Chapter 6

MULTISTAGE AMPLIFIER

Multistage amplifier and gain calculation of n-stages cascaded amplifier

- Gain obtained from single stage amplifier is limited.
- In practical applications we need higher gain(current or voltage),so multistage amplifier (MSA) is needed.
- In MSA numbers of single stage amplifiers are connected in cascade arrangement.
- Output of first stage is input to second stage through suitable coupling mechanism.

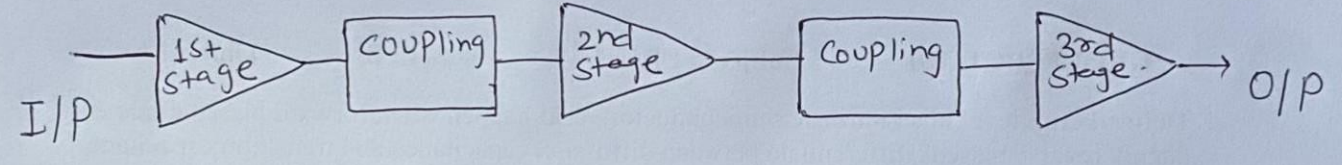


Figure:- Block diagram of 3-stage amplifier.

N – stages cascaded amplifiers

- I/p of first stage let, $V_{in} = V_s$, signal voltage
- O/P of first stage $V_1 = A_{v1}V_{in}$ where A_{v1} is voltage gain of first amplifier
- O/P of second stage $V_2 = A_{v2}V1$ where A_{v2} is voltage gain of first amplifier
- Similarly O/P of n_{th} stage amplifier (final stage) $V_o = V_n = A_{vn}\ V_{n-1}$

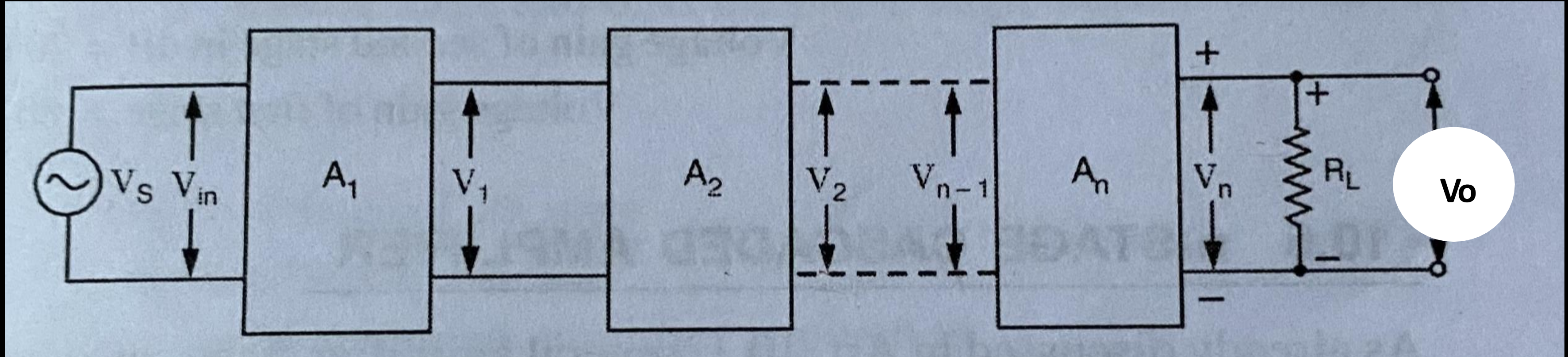


Fig. 10.4 *n-Stage Amplifier*

- Now, voltage gain of first stage amplifier $A_{v1} = V_1/V_{in}$
  voltage gain of second stage amplifier A_{v2} = V2/V1 And so on.......................

  voltage gain of nth stage amplifier A_{vn} = Vn/Vn-1

  Therefore over all gain of nth stage cascade amplifier **$(A) = (V_o/V_s) = (V_1/V_s) \times (V_2/V_1) \times (V_3/V_2) \times \ldots\ldots\ldots\ldots \times (V_{n-1}/V_{n-2}) \times (V_o/V_{n-1})$**

The gain of multistage amplifier is equal to the product of gain of individual stages.

