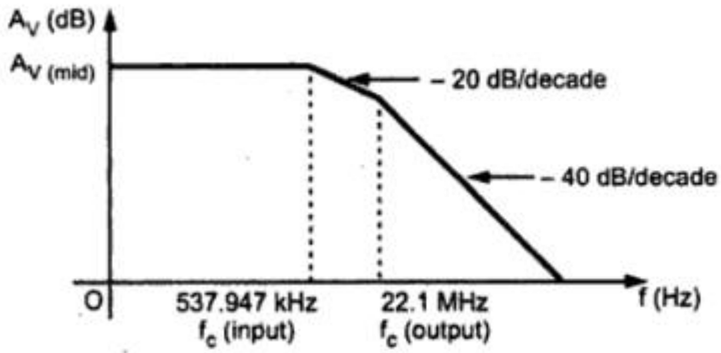


Fig. 4.18 High frequency response of the amplifier

4.5 High Frequency analysis of FET

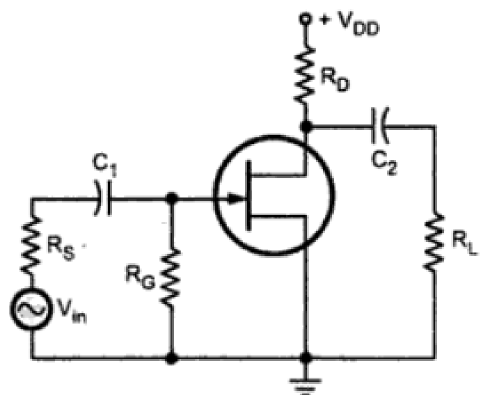


Fig. 4.19 Typical RC coupled common source amplifier

Let us consider a typical common source amplifier as shown in Fig. 4.19.

Fig. 4.20 shows the high frequency equivalent circuit for the given amplifier circuit. It shows that at high frequencies coupling and bypass capacitors act as short circuits and do not affect the amplifier high frequency response. The equivalent circuit shows internal capacitances which affect the high frequency response.

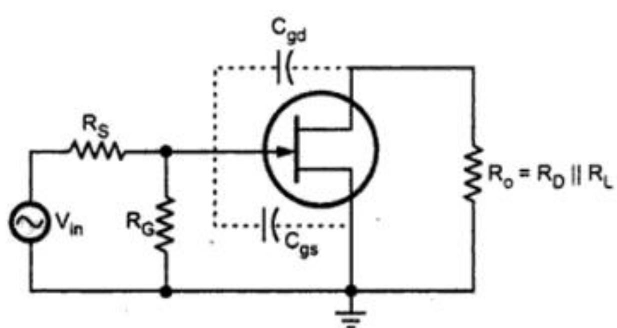


Fig. 4.20 High frequency equivalent circuit

Using Miller theorem this high frequency equivalent circuit can be further simplified as follows :

The internal capacitance C_{gd} can be splitted into $C_{in\,(miller)}$ and $C_{out\,(miller)}$ as shown in the Fig. 4.21.

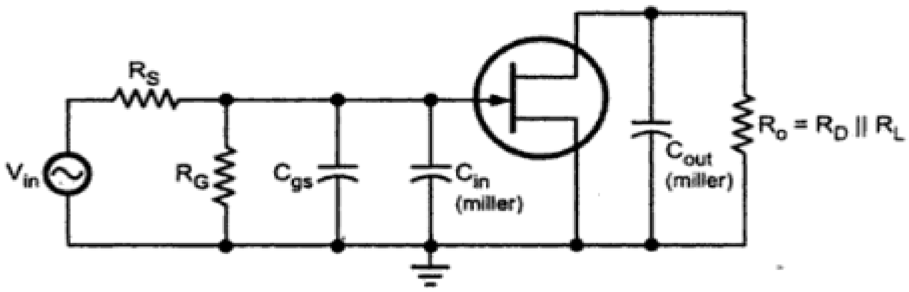


Fig. 4.21 Simplified high frequency equivalent circuit

where

$$C_{in\,(miller)} = C_{gd}\,(A_v + 1)$$

$$C_{out\,(miller)} = C_{gd}\,\frac{(A_v + 1)}{(A_v)}$$

FET data sheets do not directly provide values for C_{gs} and C_{gd} . The data sheet normally provides values for input capacitance, C_{iss} and the reverse transfer capacitance C_{rss}. From C_{iss} and C_{rss} the values for C_{gd} and C_{gs} can be calculated as follows :

$$C_{gd} = C_{rss}$$

$$C_{gs} = C_{iss} - C_{rss}$$

Fig. 4.21 shows that there are two RC networks which affect the high frequency response of the amplifier. These are :

1) Input RC network and
2) Output RC network

Input RC Network

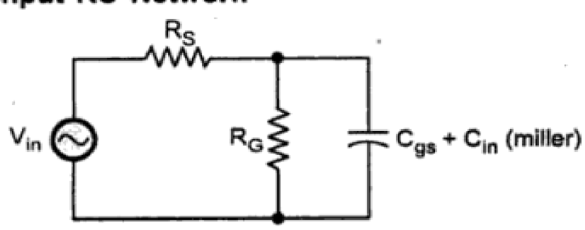


Fig. 4.22 Input RC network

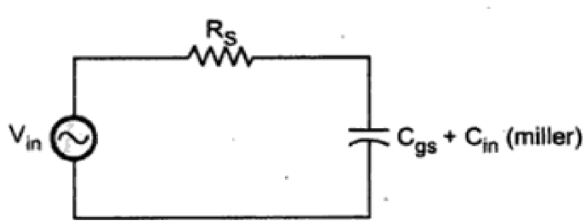


Fig. 4.23 Reduced input RC network

Fig. 4.22 shows input RC network.

This network is further reduced as shown in the Fig. 4.23 , since $R_s << R_G$.

The critical frequency for the reduced input RC network is given as

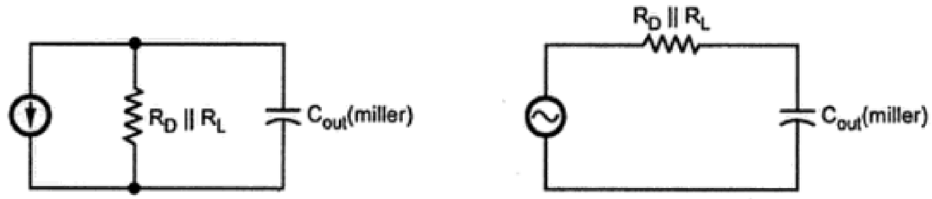
$$f_{c\,(input)} = \frac{1}{2\pi R_s C_T}$$

$$\text{or} \quad f_c = \frac{1}{2\pi R_s\ [C_{gs} + C_{in\,(miller)}]}$$

The phase shift in high frequency input RC network is $\theta = \tan^{-1}\left(\frac{R_s}{X_{C_T}}\right)$.

Output RC Network

Fig. 4.24 shows output RC network.



(a) Output network with current source (b) Output network with voltage source

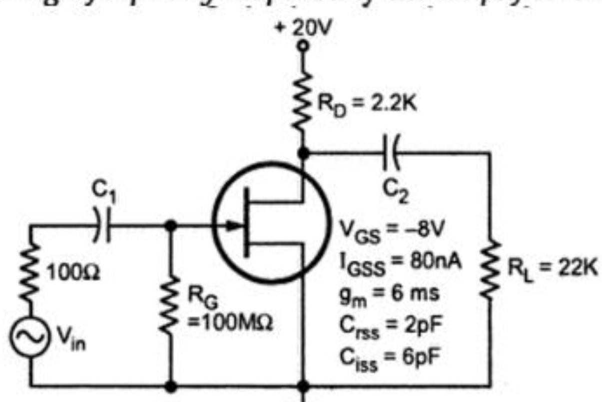
Figure 4.24

The critical frequency for the above circuit is given as

$$f_c = \frac{1}{2\pi R_o\ C_{out\,(miller)}} = \frac{1}{2\pi(R_D \| R_L)\,C_{out\,(miller)}}$$

We have seen that both the networks have critical frequencies. It is not necessary that these frequencies should be equal. The network which has lower critical frequency than other network is called dominant network.

Example : *Determine the high frequency response of the amplifier circuit shown in Fig.*



Figure

Solution : Before calculating critical frequencies it is necessary to calculate mid frequency gain of the given amplifier circuit. This is required to calculate $C_{in\,(Miller)}$ and $C_{out\,(Miller)}$.

$$A_v = -g_m R_D$$

Here, R_D should be replaced by $R_D \| R_L$.

$$\therefore \quad A_v = -g_m(R_D \| R_L) = -6\,mS(2.2\,K \| 22\,K) = -6\,mS\,(2\,K) = -12$$

$$C_{in\,(Miller)} = C_{gd}(A_v + 1) = C_{rss}(A_v + 1) = 2\,pF\,(12 + 1) = 26\,pF$$

$$C_{out\,(Miller)} = \frac{C_{gd}(A_v + 1)}{(A_v)} = \frac{C_{rss}(A_v + 1)}{(A_v)} = \frac{2\,pF(12 + 1)}{12} = 2.166\,pF$$

$$C_{gs} = C_{iss} - C_{rss} = 4\,pF$$

We now analyze input and output network for critical frequency

$$f_{c\,(input)} = \frac{1}{2\pi R_s C_T}$$

$$= \frac{1}{2\pi R_s \times [C_{gs} + C_{in\,(miller)}]}$$

$$= \frac{1}{2\pi \times 100 \times [4\text{ pF} + 26\text{ pF}]}$$

$$= \frac{1}{2\pi \times 100 \times [30\text{ pF}]} = 53\text{ MHz}$$

$$f_{c\,(output)} = \frac{1}{2\pi (R_D \,||\, R_L) \times C_{out\,(Miller)}}$$

$$= \frac{1}{2\pi (2.2\text{ K} \,||\, 22\text{ K}) \times 2.166\text{ pF}}$$

$$= 36.74\text{ MHz}$$

We have calculated both the critical frequencies :

a) f_c (input) = 53 MHz b) f_c (output) = 36.74 MHz.

The above analysis shows that the output network produces the dominant higher critical frequency. High frequency response of the given amplifier is shown in Fig. 4.25.

