CHAPTER

15 Multistage Amplifiers

15.1. INTRODUCTION

The performance of a single stage amplifier has already been discussed in the chapter 12. Although the gain* of an amplifier does depend on the parameters of the device and circuit components, there exists an upper theoretical limit for the gain obtainable from a single stage. The voltage amplification or power gain or frequency response obtained with a single stage of amplification is usually not sufficient to meet the needs of either a composite electronic circuit or load device. Hence, several amplifier stages (two or more single stages of amplification) are usually employed to achieve greater voltage or current amplification or both. A transistor circuit containing more than one stage of amplification is known as a *multistage amplifier*. It may be emphasized here that a practical amplifier is always a multistage amplifier that may provide a higher voltage or current gain or both.

In a multistage amplifier, the output of first stage is combined to the next stage through a coupling device. The process is known as *cascading*. The coupling device is used to (*i*) transfer the ac output of one stage to the input of the next stage and (*ii*) block the dc to pass from one stage to the next stage *i.e.* to isolate the dc conditions.

For an ideal coupling network the following requirements should be fulfilled.

(*i*) It should not disturb the dc bias conditions of the amplifiers being coupled. This means direct currents should not pass through the coupling network.

(*ii*) The coupling network should transfer ac signal waveform from one amplifier to the next amplifier without any distortion.

(*iii*) Although some voltage loss of signal cannot be avoided in the coupling network but this loss should be minimum, just negligible.

(*iv*) The coupling network should offer equal impedance to the various frequencies of signal wave.

In other words the network impedance should not be frequency dependent.

Unfortunately, there is no coupling network which fulfils all the above demands. The four basic methods of coupling are R-C coupling, Transformer coupling, Impedance coupling, and Direct coupling.

The coupling network not only couples two stages; it also forms a part of the load impedance of the preceding stage. Thus, the performance of the amplifier will also depend upon the type of coupling network used. Amplifier is usually named after the type of coupling employed such as R-C coupled amplifier, transformer-coupled amplifier, impedance coupled amplifier, and direct-coupled amplifier.

In R-C *coupling*, a resistor and a capacitor are used as a coupling device. The capacitor connects the output of one stage to the input of next stage to pass ac signal and to block the dc bias voltages. The amplifier using R-C coupling is called the *R-C coupled amplifier*.

In *transformer coupling*, transformer is used as the coupling device. The amplifier using transformer coupling is called the *transformer-coupled amplifier*. In this case there is no need of using a coupling capacitor because the secondary of the coupling transformer conveys the ac component directly to the base of the second stage. Moreover, the secondary winding also provides a base return path and so base resistance is not required.

In *direct coupling* or dc coupling, the individual amplifier stage bias conditions are so designed that the two stages may be directly connected without the necessity of dc isolation. This coupling is used where it is desirable to connect the load directly in series with the output terminal of the active circuit element such as in case of headphones, loudspeakers etc. The amplifier using direct coupling is called the *direct-coupled amplifier*.

R-C coupling is the most commonly used coupling between the two stages of a cascaded or multistage amplifier because it is cheaper in cost and very compact circuit and provides excellent frequency response.

The most suitable transistor configuration for cascading is CE configuration because the voltage gain of common emitter amplifier is greater than unity while CC configuration has voltage gain less than unity and the voltage gain of CB configuration using cascading is also less than unity.**

However, for input stage CC or CB configuration may be required for proper impedance matching at the cost of voltage or current gain. It is worthnoting point

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* Gain of an amplifier is the ratio of the output electrical quantity (current, voltage or power) to the input one of the amplifier.

** No doubt, the voltage gain of a single stage CB amplifier is more than unity but the overall voltage gain of multistage amplifier using CB configuration is low, almost equal to the voltage gain of the last stage alone.

that for input stage, the consideration is not the maximum voltage gain but the impedance matching of the source with the input impedance of the input stage. Some driving sources may need input circuit to be an almost open-circuit while others need an almost short-circuit. In certain cases choice of configuration for the input stage, is the minimization of noise and maximization of signal/noise power ratio.

15.2. MULTISTAGE AMPLIFIER

A multistage amplifier can be represented by a block diagram, as shown in Fig. 15.1. It is to be noted that the output of the first stage makes the input for the second stage, the output of second stage makes the input for third stage and so on. The signal voltage V_s is applied to the input of the first stage and the final output V_{out} is available at the output terminals of the last stage.