Gain is expressed in dB (decibel), the overall gain of the system is,

$20\log_{10}A_v = 20\log_{10}A_{v1} + 20\log_{10}A_{v2} + \ldots\ldots\ldots + 20\log_{10}Av_{n-1} + 20\log_{10}A_{vn}$.

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 :

$$\text{Voltage gain of first stage, } A_{v_1} = \frac{V_1}{V_{in}} = \frac{\text{Output voltage of first stage}}{\text{Input voltage to first stage}} = A_{v_1} \angle \theta_1 \quad \text{...(10.16)}$$

where A_{v1} 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,

$$A_{v_n} = \frac{\text{Output voltage of } n\text{th stage}}{\text{Input voltage to } n\text{th stage}} = A_{v_n} \angle \theta_n \quad \text{...(10.17)}$$

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

$$A_v = \frac{V_{out}}{V_{in}} = \frac{\text{Output voltage of the } n\text{th stage}}{\text{Voltage input to the first stage}} = A_v \angle \theta \quad \text{...(10.18)}$$

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.

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

$$\text{So } A_v = A_{v_1} \times A_{v2} \times A_{v_3} \times \ldots \times A_{v_n} \quad \text{...(10.19)}$$

$$\text{or } A_v \angle \theta = A_{v_1} \cdot A_{v2} \cdot A_{v_3} \ldots A_{v_n} \angle \theta_1 + \theta_2 + \theta_3 + \ldots \theta_n \quad \text{...(10.20)}$$

$$\text{Hence } A_v = A_{v_1} \cdot A_{v2} \cdot A_{v3} \ldots A_{v_n} \quad \text{...(10.21)}$$

$$\text{and } \theta = \theta_1 + \theta_2 + \theta_3 + \ldots \theta_n \quad \text{...(10.22)}$$

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.

Methods of Coupling

Necessary to use a coupling network between output of one amplifier and input of following amplifier.

1. Direct Coupling

The AC output signal is fed directly to the next stage, no reactance is used in coupling network.

Used when amplification of low frequency signal is to be done.

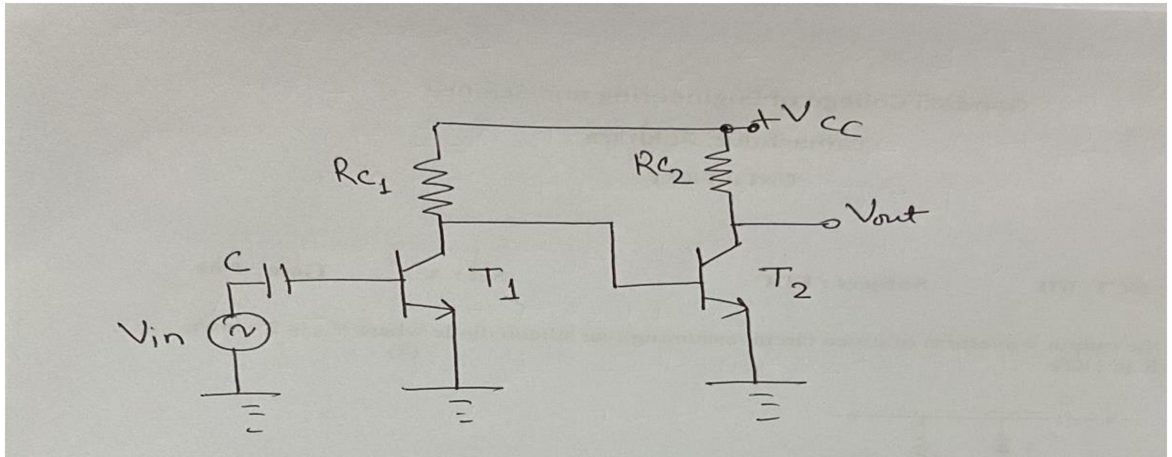


figure:- Direct coupled Amplifier.

Operations:

The input signal applied to the base of transistor T1, it gets amplified due to transistor action and amplified output appears at the collector resistor of T1 which is given as input to transistor T2 for amplification.