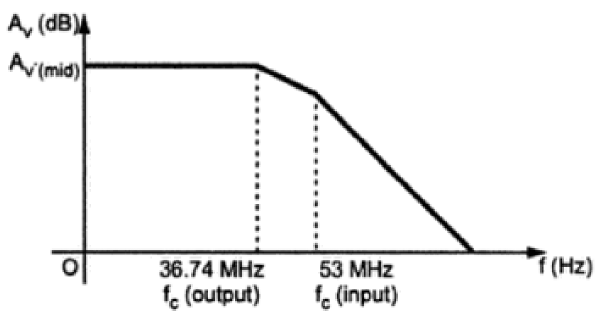


Figure 4.25 High frequency response of the amplifier

4.6 Miller's Effect

Miller effect is the increase in the equivalent input capacitance of a voltage amplifier due to a capacitance connected between two gain-related nodes, one on the input side of an amplifier and the other the output side.

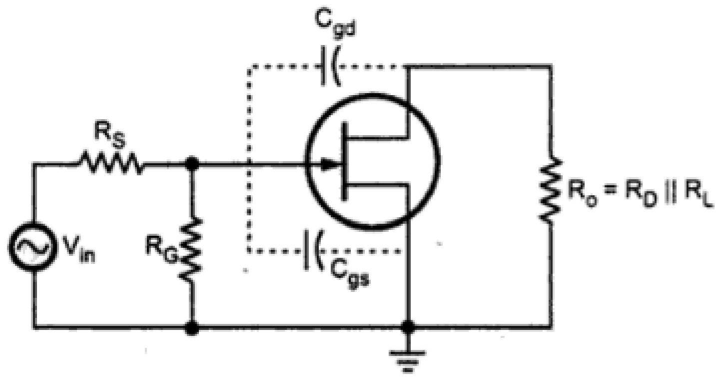


Fig. High frequency equivalent circuit

4.6.1 Miller Capacitance

Using Miller theorem this high frequency equivalent circuit can be further simplified as follows :

The internal capacitance C_{gd} can be splitted into $C_{in\,(miller)}$ and $C_{out\,(miller)}$ as shown in the Fig.

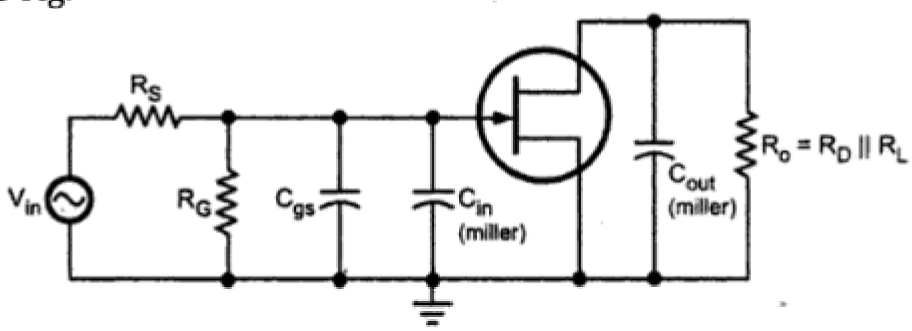


Fig. Simplified high frequency equivalent circuit

where

$$C_{in\,(miller)} = C_{gd}\,(A_v + 1)$$

$$C_{out\,(miller)} = C_{gd}\,\frac{(A_v + 1)}{(A_v)}$$

4.7 Multistage amplifiers

It has been observed that the voltage (or power) gain, obtained from a single stage small signal amplifier, is limited. Moreover, it is not sufficient for all practical applications. Therefore in order to achieve greater voltage and power gain, we have to use more than one stage of amplification. Such an amplifier is called a *multistage amplifier*. It will be interesting to know that when we use multistage amplifier, then we feed the output of one stage to the input of the next as shown in Figure 4.26. Such a connection of amplifiers is called *cascading*. The amplifier used in radio and television receivers is, usually, a multistage amplifier.

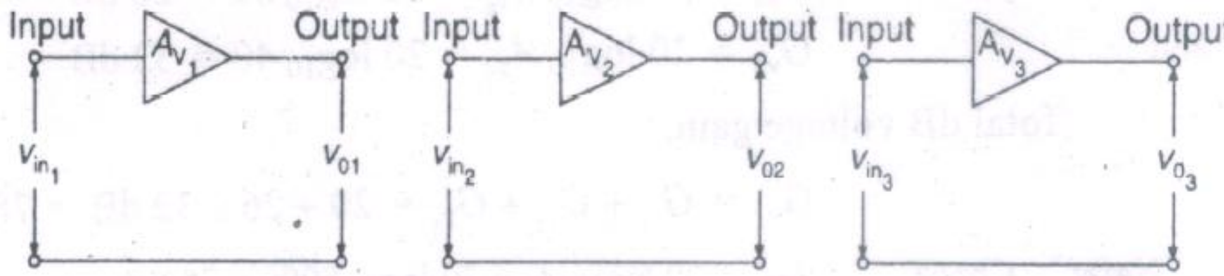


Fig. 4.26. A general multistage amplifier.

4.7.1 Gain of a multistage amplifiers

We have already discussed in the last article that in a multistage amplifier the output voltage of the first stage acts as an input voltage to the second stage. And the output voltage of second stage as an input to the third stage and so on. *The voltage gain of a multistage amplifier is equal to the product of the gains of the individual stages*. Thus if A_{v_1}, A_{v_2} and A_{v_3} are the individual stage gains, then overall voltage gain,

$$A_v = A_{v_1} \times A_{v_2} \times A_{v_3}$$

The amplifier voltage gain may also be expressed in decibels (dB). However, in that case the overall decibel voltage gain is the sum of the decibel gains of the individual stages. Thus if G_{v_1}, G_{v2} and G_{v3} are the individual stage decibel gains, then overall decibel voltage gain,

$$G_v = G_{v_1} + G_{v_2} + G_{v_3}$$
$$= 20\log_{10} A_{v_1} + 20\log_{10} A_{v_2} + 20\log_{10} A_{v_3}$$
$$= 20\log_{10} A_v \text{ (dB)}$$

Similarly, the overall current amplification,

$$A_i = A_{i_1} \times A_{i_2} \times A_{i_3}$$

Then the overall power gain,

$$A_p = A_v \cdot A_i$$

and the overall decibel power gain,

$$G_p = 10\log_{10} A_p$$

Example *A given amplifier arrangement has the following voltage gains. $A_{v1} = 10$, $A_{v2} = 20$ and $A_{v3} = 40$. What is the overall voltage gain? Also express each gain in dB and determine the total dB voltage gain.*

Solution. Given: $A_{v_1} = 10$; $A_{v_2} = 20$ and $A_{v_3} = 40$

Overall voltage gain

We know that the overall voltage gain,

$$A_v = A_{v1} \times A_{v2} \times A_{v3} = 10 \times 20 \times 40 = 8000 \textbf{ Ans.}$$

Total dB voltage gain

We know that dB voltage gain of the first stage

$$G_{v1} = 20 \log_{10} A_{v_1} = 20 \log_{10} 10 = 20 \text{ dB}$$

Similarly, $$G_{v2} = 20 \log_{10} A_{v_2} = 20 \log_{10} 20 = 26 \text{ dB}$$

and $$G_{v3} = 20 \log_{10} A_{v_3} = 20 \log_{10} 40 = 32 \text{ dB}$$

∴ Total dB voltage gain,

$$G_v = G_{v_1} + G_{v_2} + G_{v_3} = 20 + 26 + 32 \text{ dB} = 78 \text{ dB}$$ **Ans.**

Note: Check $G_v = 20 \log_{10} A_v = 20 \log_{10} 8000 = 78$ dB.

4.7.2 Need for multistage amplifiers

- **When the amplification of a single stage amplifier is not sufficient, or,**
- **When the input or output impedance is not of the correct magnitude, for a particular application two or more amplifier stages are connected, in cascade. Such amplifier, with two or more stages is also known as multistage amplifier.**

4.8 Methods of interconnecting multistage amplifiers

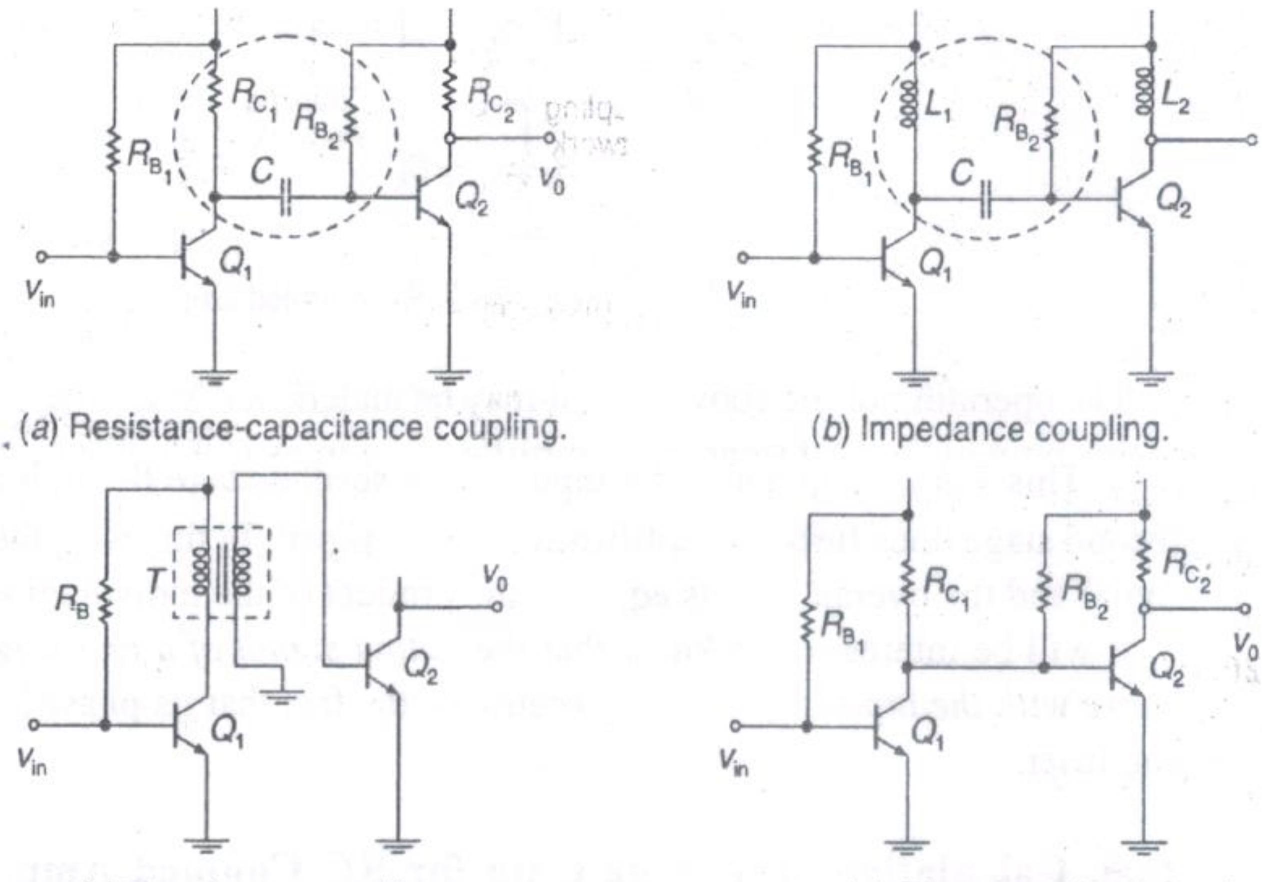
As a matter of fact, all amplifiers, need some kind of *coupling* network. Even a single stage amplifier, needs coupling to the input source and output load. The multistage amplifiers need coupling between their individual stages. This type of coupling is called interstage coupling. It serves the following two purposes:

1. It transfers a.c. output of one stage to the input of the next stage.
2. It isolates the d.c. conditions of one stage to the next. It is necessary to prevent the shifting of *Q*-points.

The coupling network (or coupling device) must ensure that both the above purposes are fulfilled, when an a.c. signal is to be amplified. Following are the four coupling schemes used in amplifiers.

1. *Resistance-capacitance (RC) coupling*. It is the most important method of coupling the signal from one stage to the next and is shown in Figure 4.27 (*a*). In this method, the signal developed across the collector resistor of each stage is coupled through capacitor into the base of the next stage. The cascaded stages amplify the signal and the overall gain is equal to the product of individual stage gains. The amplifiers, using this coupling scheme, are called *RC-coupled amplifiers*.

2. *Impedance coupling*. This coupling is shown in Figure 4.27 (*b*). It may be noted that the collector resistor (R_C) is replaced by an inductor (L). As the frequency increases, inductive reactance X_L (equal to $\omega \cdot L$) approaches infinity and each inductor appears open. In other words, the inductors pass direct current but block alternating current. The amplifiers, using this coupling scheme, are called *impedance-coupling amplifiers*.



(*a*) Resistance-capacitance coupling.

(*b*) Impedance coupling.

(*c*) Transformer coupling.

(*d*) Direct coupling.

Fig. 4.27. Coupling schemes in amplifiers.

3. *Transformer coupling*. This coupling is shown in Figure 4.27 (*c*). In this method, primary winding of the transistor acts as a collector load and the secondary winding conveys the a.c. output signal directly to the base of the next stage. It may be noted that there is no need of coupling capacitor in the transformer coupling. The amplifiers, using this coupling scheme, are called *transformer-coupled amplifiers*.

4. *Direct-coupling*. This coupling is shown in Figure 4.27 (*d*). In this method, the a.c. output signal is fed directly to the next stage. This type of coupling is used where low frequency signals are to be amplified. The coupling devices such as capacitors, inductors and transformers cannot be used at low frequencies because their size becomes very large. The amplifiers, using this coupling scheme, are called *direct coupled amplifiers or d.c. amplifiers*.

4.8.1 Comparison of different coupling methods

Parameter	RC Coupled	Transformer Coupled	Direct Coupled
Coupling Components	Resistor and Capacitor	Impedance matching transformer	–
Block DC	Yes	Yes	No
Frequency response	Flat at middle frequencies	Not uniform, high at resonant frequency and low at other frequencies	Flat at middle frequencies and improvement in the low frequency response
Impedance matching	Not achieved	Achieved	Not achieved
DC amplification	No	No	Yes
Weight	Light	Bulky and heavy	
Drift	Not present	Not present	Present
Hum	Not present	Present	Not present
Application	Used in all audio small signal amplifiers. Used in record players, tape recorders, public address systems, radio receivers and television receivers.	Used in amplifier where impedance matching is an important criteria. Used in the output stage of the pubic address system to match the impedance of loudspeaker. Used in the RF amplifier stage of the receiver as a tuned voltage amplifier.	Used in amplification of slow varying parameters and where DC amplification is required.

4.9 Types of Multistage amplifiers

- RC coupled Amplifiers (or) Cascade amplifier
- Direct Coupled Amplifiers
- Transformer Coupled Amplifiers
- Cascode amplifier
- Darlington Emitter Follower Amplifier

4.10 Two stage RC Coupled amplifiers (or) Cascade amplifier

Figure 4.28 shows a two-stage RC coupled transistor amplifier. The circuit consists of two single-stage common emitter transistor amplifiers. The resistors R_C, R_B and capacitor C_C form the coupling network. The capacitor C_1 is used to couple the input signal to the base of Q_1, while the capacitor C_2 is used to couple the output signal from the collector of Q_2 to the load. The capacitor C_E, connected at the emitters of Q_1 and Q_2, are needed because they *bypass* the emitter to the ground. Without these capacitors, the voltage gain of each stage will be lost.

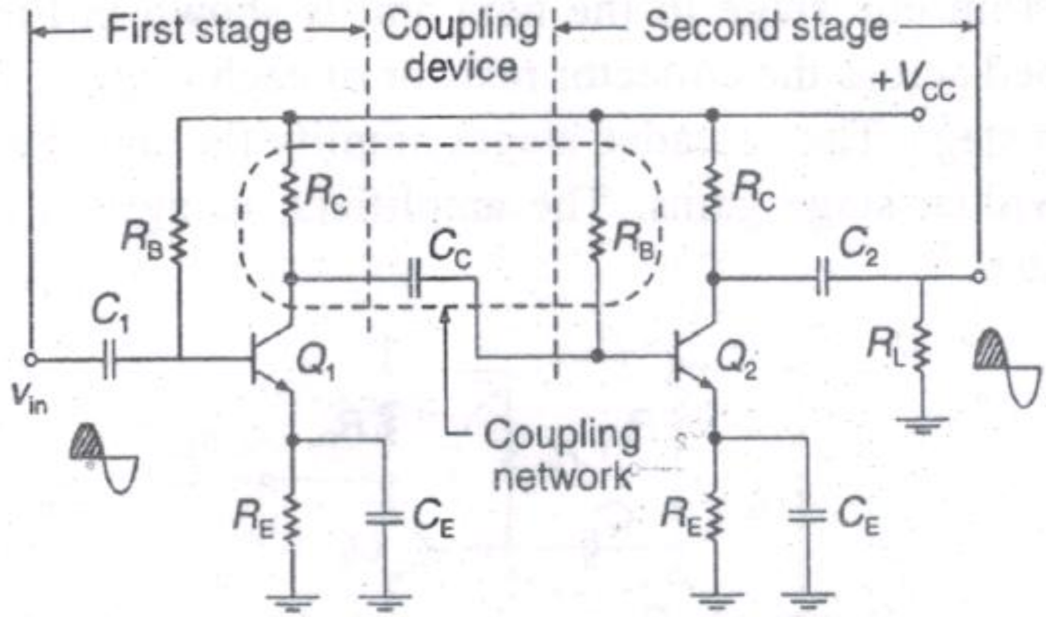


Fig. 4.28. RC coupled amplifier.

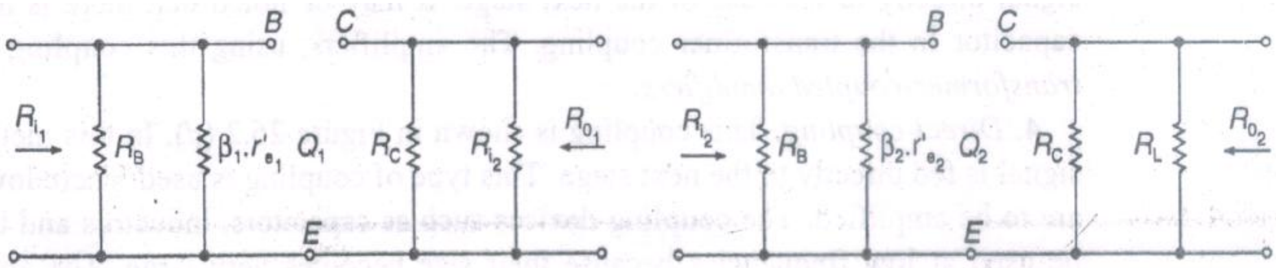
The operation of the above circuit may be understood as follows: When an a.c. signal is applied to the input of the first stage, it is amplified by a transistor and appears across the collector resistor (R_C). This signal is given to the input of the second stage through a coupling capacitor C_C. The second stage does further amplification of the signal. In this way, the cascaded stages amplify the signal and the overall gain is equal to the product of the individual stage gains.

It will be interesting to know that the *output signal of a two-stage RC coupled amplifier is in phase with the input signal*. It is because of the fact that its phase has been reversed twice by the amplifier.

4.10.1 Calculation of Voltage Gain for RC Coupled Amplifier

Consider a two stage RC coupled transistor amplifier circuit as shown in Figure 4.28. The a.c. equivalent circuit for each amplifying stage of that circuit is shown in Figure 4.29 (*a*) and (*b*) respectively. Here we have not shown the complete small signal a.c. equivalent circuit of the transistor. Rather, it is represented by an a.c. emitter diode resistance ($\beta \cdot r'_e$) and the three points marked *E* (for emitter), *B* (for base) and *C* (for collector). It has been done because a.c. equivalent circuit of a transistor is slightly different at low and high-frequencies.

The parameters R_{i_1} and R_{o_1}, in the equivalent circuits shown below, represent the input resistance and output resistance of the first stage respectively. Similarly, the parameters R_{i_2} and R_{o_2} represent the input resistance and output resistance of the second stage.