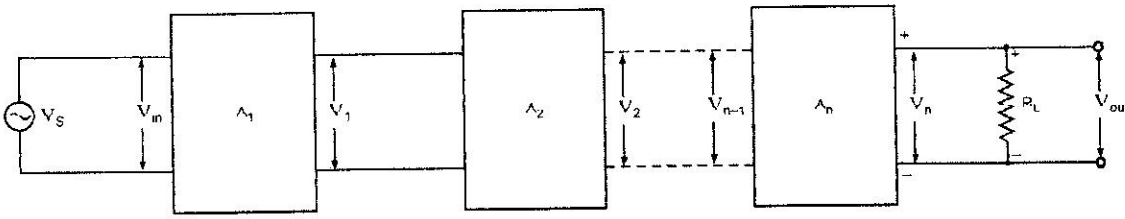

Fig. 15.1. *n-Stage Amplifier*

Input to the first stage, V_{in} = Signal voltage V_s
Output of first stage or input to the second stage
$V_1 = A_{v_1} V_{in}$ where A_{v_1} is the voltage gain of first stage
Output of second stage or input to the third stage
$V_2 = A_{v_2} V_1$ where A_{v_2} is the voltage gain of the second stage
Similarly the output of nth stage (or final output),
$V_{out} = V_n = A_{v_n} V_{n-1}$
where A_{v_n} is the voltage gain of the last stage.
Overall voltage gain of the amplifier is given as

$A = \frac{V_{out}}{V_s}$ (visualising the multistage amplifier as a single amplifier with input voltage V_s and output voltage V_{out})

$$= \frac{V_1}{V_s} \times \frac{V_2}{V_1} \times \frac{V_3}{V_2} \times \dots \frac{V_{n-1}}{V_{n-2}} \times \frac{V_n}{V_{n-1}}$$

$$= A_{v_1} \times A_{v_2} \times \dots \times A_{v_{n-1}} \times A_{v_n} \qquad \text{...(15.1)}$$

i.e. the gain of a multistage amplifier is equal to the product of gains of individual stages. It is worthwhile to mention here that in practice total gain A is less than $A_{v_1} \times A_{v_2} \times \dots \times A_{v_{n-1}} \times A_{v_n}$ due to the loading effects of the following stages.

When the gains are expressed in dB, the overall gain of a multistage amplifier is given as the sum of gains of individual stages in decibels (dB).

Taking logarithm (to the base 10) of Eq. (15.1) and then multiplying each term by 20 we have

$$20 \log_{10} A_v = 20 \log_{10} A_{v_1} + 20 \log_{10} A_{v_2} + \dots + 20 \log_{10} A_{v_{n-1}} + 20 \log_{10} A_{v_n}$$

In the above equation, the term to the left is the overall gain of the multistage amplifier expressed in decibels. The terms on the right denote the gains of the individual stages expressed in decibels. Thus

$$A_{v\,dB} = A_{v\,dB_1} + A_{v\,dB_2} + \dots + A_{v\,dB_n} \qquad \text{...(15.2)}$$

Example 15.1. A 3-stage amplifier has voltage gains of 50, 100 and 200 for first, second and third stage. Find the overall voltage gain of the amplifier in decibels.

Solution : Voltage gain of first stage in dB $= 20 \log_{10} 50 = 34$
Voltage gain of second stage in dB $= 20 \log_{10} 100 = 40$
Voltage gain of third stage in dB $= 20 \log_{10} 200 = 46$
Overall voltage gain of the amplifier $= 34 + 40 + 46 = 120.$

15.3. *n*-STAGE CASCADED AMPLIFIER

As already discussed in Art. 15.1, several amplifier stages are usually cascaded to increase the overall voltage gain of the amplifier. However, sometimes cascading is done to obtain the desired output and input impedance for specific applications. Block diagram of an n-stage cascaded amplifier is given in Fig. 15.1. The first stage is driven by a voltage source V_s (or a current source I_s). The output of first stage is fed to the input of the second stage, the output of second stage is supplied to the input of the third stage and so on. The output of the nth or last stage is fed to the load R_L. Actual voltage available at the input of the first stage is V_{in} (V_{in} equals signal voltage V_s if source resistance R_S is negligible) and the voltage available at the output terminals of the last stage is V_{out}. Then the ratio $\frac{V_{out}}{V_{in}}$ gives the voltage gain of the n-stage cascaded amplifier. Thus by designing properly a cascaded amplifier, a weak input signal V_{in} of just a few microvolts can be amplified giving output voltage V_{out} of several volts.