Directly given to next stage .(without coupling)

- Low cost and simple circuit

Disadvantages

- Cannot be used for high frequencies, poor stability.

Applications:

- Low frequencies application
- Low current application

2. RC coupling (resistance capacitance)

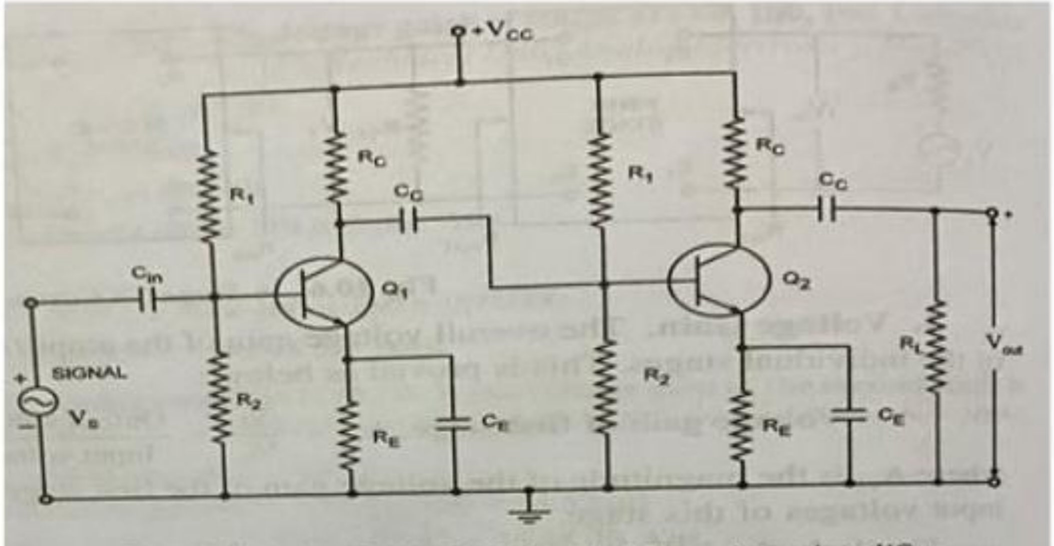


Fig. 10.7 *Two-Stage R-C Coupled Transistor Amplifier*

Here, Q1 and Q2 are identical with common source Vcc is used for biasing.

Cin allows only ac signal to input of Q1, Cc transmits ac signal from one stage to another and blocks all dc components.(coupling capacitor or blocking capacitor)

C_E offers low reactance path to the signal , if not present there is voltage drop at R_E hence enhance the gain.(by pass capacitor)

Operations:

When I/P signal is applied to the base of Q1, it amplified and appears across collector(RC) of Q1 and given to next stage for amplification through coupling capacitor Cc.

Again Q2 amplifies the given signal and give to the output. In this way cascaded stages amplify the signal and increases the overall gain.

In the mid frequency range (50hz –20Khz), the voltage gain of amplifier is constant.

At low frequency < 50hz higher capacitive reactance of coupling capacitor Cc ,C_E offers high reactance and voltage gain falls off at low frequencies.

At high frequencies > 200Khz smaller capacitive reactance of coupling capacitor Cc and acts as short circuit ,which increases load effect and reduces the voltage gain.

Here f1 and f2 are lower and upper cut-off frequencies. BW = f2-f1.

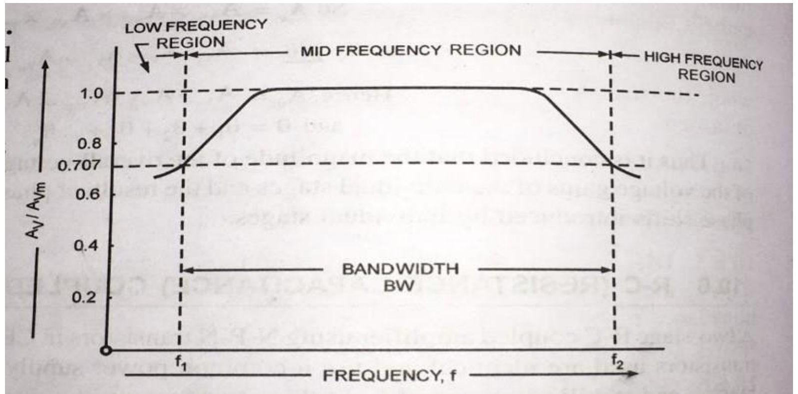


Fig. 10.8 *Frequency Response Curve of an R-C Coupled Amplifier*

- Excellent frequency response, constant gain over the audio range
- Cheaper
- Stable Q point