(*a*) A.C. equivalent circuit for first stage. (*b*) A.C. equivalent circuit for second stage.

Fig. 4.29. A.C. equivalent circuit of a two-stage RC coupled amplifier.

The parameters r'_{e1} and r'_{e2} represent the a.c. emitter diode resistances of the transistors Q_1 and Q_2 respectively. The values of r'_{e1} and r'_{e2} may be obtained from the relations,

$$r'_{e1} = \frac{25}{I_{E_1}} \quad \text{and} \quad r'_{e2} = \frac{25}{I_{E_2}}$$

where I_{E_1} and I_{E_2} are the values of emitter current in milliamperes. Now the input resistance of the first stage as seen from the Figure 26.4 (*a*),

$$R_{i_1} = R_B \parallel (\beta_1 \cdot r'_{e1}) = \beta_1 \cdot r'_{e1} \qquad \text{... (If } R_B >> \beta_1 \cdot r'_{e1})$$

and the output resistance,

$$R_{o_1} = R_C \parallel R_{i_2}$$

where R_{i_2} is the input resistance of the second stage and its value is given by the relation,

$$R_{i_2} = R_B \parallel (\beta_2 \cdot r'_{e2}) = \beta_2 \cdot r'e_2 \qquad \text{... (If } R_B >> \beta_2 \cdot r'_{e2})$$

The output resistance of the second stage,

$$R_{o_2} = R_C \parallel R_L$$

Now the voltage gain of the first stage,

$$A_{v_1} = \beta_1 \times \frac{R_{o_1}}{R_{i_1}} = \beta_1 \times \frac{R_{o1}}{\beta_1 \cdot r'_{e_1}} = \frac{R_{o_1}}{r'_{e_1}}$$

Similarly, voltage gain of the second stage,

$$A_{v_2} = \frac{R_{o_2}}{r'_{e_2}}$$

∴ Overall voltage gain of the amplifier,

$$A_v = A_{v_1} \cdot A_{v_2} = \frac{R_{o_1}}{r'_{o_1}} \times \frac{R_{o_2}}{r'_{o_2}}$$

If the transistors used in both the stages are identical, then current gain of the transistors Q_1 and Q_2 (*i.e.*, β_1 and β_2) will be equal. In that case, the emitter currents will also be equal. Thus $r'_{e_1} = r'_{e_2} = r_e$. Then overall voltage gain,

$$A_v = R_{o_1} \cdot R_{o_2} / r_e^2$$

4.10.2 Frequency Response of RC Coupled Amplifier

The frequency response of an amplifier is a graph, which indicates the relationship between the voltage gain as a function of frequency. Usually, the voltage gain (in decibels) is plotted along the vertical axis and the frequency (in hertz or kilohertz) along the horizontal axis of the frequency response graph. Figure 4.30 shows the frequency response of RC coupled amplifier.

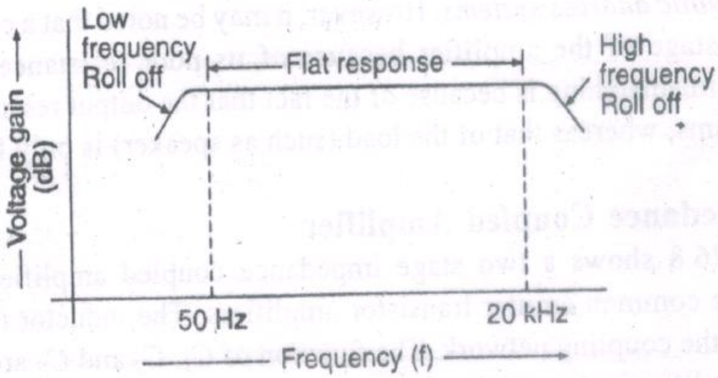


Fig. 4.30 Frequency response of RC coupled amplifier.

It is evident from the graph that the voltage gain *drops off* (or rolls off) at low frequencies (*i.e.*, frequencies below 50 Hz) and at high frequencies (*i.e.*, frequencies above 20 kHz), while it remains *constant* in the mid-frequency range. The behaviour is discussed in more detail as follows:

1. *At low frequencies (i.e., below 50 Hz)*. We know that the capacitive reactance (X_C) is inversely proportional to the frequency. Thus at low frequencies, the reactance of the capacitor C_C is quite large. Therefore it will allow only a small part of the signal to pass from one stage to the next stage. In addition to this, the emitter bypass capacitor (C_E) cannot shunt the emitter resistor effectively, because of its large reactance at low frequencies. As a result of these two factors, the voltage gain rolls off at low frequencies.

2. *At high frequencies (i.e., above 20 kHz)*. In this frequency range, the reactance of capacitor C_C becomes quite small, therefore it behaves like a short-circuit. As a result of this, the loading effect of the next stage increases, which reduces the voltage gain. In addition to this, the capacitance of the emitter diode plays an important role at high frequencies. It increases the base current of the transistor due to which the *current gain (β) reduces*. Hence the voltage gain rolls off at high frequencies.

3. *At mid-frequencies (i.e., 50 Hz to 20 kHz)*. The effect of coupling capacitor, in this frequency range, is such that it maintains a constant voltage gain. Thus as the frequency increases, the reactance of capacitor C_C decreases, which tends to increase the gain. However, at the same time, the lower capacitive reactance increases the loading effect of the next stage due to which the gain reduces. These two factors almost cancel each other. Thus a constant gain is maintained throughout this frequency range.

4.10.3 Advantages and Disadvantages of RC Coupled Amplifier

Advantages

1. It is the most convenient and least expensive multistage amplifier.
2. It has a wide frequency response *i.e.*, its gain versus frequency curve remains constant over a wide frequency range.
3. It provides less frequency distortion.

Disadvantages

1. The overall gain of the amplifier is comparatively small because of the loading effect of successive stages.
2. It has a tendency to become noisy with age, especially in moist climates.
3. It provides poor resistance (or impedance) matching between the stages.

4.10.4 Applications of RC Coupled Amplifiers

We have already discussed in Art. 4.30 that an RC coupled amplifier has an excellent frequency response from 50 Hz to 20 kHz. This property makes it very useful in the initial stages of all the *public address systems*. However, it may be noted that a coupled amplifier cannot be used as a final stage of the amplifier because of its poor resistance matching characteristics. The resistance mismatching is because of the fact that the output resistance of the amplifier is several hundred ohms, whereas that of the load (such as speaker) is only few ohms.

Example *Figure shows the circuit of a two stage RC coupled amplifier.*

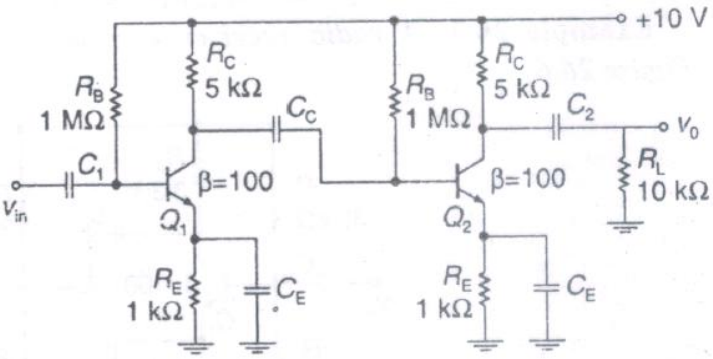


Fig.

Determine the values of input resistance, output resistance, current gain, voltage gain for the first and second stages. Also determine the overall voltage gain and overall dB voltage gain.

Solution. Given: V_{CC} = 10 volts; R_C = 5 kΩ = 5000 Ω; R_B = 1 MΩ = 1×10^6 Ω; R_E = 1 kΩ = 1×10^3 Ω; R_L = 10 kΩ = 10 000 Ω and $\beta_1 = \beta_2 = 100$.

Input resistance of the first and second stage

We know that the value of emitter current for the first as well as second stage,

$$I_E = \frac{V_{CC}}{R_E + \frac{R_B}{\beta}} = \frac{10}{1 \times 10^3 + \frac{1 \times 10^4}{100}}$$

$$= 0.91 \times 10^{-3} \text{ A} = 0.91 \text{ mA}$$

and the value of a.c. emitter diode resistance,

$$r'_e = \frac{25}{I_E} = \frac{25}{0.91} = 27.5\ \Omega$$

∴ Input resistance of the first stage,

$$R_{i_1} = \beta \cdot r'_e = 100 \times 27.5 = 2750\ \Omega\ \textbf{Ans.}$$

and input resistance of the second stage,

$$R_{i_2} = \beta \cdot r'_e = 100 \times 27.5 = 2750\ \Omega\ \textbf{Ans.}$$

Output resistance of the first and second stage

We know that output resistance of the first stage,

$$R_{o_1} = R_C \parallel R_{i_2} = 5000 \parallel 2750 = 1774\ \Omega\ \textbf{Ans.}$$

and output resistance of the second stage,

$$R_{o_2} = R_C \parallel R_L = 5000 \parallel 10\,000 = 3333\ \Omega\ \textbf{Ans.}$$

Voltage gain of the first and second stage,

We know that the voltage gain of the first stage,

$$A_{v_1} = \frac{R_{o_1}}{r'_e} = \frac{1774}{27.5} = 64.5\ \textbf{Ans.}$$

and voltage gain of the second stage,

$$A_{v_2} = \frac{R_{o_2}}{r'_e} = \frac{3333}{27.5} = 121.2\ \textbf{Ans.}$$

Overall voltage gain and dB voltage gain

We also know that the overall voltage gain,

$$A_v = A_{v_1} \cdot A_{v_2} = 64.5 \times 121.2 = 7817.4\ \textbf{Ans.}$$

and the overall dB voltage gain,

$$G_v = 20 \log_{10} A_v = 20 \log_{10} 7817.4 = 77.9\ \text{dB}\ \textbf{Ans.}$$

Example *A radio receiver uses a two stage RC coupled amplifier as shown in Figure Determine the values of voltage gain of each stage and overall voltage gain. Also express the overall voltage gain in decibels.*

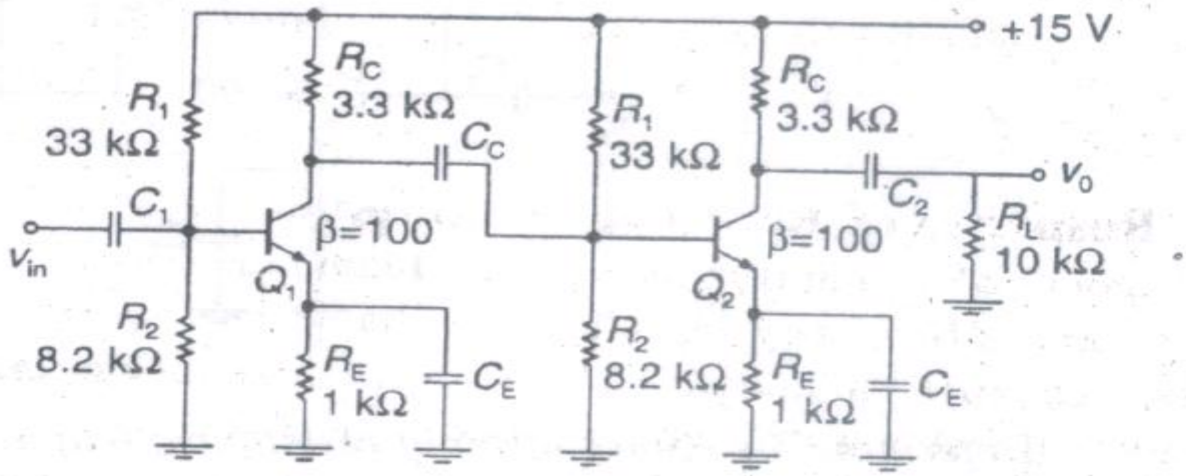


Fig.