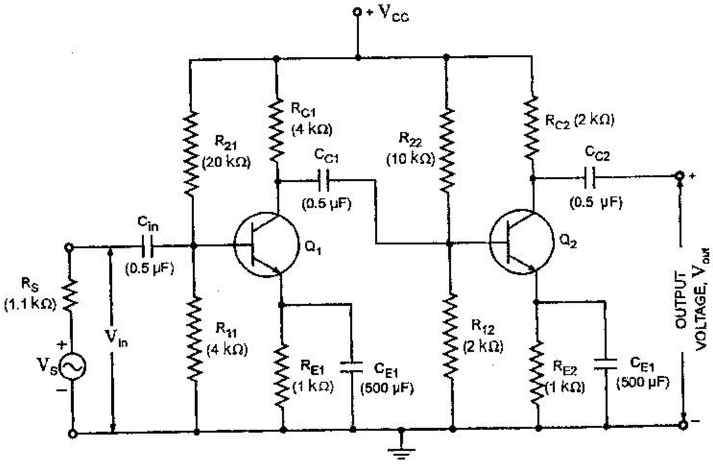

Fig. 15.2. *Two-Stage R-C Coupled Transistor Amplifier*

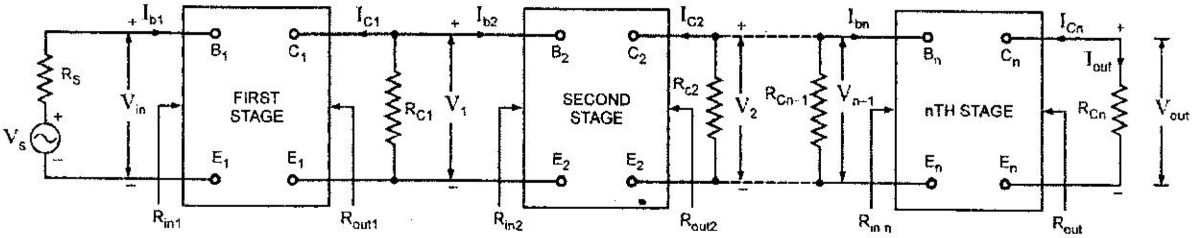

Fig. 15.3. *n-Stage CE Cascaded Amplifier*

Here we take up R-C coupled amplifier, being the most popular amplifier employed for audio-frequency amplification. A two-stage R-C coupled amplifier using N-P-N transistors in common emitter configuration (the most suitable transistor configuration for cascading) is given in Fig. 15.2. Detailed discussion of R-C coupled amplifier will be taken up in Art. 15.5. Typical values of circuit components are given in the brackets.

The block diagram of a two stage R-C coupled transistor amplifier shown in Fig. 15.2 indicating the various voltages, currents and resistances involved is given in Fig. 15.3. The biasing arrangements and coupling capacitors have been omitted for sake of simplicity and clarity.

1. Voltage Gain. The overall voltage gain of the amplifier is given by the product of the voltage gains of the individual stages. This is proved as below :

Voltage gain of first stage,

$$A_{v_1} = \frac{V_1}{V_{in}} = \frac{\text{Output voltage of first stag}}{\text{Input voltage to first stag}} = A_{v_1} \angle \theta_1 \quad ....(15.3)$$

where A_{v_1} is the magnitude of the voltage gain of the first stage and θ_1 is the phase angle between output and input voltages of this stage.