Disadvantages

- Low voltage and power gain
- Impedance matching is poor

Applications

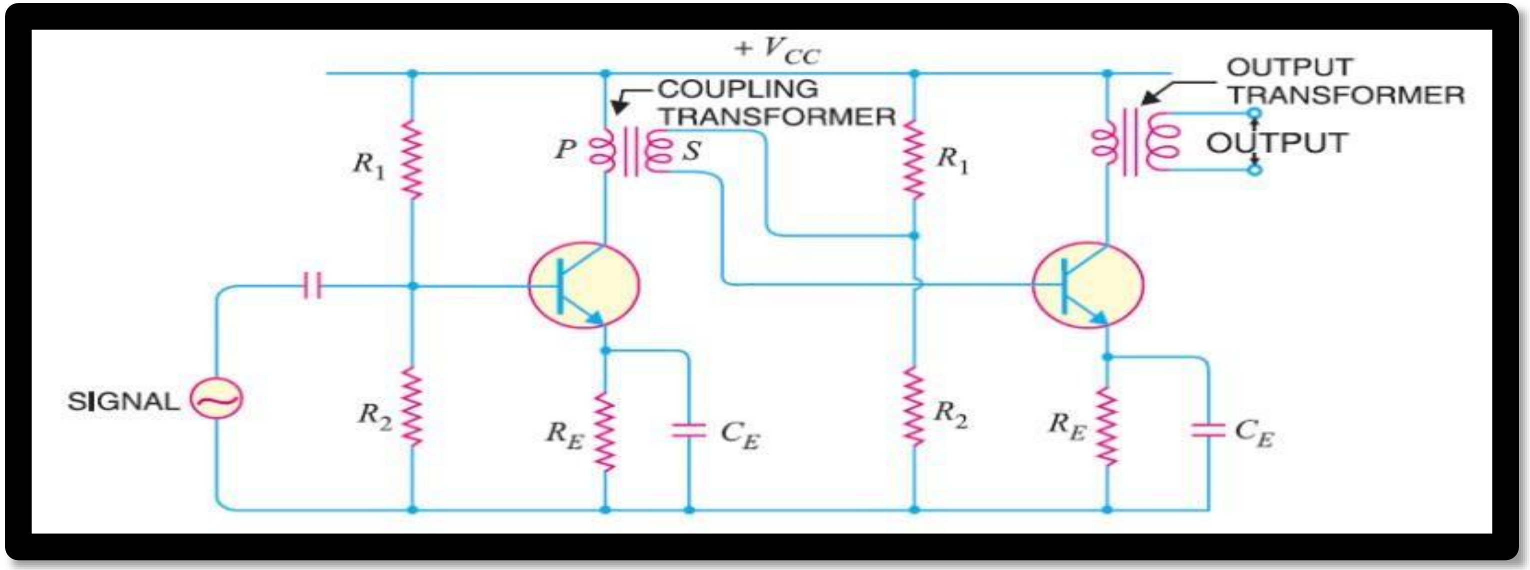
Widely used as voltage amplifier in initial stages.

3. Transformer coupled amplifier

In RC coupled amplifier the voltage and power gain are low since, the effective load resistance of each stage is decreased due to the low resistance presented by the input of each stage to the next stage.

If the effective load resistance of each stage could be increased, the voltage and power gain could also be increased.

This can be achieved by transformer coupling. By using the impedance matching properties of transformer, the low resistance of one stage or load can be reflected as a high load resistance to the previous stage.



A coupling transformer is used to feed the output of one stage to the input of the next stage.