Solution. Given: V_{CC} = 15 volts; R_C = 3.3 kΩ = 3300 Ω; R_E = 1 kΩ = 1000 Ω; R_1 = 33 kΩ; R_2 = 8.2 kΩ; R_L = 10 kΩ = 10 000 Ω and $\beta_1 = \beta_2 = 100$.

Voltage gain of each stage

We know that voltage drop across the resistor R_2,

$$V_{TH} = V_{CC}\left(\frac{R_2}{R_1 + R_2}\right) = 15\left(\frac{8.2}{33 + 8.2}\right) \text{ V} = 2.985 \text{ V}$$

and the parallel combination of resistances R_1 and R_2,

$$R_{TH} = R_1 \,||\, R_2 = 33 \,||\, 8.2 = 6.57 \text{ k}\Omega = 6570 \ \Omega$$

∴ Emitter current,

$$I_E = \frac{V_{TH} - V_{BE}}{R_E + \frac{R_{TH}}{\beta}} = \frac{2.985 - 0.7}{1000 + \frac{6570}{100}} \text{ A}$$

$$= 2.14 \times 10^{-3} \text{ A} = 2.14 \text{ mA}$$

and the a.c. emitter diode resistance,

$$\therefore r'_e = \frac{25}{I_E} = \frac{25}{2.14} = 11.7 \ \Omega$$

We also know that input resistance of the second stage,

$$R_{i_2} = \beta \cdot r'_e = 100 \times 11.7 = 1170 \ \Omega$$

and the output resistance of the first stage,

$$R_{o_1} = R_C \,||\, R_{i_2} = 3300 \,||\, 1170 = 864 \ \Omega$$

Similarly, output resistance of the second stage,

$$R_{o_2} = R_C \,||\, R_L = 3300 \,||\, 10\,000 = 2481 \ \Omega$$

∴ Voltage gain of the first stage,

$$A_{v_1} = \frac{R_{o_1}}{r'_e} = \frac{864}{11.7} = 73.8 \textbf{ Ans.}$$

and voltage gain of the second stage,

$$A_{v_2} = \frac{R_{o_2}}{r'_e} = \frac{2481}{11.7} = 212 \textbf{ Ans.}$$

Overall voltage gain

We know that the overall voltage gain,

$$A_v = A_{v_1} \cdot A_{v_2} = 73.8 \times 212 = 15\ 646 \textbf{ Ans.}$$

Overall voltage in decibels

We also know that the overall voltage gain in decibels (called the dB voltage gain),

$$G_v = 20 \log_{10} A_v = 20 \log_{10} 15\ 646 = 83.9 \text{ dB} \textbf{ Ans.}$$

4.11 Two stage Transformer Coupled Amplifiers

Figure 4.31 shows a two-stage transformer coupled amplifier. The circuit consists of two single-stage common emitter transistor amplifiers. The function of transformer (T_1) is to couple the a.c. output signal from the output of the first stage to the input of the second stage, while transformer (T_2) couples the output signal to the load. The input coupling capacitor is C_1, while the emitter bypass capacitor is C_E,

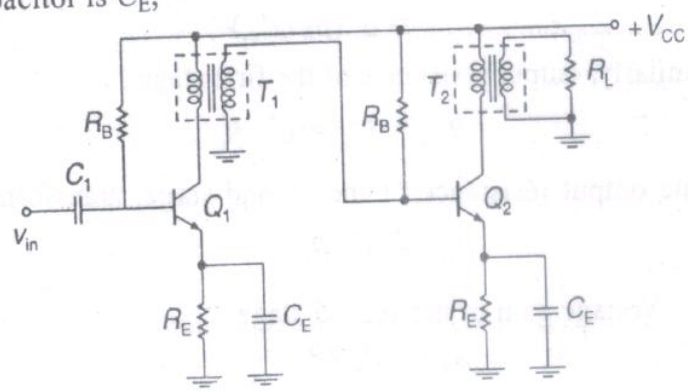


Figure 4.31 Two stage Transformer Coupled Amplifier

The operation of the above circuit may be understood from the condition that when an a.c. input signal is applied to the base transistor Q_1, it appears in the amplified form across primary winding of the transformer (T_1). The voltage developed across the primary winding is then transferred to the input of the next stage by the secondary winding of the transformer (T_1). The second stage does amplification in an exactly similar manner.

In actual practice, a bypass capacitor is used on the bottom of each primary winding to produce an a.c. ground. This avoids the load inductance of the connecting line that returns to the d.c. supply point. Similarly, a bypass capacitor is used on the bottom of each secondary winding to get an a.c. ground. This prevents the signal power loss in the biasing resistors.

4.11.1 Calculations of Voltage Gain for Transformer Coupled Amplifier

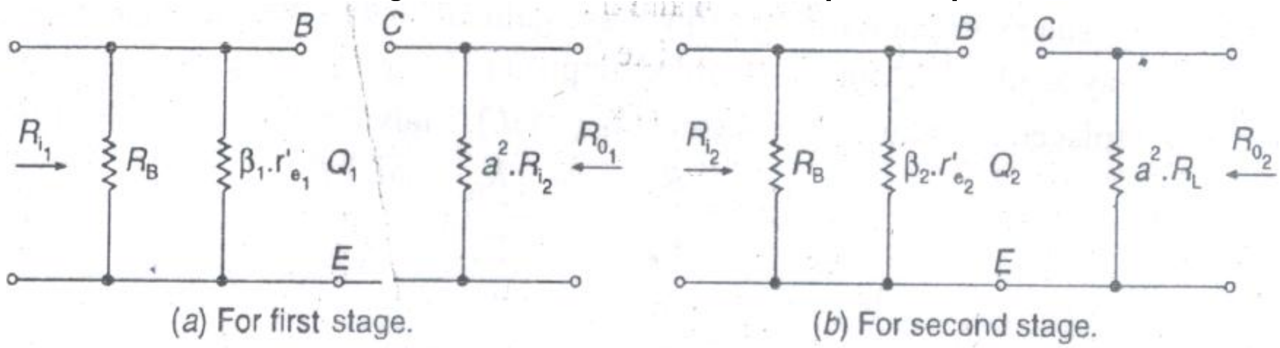


Fig. 4.32. A.C. equivalent circuit for two stage transformer coupled amplifier.

Consider the circuit of a two-stage transformer coupled amplifier shown in Figure 4.31. The a.c. equivalent circuit for the amplifier is shown in Figure 4.32 (*a*) and (*b*). In these figures, the a.c. equivalent circuit of the transistor is shown by the a.c. emitter diode resistance and three points marked *E*, *B* and *C*. Assuming the transformer to be an ideal (*i.e.*, neglecting its leakage current, winding resistance etc.), whatever be the load on its secondary winding side, it transforms the same on the primary side. The value of the transformed load,

$$R'_L = \left(\frac{N_1}{N_2}\right)^2 R_L = a^2 \cdot R_L \quad \ldots \left(\text{where } a = \frac{N_1}{N_2}\right)$$

where N_1 = Number of primary turns, and

N_2 = Number of secondary turns.

Similarly, if R_{i_2} is the input resistance of the second stage, then its value transformed to the primary side,

$$R'_{i_2} = a^2 \cdot R_{i_2}$$

We know that the input resistance of the first stage is given by the relation,

$$R_{i_1} = R_B \parallel (\beta_1 \cdot r'_{e_1}) \quad \ldots (\text{If } R_B >> \beta_1 \cdot r'_{e_1})$$

and the input resistance of the second stage, transformed to the primary side,

$$R'_{i_2} = a^2 \cdot R_{i_2} = a^2 \cdot R_B \parallel (\beta_2 \cdot r'_{e_2})$$

$$= a^2 (\beta_2 \cdot r'_{e_2}) \quad \ldots (\text{If } R_B >> \beta_2 \cdot r'_{e2})$$

Similarly, output resistance of the first stage,

$$R_{o_1} = R'_{i_2} = a^2 \cdot R_{i_2}$$

and the output resistance of the second stage, transformed to the primary side,

$$R_{o_2} = a^2 \cdot R_L$$

∴ Voltage gain of the second stage,

$$A_{v_1} = R_{o_1}/r'_{e_1}$$

and voltage gain of the second stage,

$$A_{v2} = \frac{R'_{o_2}}{r'_{e_2}} = \frac{a^2 \cdot R_L}{r'_{e_2}}$$

∴ Overall voltage gain,

$$A_v = A_{v1} \cdot A_{v2} = \frac{R_{o_1}}{r'_{e_1}} \times \frac{a^2 \cdot R_L}{r'_{e_2}}$$

4.11.2 Frequency Response of Transformer Coupled Amplifier

Figure 4.33 shows the frequency response graph (*i.e.*, a graph of voltage gain *versus* frequency) for a transformer coupled transistor amplifier.