Similarly the voltage gain of *n*th stage,

$$A_{v_n} = \frac{\text{Output voltage of } n\text{th stage}}{\text{Input voltage to } n\text{th stage}} = A_{v_n} \angle \theta_n \quad ....(15.4)$$

Thus the overall voltage gain of the complete *n*-stage cascaded amplifier is given as

$$A_v = \frac{V_{out}}{V_{in}} = \frac{\text{Output voltage of the } n\text{th stage}}{\text{Voltage input to the first stage}} = A_v \angle \theta \; ...(15.5)$$

where A_v is the magnitude of the voltage gain and θ is the phase angle between the output and input voltages of the amplifier.

$$\text{Since } \frac{V_{out}}{V_{in}} = \frac{V_1}{V_{in}} \times \frac{V_2}{V_1} \times \frac{V_3}{V_2} \times ... \times \frac{V_{out}}{V_{n-1}}$$

$$\text{So } A_v = A_{v_1} \times A_{v_2} \times A_{v_3} \times ... \times A_{v_n} \quad ...(15.6)$$

$$\text{or } A_v \angle \theta = A_{v_1} \cdot A_{v_2} \cdot A_{v_3} ... A_{v_n} \angle \theta_1 + \theta_2 + \theta_3 + ... \theta_n \quad ...(15.7)$$

$$\text{Hence } A_v = A_{v_1} \cdot A_{v_2} \cdot A_{v_3} ... A_{v_n} \quad ...(15.8)$$

$$\text{and } \theta = \theta_1 + \theta_2 + \theta_3 + ... \theta_n \quad ...(15.9)$$

Thus it is concluded that the magnitude of the overall voltage gain equals the product of the magnitudes of the voltage gains of the individual stages and the resultant phase shift of the amplifier equals the sum of the phase shifts introduced by individual stages.

The voltage gain of kth stage (an intermediate stage) of an *n*-stage CE cascaded amplifier shown in Fig. 15.4 is given as

$$A_{vk} = \frac{A_{ik}\, R_{Lk}}{R_{in\,k}} \quad ...(15.10)$$

where R_{Lk} is the effective load at the collector of the kth stage.

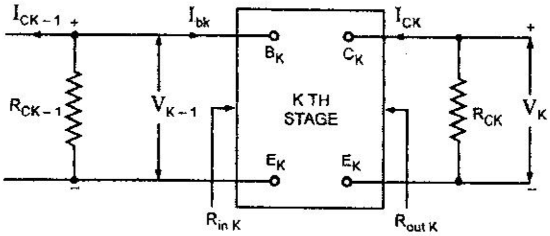

Fig. 15.4. ***k**th Stage of an n-Stage CE Cascaded Amplifier*

The quantities in above equation (*i.e.* A_{ik}, R_{Lk} and $R_{in\,k}$) are evaluated by starting with the last stage and proceeding backward. Thus for the *n*th stage, current gain A_{in} and input resistance $R_{in\,n}$ are given as

$$A_{in} = \frac{-h_{fe}}{1 + h_{oe}\, R_{Ln}} \quad ...(15.11)$$

$$\text{and } R_{in\,n} = h_{ie} + h_{re}\, A_{in}\, R_{Ln} \quad ...(15.12)$$

where R_{Ln} is the effective load impedance of the final (*i.e.* *n*th) stage and equals R_{cn}.

For the $(n-1)$th stage, effective load impedance $R_{in\,n-1}$ equals $R_{c\,n-1} \parallel R_{in\,n}$. So

$$R_{L\,n-1} = \frac{R_{cn-1} \cdot R_{in\,n}}{R_{cn-1} + R_{inn}} \quad ...(15.13)$$

Now the current gain $A_{i\,(n-1)}$, of the last but one stage [*i.e.* $(n-1)$th stage] is obtained using Eq. (15.11) by replacing R_{Ln} by $R_{L\,n-1}$. Similarly the input impedance $R_{in\,n-1}$ of the $(n-1)$th stage is determined from Eq. (15.12) by replacing A_{in} by $A_{i\,n-1}$ and R_{Ln} by $R_{L\,n-1}$. Thus proceeding backward, base-to-collector current gains and input impedances of every stage including the first one can be determined. Then the voltage gain of each stage can be determined by using Eq. (15.10).

Overall voltage gain of the *n*-stage cascaded amplifier may then be calculated from Eq. (15.6).