The primary P of this transformer is made the collector load and its secondary S supplies input to the next stage.

When an ac signal is applied to the base of first transistor, it appears in the amplified form across the primary P of the coupling transformer.

Now the voltage developed across P is transferred to the input of the next stage by the transformer secondary S.

The second stage now performs the amplification in an exactly same manner.

- Provides excellent impedance matching
- High gain
- No loss of signal power in the collector or base resistors.

Disadvantages:

- Has a poor frequency response.
- Bulky and expensive .
- Frequency distortion is higher i.e. low frequency signals are less amplified as compared to the high frequency signals.
- Transformer coupling introduces hum in the output.

Applications:

- Mostly used for impedance matching applications

4. Impedance Coupling

Similar as RC coupled amplifier.

Load resistor (Rc) is replaced by impedance (coil).

Efficiency is high , no power loss at inductor (maximum power is transfered to load).

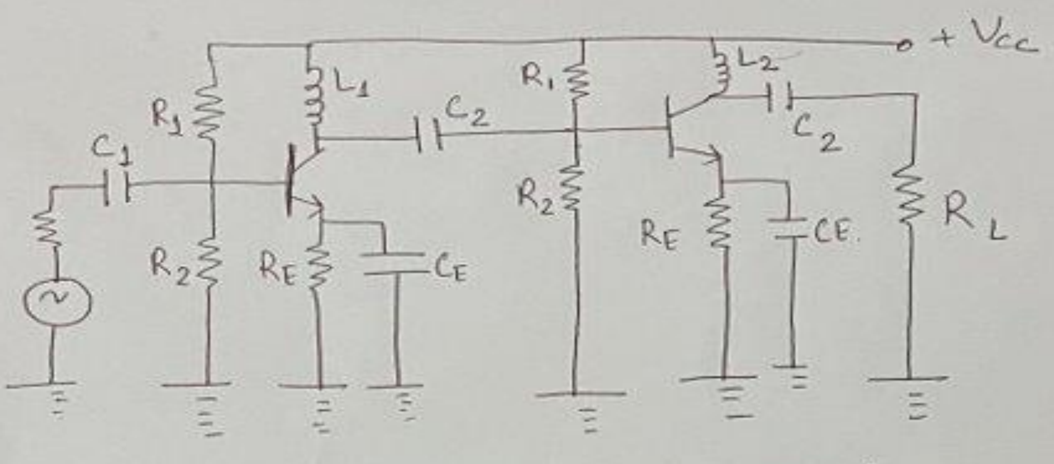
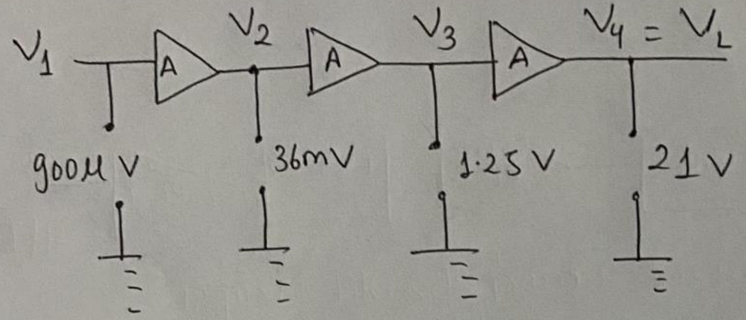


Figure:- Impedance Coupled Amplifier.

1) Three stage amplifier is shown in figure below.

Find AV_1, AV_2, AV_3 & $\frac{V_L}{V_S}$ in dB.



Now, $AV_1 = \frac{V_2}{V_1} = \frac{36 \times 10^{-3}}{900 \times 10^{-6}} = 40V = 20\log_{10}(40)$
$= 32.04dB.$

$AV_2 = \frac{V_3}{V_2} = \frac{1.25}{36 \times 10^{-3}} = 34.722V$
$= 20\log_{10}(34.722)$
$= 30.81dB.$

Again

$AV_3 = \frac{21}{1.25} = 24.5dB.$

$\frac{V_L}{V_S} = \frac{21V}{900 \times 10^{-6}} = 23333.33 = 87.35dB$ //

2) A Three stage amplifier has a 1st stage Voltage gain of 100, 2nd stage voltage gain of 200 and 3rd stage voltage gain of 400. find total voltage gain.