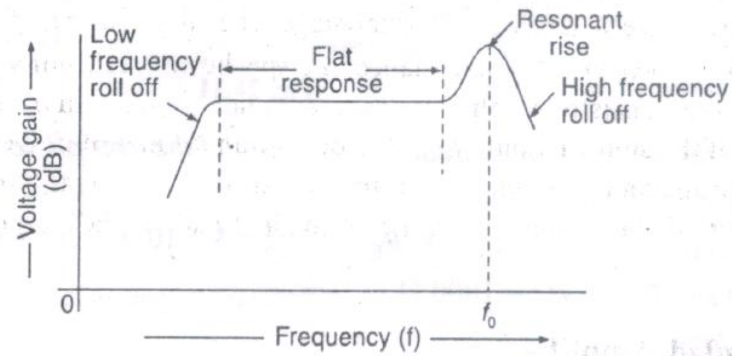


Fig. 4.33. Frequency response of a transformer coupled amplifier.

It is evident from this figure, that the voltage gain drops off (or rolls off) at low as well as at high frequencies , whereas it remains constant in mid-frequency range. Another noticeable feature is that *at one particular frequency (f_0) the voltage gain increases and then rolls off continuously*. This typical behaviour may be explained as follow:

We know that output voltage of a transformer coupled amplifier is equal to the product of collector current and the reactance of the primary winding of coupling transformer. At low frequencies, the reactance of primary winding ($X_L = \omega \cdot L$) begins to decrease, and hence the voltage gain reduces. At high frequencies, the effect of leakage inductance and distributed capacitance (*i.e.*, the capacitance between the turns of the winding) becomes significant and hence the voltage gain reduces. *The peak gain results due to the resonance (or turning) effect of inductance and distributed capacitance, which forms a resonant circuit.* The frequency, at which the peak occurs, is called resonant frequency (f_0).

It has been found that flat part of frequency response curve of transformer coupled amplifiers is small as compared to that of RC coupled amplifiers. As a result of this, *these amplifiers can not be used over a wide range of frequencies*. Moreover, if they are used, *they produce frequency distortion*, which means that all frequency components in a complete input signal (such as music, speech signal) are not equally amplified. However, the transformers can be suitably designed to provide a fairly flat response curve and excellent fidelity over the entire audio frequency range (*i.e.*, 20 Hz to 20 kHz).

4.11.3 Advantages and Disadvantages of Transformer Coupled Amplifier

Advantages

1. No signal power is lost in the collector or base resistors, because of the low winding resistance of the transformer.
2. It provides a higher voltage gain than the RC coupled amplifier.
3. It provides an excellent resistance (or impedance) matching between the stages. The resistance matching is desirable for maximum power transfer.

Disadvantages

1. The coupling transformer is expensive and bulky, particularly when operated at audio frequencies.
2. At radio frequencies, the winding inductance and distributed capacitance produces reverse frequency distortion.
3. It tends to produce '*hum*' in the circuit.

4.11.4 Applications of Transformer Coupled Amplifier

We have already discussed in the last article that transformer coupled amplifiers provide excellent impedance matching between the individual stages. This ability makes it very useful in a multistage amplifier, where it is used as a final stage. *It is used to transfer power to the low impedance load (such as speaker)*. The impedance of a speaker varies from 4 Ω to 16 Ω, whereas the output resistance of a transistor amplifier is several hundred ohms. In order to match the load impedance, with that of the amplifier output, a step-down transformer of proper turns ratio is used. The resistance of the secondary winding of the transformer is made equal to the speaker impedance, while that of the primary winding is made equal to the output resistance of the amplifier.

Example *Figure shows the circuit diagram of a two -stage transformer coupled transistor amplifier.*

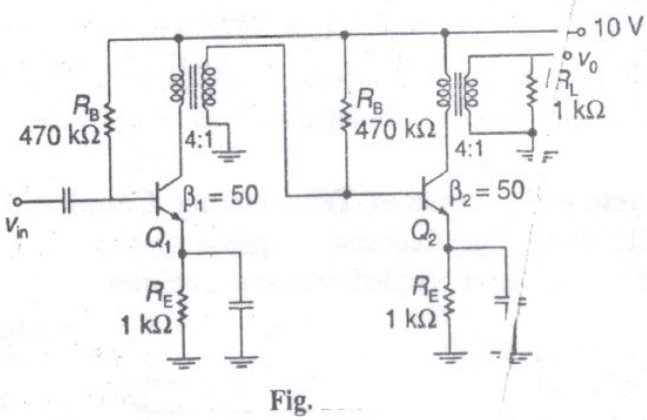


Fig.

Calculate the values of individual stage gains and the over all voltage gain in decibels. Neglect V_{BE} and take $r'_e = 25\ mV/I_E\ (mA)$.

Solution. Given: $V_{CC} = 10$ volts; $R_E = 1\ k\Omega = 1 \times 10^3\ \Omega$; $R_B = 470\ k\Omega = 470 \times 10^3\ \Omega$; $a = 4$; $\beta_1 = \beta_2 = 50$ and $R_L = 1\ k\Omega = 1000\ \Omega$.

Individual stage gains

We know that the value of emitter current,

$$I_E = \frac{V_{CC}}{R_E + \frac{R_B}{\beta}} = \frac{10}{(1 \times 10^3) + \frac{470 \times 10^3}{50}}\ A$$

$$= 0.96 \times 10^{-3}\ A = 0.96\ mA$$

and the value of a.c. emitter diode resistance,

$$r'_e = \frac{25\ mV}{I_E\ (mA)} = \frac{25}{0.96} = 26\ \Omega$$

We also know that input resistance of the first stage,

$$R_{i_1} = R_B \parallel (\beta_1 \cdot r'_{e_1}) = (470 \times 10^3) \parallel (50 \times 26)\ \Omega$$

$$= 1296\ \Omega$$

and input resistance of the second stage,

$$R_{i_2} = R_B \parallel (\beta_2 \cdot r'_{e_2}) = (470 \times 10^3) \parallel (50 \times 26)$$

$$= 1296\ \Omega$$

The input resistance of the second stage, transformed to the primary side,

$$R'_{i_2} = a^2 \cdot R_{i_2} = (4)^2 \times 1296 = 20\ 736\ \Omega$$

Similarly, output resistance of the first stage,

$$R_{o_1} = R'_{i_2} = 20\ 736\ \Omega$$

and output resistance of the second stage, transformed to the primary side,

$$R_{o_2} = a^2 \cdot R_L = (4)^2 \times 1000 = 16\ 000\ \Omega$$

∴ Voltage gain of the first stage,

$$A_{v_1} = \frac{R_{o_1}}{r'_{e_1}} = \frac{20\ 736}{26} = 797.5 \textbf{ Ans.}$$

and voltage gain of the second stage,

$$A_{v_2} = \frac{R'_{o_2}}{r'_{e_2}} = \frac{16000}{26} = 615.4 \textbf{ Ans.}$$

Overall voltage gain in decibels

We know that the overall voltage gain,

$$A_v = A_{v_1} \cdot A_{v_2} = 797.5 \times 615.4 = 490\ 782 \ \textbf{Ans.}$$

and the overall voltage gain in decibels (called dB voltage gain),

$$G_v = 20 \log_{10} A_v = 20 \log_{10} 490\ 782 = 114 \text{ dB} \ \textbf{Ans.}$$

4.12 Two stage Direct Coupled Amplifier

It is also called as *DC amplifier* and is used to *amplify very low frequency* (*i.e.*, below 10 Hz) signals including direct current or zero frequency. It may be noted that the capacitors, inductors and transformers can not be used as a coupling network at very low frequencies because the electrical size of these devices, at low frequencies, becomes very large.

Figure 4.34 shows a two-stage direct coupled transistor amplifier. It may be noted that the output of the first stage is directly connected to the base of the next transistor. Moreover, there are no input or output coupling capacitors. The operation of this circuit is discussed below:

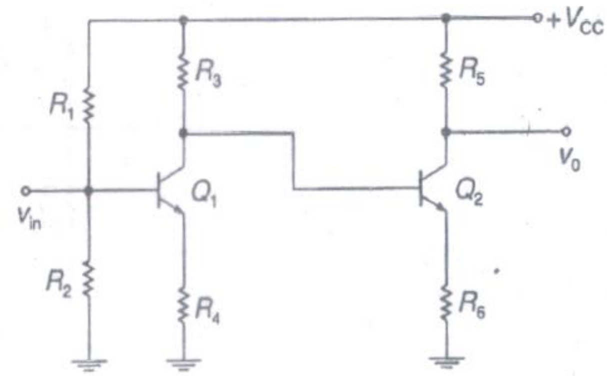


Fig. 4.34. Two stage direct coupled amplifier.

The signal to be amplified is applied directly to the input of the first stage. Due to the transistor action, it appears in the amplified form across the collector resistor or transistor Q_1. This voltage then drives the base of the second transistor Q_2 and the amplified output is obtained across the collector resistor of transistor Q_2.

4.12.1 Calculation of Voltage Gain of Direct Coupled Amplifier

Consider the circuit diagram of a. direct coupled amplifier shown in Figure 4.34. The a.c equivalent circuit for such an amplifier is shown in Figure 4.35.

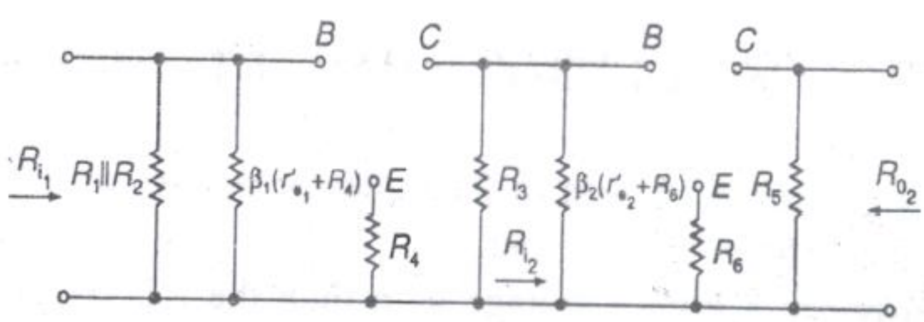


Fig. 4.35. A.C. equivalent circuit of a two stage direct coupled amplifier.