2. Current Gain. Overall voltage gain of an *n*-stage cascaded amplifier can be obtained, without determining the voltage gain of individual stage, from the following equation

$$A_v = A_i \frac{R_{cn}}{R_{in1}} \quad ...(15.14)$$

where A_i is the overall current gain of the *n*-stage cascaded amplifier and

$$A_i = \frac{\text{Output current of the } n\text{th stage}}{\text{Input current (or base current of first stage)}}$$

$$= \frac{I_{out}}{I_{bi}} = \frac{-I_{cn}}{I_{bi}} = -\frac{I_n}{I_{bi}} \quad ...(15.15)$$

where $I_{cn} \cong I_n$, the collector current of the nth stage.

Now let us obtain equations so as to calculate current gain A_i in terms of circuit parameters.

Since $\frac{I_n}{I_{bi}} = \frac{I_i}{I_{bi}} \cdot \frac{I_2}{I_1} \cdot \ldots \frac{I_{n-1}}{I_{n-2}} \cdot \frac{I_n}{I_{n-1}}$

then $A_i = A_{i_1} \cdot A'_{i_2} \cdot A'_{i_3} \ldots A'_{i_{n-1}} \cdot A'_{in}$ ...(15.16)

where A_{i_1} is the base-to-collector current gain of the first stage and is equal to $\frac{-I_{ci}}{I_{bi}}$ while A'_{i_2}, A'_{i_3} etc. are the collector-to-collector current gains of second, third etc. stages.

For kth stage, collector-to-collector current gain A'_{ik} is given as

$$A'_{ik} = \frac{I_{ck}}{I_{ck-1}} \quad ...(15.17)$$

Similarly base-to-collector current gain of first stage A_{ik} is given as

$$A_{ik} = \frac{-I_{ck}}{I_{bk}} \quad ...(15.18)$$

Now from Fig. 15.4,

$$I_{bk} = -I_{ck-1} \frac{R_{ck-1}}{R_{ck-1} + R_{ink}} \quad ...(15.19)$$

where $R_{in\,k}$ is the input impedance of the kth stage.

$$\text{Hence } A'_{ik} = \frac{I_{ck}}{I_{ck-1}} = \frac{I_{ck}}{I_{bk}} \cdot \frac{I_{bk}}{I_{ck-1}} = A_{ik} \cdot \frac{R_{ck-1}}{R_{ck-1} + R_{ink}} \quad ...(15.20)$$

Base-to-collector current gain A_{ik} is determined by starting with the output stage and proceeding backward to the kth stage, as indicated in connection with Eqs. (15.11), (15.12) and (15.13). The collector-to-collector current gains are then determined by using Eq. (15.20) and the overall current gain of the n-stage amplifier is determined by using Eq. (15.16).

3. Input Impedance. The input impedance of the complete cascaded amplifier is determined, as discussed above, by starting with the last stage and proceeding backward.

4. Output Impedance. The output impedance of each transistor stage and of the overall amplifier is determined starting with the first stage and using equation

$$Y_{out\,1} = h_{oe} - \frac{h_{fe}\, h_{re}}{h_{ie} + R_S} \quad ...(15.21)$$

Then $\frac{1}{Y_{out\,1}}$ gives the corresponding output impedance $R_{out\,1}$.

The output impedance $R'_{out\,k}$ of the kth stage is the parallel combination of the output impedance $R_{out\,k}$ of kth stage and $R_{c\,k}$. The effective source impedance of the (k + 1)th stage is also $R'_{out\,k}$.

5. Power Gain. The overall power gain of the n-stage cascaded amplifier is given as

$$A_p = \frac{\text{Output power}}{\text{Input power}} = \frac{V_{out}\, I_n}{V_{in}\, I_{bi}} = A_v A_i \quad ...(15.22)$$

$$\text{or } A_p = (A_i)^2 \frac{R_{cn}}{R_{in1}} \quad ...(15.23)$$

15.4. FREQUENCY RESPONSE OF COUPLED AMPLIFIERS

As already mentioned in Art. 13.1, the curve drawn between the voltage gain and signal frequency of an amplifier is known as the *frequency response*. The performance of an amplifier is judged to a considerable extent by its frequency response. In the design of an amplifier, appropriate steps are taken to ensure that gain is essentially uniform over some specified range.

Video amplifiers are almost invariably of the R-C coupled type. For such a stage the frequency characteristics may be divided into three regions: Midband-frequency region, low-frequency region and high-frequency region.

In midband-frequency region, the amplification remains reasonably constant and equal to A_{vm}. For the present discussion midband gain may be assumed to be normalized to unity, *i.e.*, $A_{vm} = 1$.

Low-Frequency Response. In the low-frequency region, below the midband, an amplifier stage behaves like the simple high-pass circuit (Fig. 15.5) of time constant $\tau_1 = R_1C_1$.

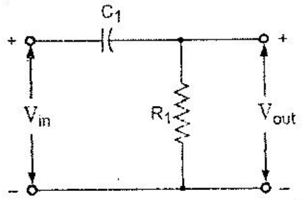

Fig. 15.5. ***A High-Pass R-C Circuit For Determination of Low-Frequency Response of an Amplifier***

The current through the circuit is given by

$$I = \frac{V_{in}}{R_1 - jX_1}$$

and output voltage,

$$V_{out} = \text{Voltage drop across } R_1$$

$$= IR_1 = \frac{R_1}{R_1 - jX_1} V_{in}$$

$$= \frac{R_1}{R_1 - \frac{j}{2\pi f C_1}} V_{in} = \frac{V_{in}}{1 - \frac{j}{2\pi f C_1 R_1}} \quad ...(15.24)$$

The voltage gain at low frequencies A_{vl}, is defined as the ratio of the output voltage V_{out}, to the input voltage V_{in}.

$$i.e. \quad A_{vl} = \frac{V_{out}}{V_{in}} = \frac{1}{1 - \frac{j}{2\pi f C_1 R_1}} = \frac{1}{1 - \frac{jf_1}{f}} \quad ...(15.25)$$

where f_1 is the cutoff frequency and $= \frac{1}{2\pi R_1 C_1}$ ...(15.26)

Now magnitude of A_{vl} and phase angle θ are given by

$$|A_{vl}| = \frac{1}{\sqrt{1 + (f_1/f)^2}} \quad ...(15.27)$$

$$\text{and phase angle } \theta_1 = \text{Tan}^{-1} \frac{f_1}{f} \quad ...(15.28)$$

At the frequency $f = f_1$, $A_{vl} = \frac{1}{\sqrt{2}} = 0.707$ whereas in the midband region ($f >> f_1$), $A_{vl} \rightarrow 1$. Hence f_1 is the frequency at which the gain has fallen to 0.707 times its midband value A_{vm}. From Eq. (15.3) this drop in signal level (assuming equal input and output impedances) corresponds to a decibel reduction of $20 \log \frac{1}{\sqrt{2}}$ or −3 dB. Accordingly, f_1 is referred to as the *lower 3 dB frequency*. From Eq. (15.26) it is observed that f_1 is that frequency for which the resistance R_1 equals the capacitive reactance *i.e.* $R_1 = \frac{1}{2\pi f_1 C_1}$.

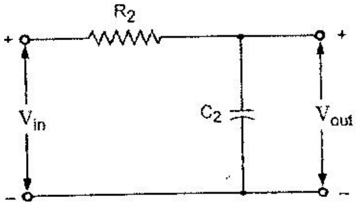

Fig. 15.6. ***A Low-Pass R-C Circuit For Determination of High-Frequency Response of an Amplifier***