It is evident from the figure shown above that the input resistancc of the first stage,

$$R_{i_1} = (R_1 \parallel R_2) \parallel \beta_1 (r'_{e_1} + R_4)$$

and input resistance of the second stage,

$$R_{i_2} = \beta_2 (r'_{e_2} + R_6)$$

Similarly, the output resistance of the first stage,

$$R_{o_1} = R_3 \parallel R_{i_2}$$

and output resistance of the second stage,

$$R_{o_2} = R_5$$

∴ Voltage gain of the first stage,

$$A_{v_1} = \beta \times \frac{R_{o_1}}{R_{i_1}} = \frac{R_{o_1}}{r'_{e1} + R_4}$$

and voltage gain of the second stage,

$$A_{v_2} = \beta_2 \times \frac{R_{o_2}}{R_{i_3}} = \frac{R_{o_2}}{r'_{e2} + R_4}$$

Now the overall voltage gain is given by the relation,

$$A_v = A_{v_1} \cdot A_{v_2}$$

4.12.2 Frequency Response of Direct Coupled Amplifier

Figure 4.36 shows the frequency response (*i.e.*, a graph of dB voltage gain versus frequency) of a direct coupled amplifier. It is evident from this figure, the *gain is uniform up to a certain frequency denoted by f_2. Beyond this frequency, the gain rolls off slowly*. The gain rolls off at high frequencies due to the increased emitter diode capacitance and stray wiring capacitance.

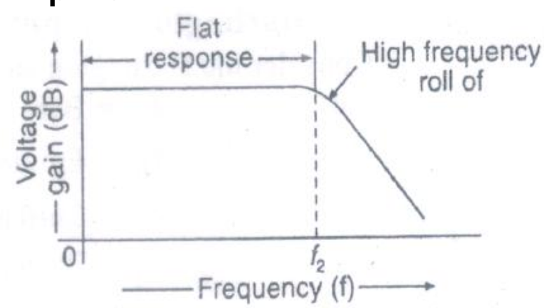


Fig. 4.36. Frequency response of direct coupled amplifier.

4.12.3 Advantages and Disadvantages of Direct Coupled Amplifier

Advantages

1. The circuit arrangement is very simple because it uses a minimum number of resistors.
2. The circuit cost is low because of the absence of expensive coupling devices.
3. It can amplify very low frequency signals down to zero frequency.

Disadvantages

1. It cannot amplify high frequency signals.
2. It has poor temperature stability. Because of this, its, Q-point shifts. In a multistage direct coupled amplifier, the Q-point shifts are amplified in succeeding stages. Thus a small d.c. shift, in the first stage can cause the final stage to be either saturated or cut-off. All integrated circuit amplifiers are direct coupled because of the difficulty of fabricating large integrated capacitors.

4.12.4 Applications of Direct Coupled Amplifiers

The direct coupled amplifiers are used in many electronic systems that handle signals, which change very slowly with time. Some of the important applications are as given below.

1. Analog computation.
2. Power supply regulators.
3. Bioelectric measurements.
4. Linear integrated circuits.

Example *Figure shows a direct coupled two-stage amplifier. The d.c. bias of the first stage sets the d.c. bias of the second.*

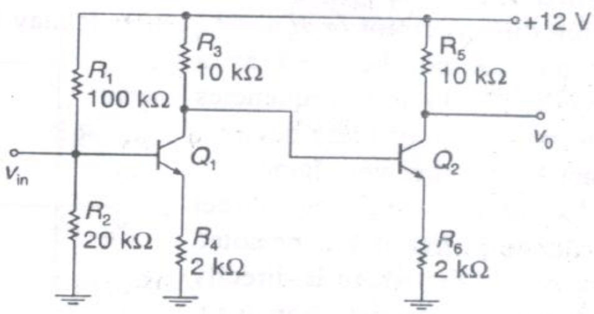


Fig.

Determine the individual stages a.c. voltage gain and the overall voltage gain. Neglect V_{BE} and use $r'_e = 25/I_E$ in mA. Take $\beta_1 = \beta_2 = 100$.

Solution. Given: $V_{CC} = 12$ volts; $R_1 = 100$ kΩ; $R_2 = 20$ kΩ; $R_3 = 10$ kΩ = 10 000 Ω; $R_4 = 2$ kΩ = 2000 Ω; $R_5 = 10$ kΩ = 10 000 Ω; $R_6 = 2$ kΩ = 2000 Ω; $r'_e = 25/I_E$ and $\beta_1 = \beta_2 = 100$.

Individual stages a.c. voltage gain

We know that voltage drop across resistor R_2,

$$V_{TH} = V_{CC}\left(\frac{R_2}{R_1 + R_2}\right) = 12\left(\frac{20}{100 + 20}\right) = 2 \text{ V}$$

As the voltage drop across the resistor R_4 is the same as that across R_2. Therefore emitter current of Q_1 transistor,

$$I_{E_1} = \frac{V_{TH}}{R_4} = \frac{2}{2000} = 0.001 \text{ A} = 1 \text{ mA}$$

and the a.c. emitter diode resistance,

$$r'_{e_1} = \frac{25}{I_{E_1}} = \frac{25}{1} = 25\ \Omega$$

Again neglecting V_{BE}, the voltage drop across resistor, R_e is the same as the collector voltage of Q_1 transistor and its value,

$$V_{R_6} = V_{C_1} = V_{CC} - I_{E_1} \cdot R_3$$
$$= 12 - (0.001 \times 10\,000) = 12 - 10 = 2 \text{ V}$$

∴ Emitter current of Q_2 transistor,

$$I_{E_2} = \frac{V_{R_6}}{R_6} = \frac{2}{2000} = 0.001 \text{ A} = 1 \text{ mA}$$

and the a.c. emitter diode resistance,

$$r'_{e_2} = \frac{25}{I_{E_2}} = \frac{25}{1} = 25\ \Omega$$

We also know that input resistance of the second stage

$$R_{i_2} = \beta_2 (r'_{e2} + R_6) = 100\ (25 + 2000) = 202\ 500$$

and output resistance of the first stage,

$$R_{o_1} = R_3 \parallel R_{i_2} = 10\,000 \parallel 2\,02\,500 = 10\,000\ \Omega$$

Similarly, output resistance of the second stage,

$$R_{o_2} = R_5 = 10\ 000\ \Omega$$

∴ Voltage gain of the first stage.

$$A_{v1} = \frac{R_{o_1}}{r'_{e_1} + R_4} = \frac{10000}{25 + 2000} = 4.9 \textbf{ Ans.}$$

and voltage gain of second stage,

$$A_{v_2} = \frac{R_{o_2}}{r'_{e_2} + R_6} = \frac{10000}{25 + 2000} = 4.9 \textbf{ Ans.}$$

Overall voltage gain

We know that overall voltage gain,

$$A_v = A_{v_1} \cdot A_{v_2} = 4.9 \times 4.9 = 24 \textbf{ Ans.}$$

4.13 Darlington Emitter Follower Amplifier

The Darlington Amplifier consists of two cascaded emitter followers as shown in Figure 4.36. The configuration results in a set of improved amplifier characteristics.

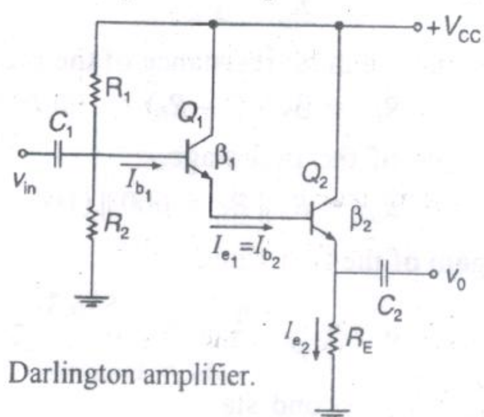


Fig. 4.36. Darlington amplifier.

The Darlington amplifier has a high input resistance, low output resistance and high current gain. These characteristics make it very useful as a current amplifier. The voltage gain of a Darlington amplifier is less than unity.

4.13.1 Darlington Amplifier Characteristics

Consider the Darlington amplifier circuit shown in Figure 4.36.

Let I_{b_1} = Base current of Q_1 transistor,

I_{e_1} = Emitter current of Q_1 transistor,

β_1 = Current gain of Q_1 transistor,

I_{b_2} = Base current of Q_2 transistor. Its value is equal to the emitter current of Q_1 transistor,

I_{e_2} = Emitter current of Q_2 transistor, and

β_2 = Current gain of Q_2 transistor.

1. *Current gain*. We know that the emitter current of Q_2 transistor,

$$I_{e_1} = \beta_1 \cdot I_{b_1}$$

and emitter current of Q_2 transistor,

$$I_{e_2} = \beta_2 \cdot I_{b_2} = \beta_2 \cdot I_{e_1} \qquad \ldots (\because I_{b_2} = I_{e_1})$$

$$= \beta_2 (\beta_1 \cdot I_{b_1}) \qquad \ldots (\because I_{e_1} = \beta_1 \cdot I_{b_1})$$

$$= \beta_1 \cdot \beta_2 \cdot I_{b_1} = \beta^2 \cdot I_{e_1}$$

Now let both the transistors used in the amplifier be identical. Then current gain β_1 and β_2 will be equal. In that case, emitter current of Q_2 transistor,

$$I_{e_2} = \beta^2 \cdot I_{b_1} \qquad \ldots (\because \beta_1 = \beta_2 = \beta^2)$$

$\therefore$ Overall current gain,

$$A_i = \frac{I_{e_2}}{I_{b_1}} = \beta^2$$

2. *Input resistance*. We know that input resistance of the second stage is given by the relation,

$$R_{i_2} = \beta_2 (r'_{e_2} + R_E)$$

$$= \beta_2 \cdot R_E \qquad \ldots (\text{If } R_E \quad r_{e2})$$

It is the value of resistance seen by the emitter of Q_1 transistor and is given by the relation,

$$R'_{i_1} = \beta_1 (r'_{e_1} + R_{i_2})$$

$$= \beta_1 \cdot R_{i_2} \qquad \ldots (\text{If } R_{i_2} >> r'_{e_1})$$

$$= \beta_1 \cdot \beta_2 \cdot R_E \qquad \ldots (\because R_{i2} = \beta_2 \cdot R_E)$$