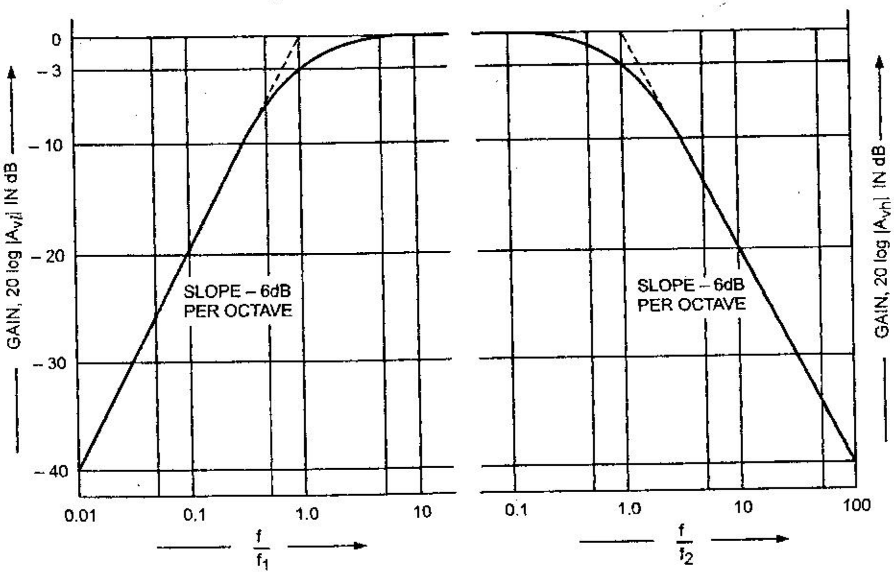

Fig. 15.7. ***A Log-Log Plot of The Amplitude Frequency-Response Characteristic of an R-C Coupled Amplifier***

High-Frequency Response. In the high-frequency region, above midband, the stage behaves like a simple low-pass circuit shown in Fig. 15.6.

Proceeding as above, we obtain for the magnitude $|A_{vh}|$ and phase angle θ_2 of the gain

$$|A_{vh}| = \frac{1}{\sqrt{1+(f/f_2)^2}} \quad ...(15.29)$$

$$\theta_2 = \text{Tan}^{-1} \frac{f}{f_2} \quad ...(15.30)$$

$$\text{where } f_2 = \frac{1}{2\pi R_2 C_2} \quad ...(15.31)$$

Since at $f = f_2$ the gain is reduced to $\frac{1}{\sqrt{2}}$ times its midband value, then f_2 is called the *upper 3 dB frequency*. It also represents that frequency for which the resistance R_2 is equal to the capacitive reactance $\frac{1}{2\pi f_2 C_2}$. In the above expressions θ_1 and θ_2 represent the angle by which the output lags the input, neglecting the initial 180° phase shift through the amplifier. The frequency dependence of the gains in the high- and low-frequency range is to be seen in Fig. 15.7.

Bandwidth. The frequency range from f_1 to f_2 is called the *bandwidth* (BW) of the amplifier stage.

15.5. R-C (RESISTANCE-CAPACITANCE) COUPLED TRANSISTOR AMPLIFIER

A two-stage R-C coupled amplifier using N-P-N transistors in CE configuration is shown in Fig. 15.8. The two transistors used are identical and use a common power supply V_{CC}. The resistors R_1, R_2 and R_E form the biasing and stabilization network. In this arrangement, the signal developed across collector resistor R_C of the first stage is coupled to the base of the second stage through the coupling-capacitor C_C. As the coupling from one stage to the next is obtained by a coupling capacitor followed by a connection to a shunt resistor, therefore, such amplifiers are called *resistance-capacitance coupled* or *R-C coupled amplifiers*. The input capacitor C_{in} couples ac signal voltage to the base of transistor Q_1. In the absence of C_{in} the signal source will be in parallel with resistor R_2 and the bias voltage of the base will be affected. Thus the function of C_{in} is to allow only the alternating current from signal source to flow into the input circuit.

The emitter-bypass capacitor C_E, offers low reactance path to the signal. If it is not present, then the

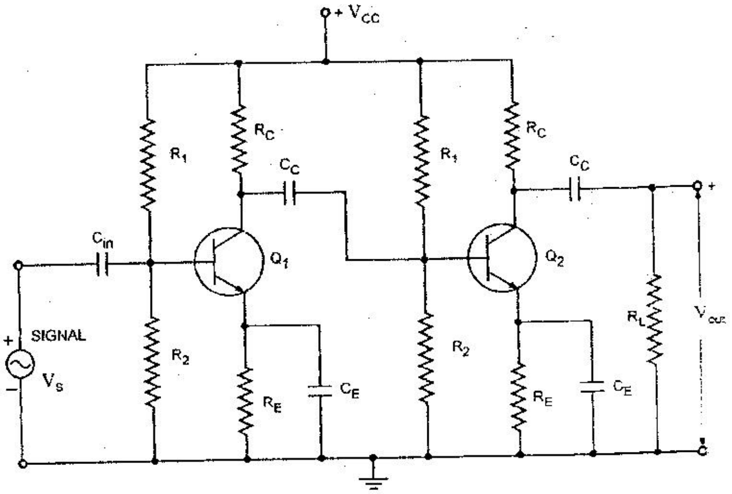

Fig. 15.8. *Two-Stage R-C Coupled Transistor Amplifier*