For identical transistor, we know that current gain β_1 and β_2 are also equal. Therefore input resistance,

$$R'_{i_1} = \beta^2 \cdot R_E$$

and input resistance of the amplifier stage,

$$R_{i_1} = (R_1 \parallel R_2) \parallel R'_{i_1} = (R_1 \parallel R_2) \parallel \beta^2 \cdot R_E$$

$$= R_1 \parallel R_2 \qquad \dots (\because (R_1 \parallel R_2) << \beta^2 \cdot R_E)$$

3. *Output resistance*. The output resistance of the first stage is given by the relation,

$$R_{o_1} = r'_{e_1} + \frac{R_1 \parallel R_2}{\beta_1}$$

and output resistance of the second stage,

$$R_{o_2} = r'_{e_2} + \frac{R_{o_1}}{\beta_2}$$

$$= r'_{e_2} + \frac{r'_{e_1} + \frac{R_1 \parallel R_2}{\beta_1}}{\beta_2}$$

$$= r'_{e_2} + \frac{r'_{e_1}}{\beta_2} + \frac{R_1 \parallel R_2}{\beta_1 \cdot \beta_2}$$

$$= r'_{e_2} \qquad \dots \left(\because \frac{r'_{e1}}{\beta_2} \text{ and } \frac{(R_1 \parallel R_2)}{\beta_1 \cdot \beta_2} \text{ are negligible}\right)$$

4. *Voltage gain*. The voltage gain of Darlington amplifier is given by the relation,

$$A_v = \frac{v_o}{v_{in}} \qquad \dots (i)$$

The value of output voltage of a Darlington amplifier,

$$v_o = I_{e_2} \cdot R_E$$

and the input voltage,

$$v_{in} = I_{e_1} \cdot r'_{e_1} + I_{e_2} (r'_{e_2} + R_E) \qquad \dots (ii)$$

The above expression is obtained by applying Kirchoff's Voltage Law to the input circuit of the Darlington amplifier. Substituting the value of I_{e_1} (equal to I_{e2}/β_2) in equation (*ii*)

$$v_{in} = \frac{I_{e_2}}{\beta_2} r'_{e_1} + I_{e_2} (r'_{e_2} + R_E)$$

∴ Voltage gain,

$$A_v = \frac{I_{e_2} \cdot R_E}{\frac{I_{e_2}}{\beta_2} \cdot r'_{e_1} + I_{e_2} (r'_{e_2} + R_E)} = \frac{R_E}{\frac{r'_{e_1}}{\beta_2} + (r'_{e_2} + R_E)}$$

$$\approx 1 \qquad \dots (\because R_E >> r'_{e_2} \text{ or } r'_{e1}/\beta_2)$$

Example *Figure shows the circuit diagram of a Darlington amplifier. Determine (a) the overall gain; (b) the a.c. emitter diode resistance for each transistor; (c) total input resistance; and (d) the overall voltage gain.*

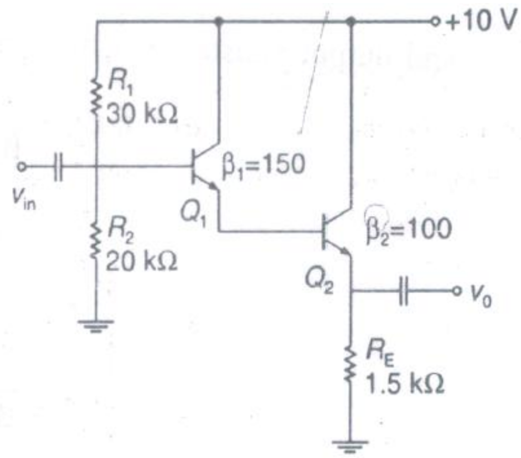


Fig.

Solution. Given V_{CC} = 10 volt; R_1 = 30 kΩ; R_2 = 20 kΩ; $R_E = 1.5\ k\Omega = 1.5 \times 10^3\ \Omega$; β_1 = 150 and β_2 = 100.

(*a*) *Overall current gain*

We know that overall current gain,

$$\therefore\ A_i = \beta_1 \cdot \beta_2 = 150 \times 100 = 15\ 000\ \textbf{Ans.}$$

(*b*) *A.C. emitter diode resistance for each transistor*

We know that voltage drop across resistor R_2

$$V_{R_2} = V_{CC} \times \frac{R_2}{R_1 + R_2} = 10\left(\frac{20}{30+20}\right) = 4\ \text{V}$$

and the voltage at the base of Q_2 (or emitter of Q_1),

$$V_{B_2} = V_{R_2} - V_{BE_1} = 4 - 0.7 = 3.3\ \text{V}$$

Similarly, voltage at the emitter of Q_2,

$$V_{E_2} = V_{B_2} - V_{BE_2} = 3.3 - 0.7 = 2.6\ \text{V}$$

and the value of emitter current of Q_2,

$$I_{E2} = \frac{V_{E_2}}{R_E} = \frac{2.6}{1.5 \times 10^3} = 1.73 \times 10^{-3}\ \text{A} = 1.73\ \text{mA}$$

$\therefore$ A.C. emitter diode resistance of Q_2 transistor

$$r'_{e_2} = \frac{25}{I_{E_2}\ (\text{in } mA)} = \frac{25}{1.73} = 14.5\ \Omega\ \textbf{Ans.}$$

Now the base current of Q_2,

$$I_{b_2} = \frac{I_{E_2}}{\beta_2} = \frac{1.73}{100} = 0.0173\ \text{mA}$$

and the emitter current of Q_1,

$$I_{E_1} = I_{b_2} = 0.0173\ \text{mA}$$

$\therefore$ A.C. emitter diode resistance of Q_1,

$$r'_{e_1} = \frac{25}{I_{E1}\ (\text{in } mA)} = \frac{25}{0.0173} = 1445\ \Omega\ \textbf{Ans.}$$

(c) Total input resistance

We know that total input resistance (*i.e.*, input resistance of the amplifier stage),

$$R_{i_1} = R_1 \,||\, R_2 = 30 \,||\, 20 = 12 \text{ k}\Omega \textbf{ Ans.}$$

(d) Overall voltage gain

We also know that overall voltage gain,

$$A_v = \frac{R_E}{\frac{r'_{e_1}}{\beta_2} + (r'_{e_2} + R_E)} = \frac{1.5 \times 10^3}{\frac{1445}{100} + [14.4 + (1.5 \times 10^3)]}$$

$$= 0.98 \textbf{ Ans.}$$

4.14 Cascode amplifier

An amplifier consisting of a common emitter input stage that drives a common base output stage.

Figure 4.37 show the cascode-amplifier configuration using BJT's. In this case, a common-emitter amplifier drives a common-base amplifier. It is a well-known fact that, at higher frequencies, the gain of the *RC*-coupled amplifier drops. This is because of the shunting effect of the Miller capacitance C_μ and the emitter-base capacitance C_π. With cascode connection, the effect of the Miller capacitance can be seen to get reduced; as a result, the high-frequency cut off gets extended by a factor of about 10.

Figure 4.37 shows the basic cascode amplifier circuit. As shown in the figure, and as stated above, a cascode amplifier consists of a *CE* amplifier driving a *CB* amplifier. To make a simplified analysis of the cascode amplifier, assume that the current gain (*CE*) of transistor T_1 is β and that (*CB*) of transistor T_2 is α. From basic principles, we find that for the *CE* stage.

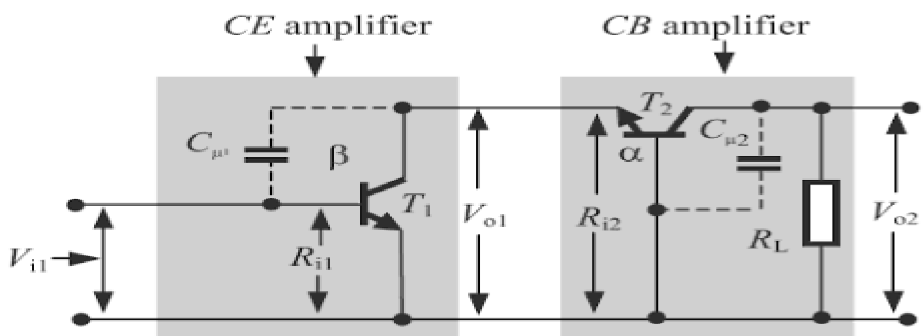


Fig. 4.37 Cascode amplifier using BJT's

$$A_{V1} = \beta \frac{R_{o1}}{R_{i1}} \qquad (1)$$

where A_{V1} = voltage gain, R_{i1} = input impedance and R_{o1} = output impedance of the *CE* stage. Similarly, we have

$$A_{V2} = \alpha \frac{R_{o2}}{R_{i2}} \qquad (2)$$

where A_{V2} = voltage gain, R_{i2} = input impedance and R_{o2} = output impedance of the *CE* stage. From Fig. 4.37, we find that $R_{o2} = R_L$. Using Eqs. (1) and (2), we get the overall gain of the cascode amplifier as

$$A_V = A_{V1} \times A_{V2} = \beta_1 \frac{R_{o1}}{R_{i1}} \times \alpha_2 \frac{R_L}{R_{i2}} \quad (3)$$

But, we see from Fig. 4.37 that $R_{i2} = R_{o1}$. Also, we have $\alpha_2 = 1$. Then, we get

$$A_V = \beta_1 \times \frac{R_L}{R_{i1}} \quad (4)$$

From Eq. (4), we find that the gain of the cascode amplifier is equal to that of a single stage of the *CE* amplifier.

Even though the cascode amplifier has a gain equal to that of a *CE* amplifier, we find that its high-frequency region of operation extends beyond that of the *CE* amplifier. This is because, as stated before, the parasitic Miller capacitances ($C_{\mu1}$ and $C_{\mu2}$) of the two transistors are not directly connected, as can be seen from Fig. 4.37. This prevents direct feedback connection between the output and the input of the cascode amplifier.

4.15 Comparison of Cascade and Cascode amplifier

Cascade amplifier	Cascode amplifier
Combination of two or more transistor's in any of the configuration.	combination of common collector and Common base configuration
output of the first amplifying device (transistor) is fed as input to the second amplifying device	An amplifier consisting of a common emitter input stage that drives a common base output stage.