∴ Total voltage gain in dB is,

$$A_v = A_{V1} \times A_{V2} \times A_{V3}$$

$$= 20\log_{10} A_{V1} + 20\log_{10} A_{V2} + 20\log_{10} A_{V3}$$

$$= 20\log_{10}(100) + 20\log_{10}(200) + 20\log_{10}(300)$$

$$= 138 dB$$

Choice of Configuration in Cascade

Common Emitter configuration

- Has high current and voltage gain, used for amplification

Common Base configuration

•High voltage gain, low current gain , can't be used intermediate stage while cascading

Common Collector configuration

- Used in impedance matching, less than unity voltage gain

Characteristics / Configuration	Common Base	Common Emitter	Common Collector
Input impedance	Low (about 100 Ω)	Medium (about 800 Ω)	Very high (about 750 kΩ)
Output impedance	Very high (about 500 kΩ)	High (about 50 kΩ)	Low (about 50 Ω)
Current gain	Less than unity but usually more than 0.9 (about 0.98)	High (about 80)	High (about 100)
Voltage gain	About 150	About 500	Less than unity
Leakage current	Very small (5 μA for Ge and 1 μA for Si)	Very large (500 μA for Ge and 20 μA for Si)	Very large
Output Signal phase	In phase with input	Reverse	In phase with input
Applications	For high frequency applications	For AF applications	For impedance matching

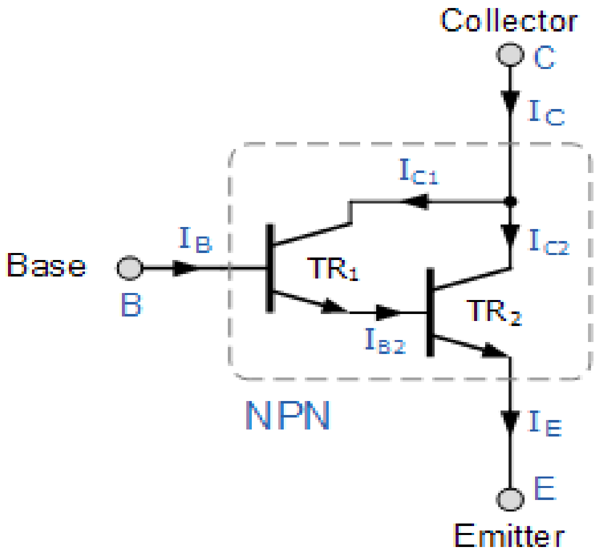
Darlington Pair Amplifier (Super Beta Amplifier)

- Darlington is a special arrangement of two standard NPN or PNP bipolar junction transistors (BJT) connected together
- Emitter of one transistor is connected to the Base of the other to produce a more sensitive transistor with a much larger current gain
- useful in applications where current amplification or switching is required
- the first transistor TR_1 becomes the base current of the second transistor TR_2, TR1 is connected as an emitter follower and TR2 as a common emitter

We have,

$$I_C = I_{C1} + I_{C2}$$

$$I_C = \beta_1 . I_B + \beta_2 . I_{B2}$$



the base current, I_{B2} is equal to transistor TR1 emitter current, I_{E1} as the emitter of TR1 is connected to the base of TR2. Therefore

$$I_{B2} = I_{E1} = I_{C1} + I_B = \beta_1 . I_B + I_B = (\beta_1 + 1) . I_B$$

Then substituting in the first equation:

$$I_C = \beta_1 . I_B + \beta_2 . (\beta_1 + 1) . I_B$$

$$I_C = \beta_1 . I_B + \beta_2 . \beta_1 . I_B + \beta_2 . I_B$$

$$I_C = (\beta_1 + (\beta_2 . \beta_1) + \beta_2) . I_B$$

Where β_1 and β_2 are the gains of the individual transistors. If **$\beta 1 = \beta 2 = \beta$,**

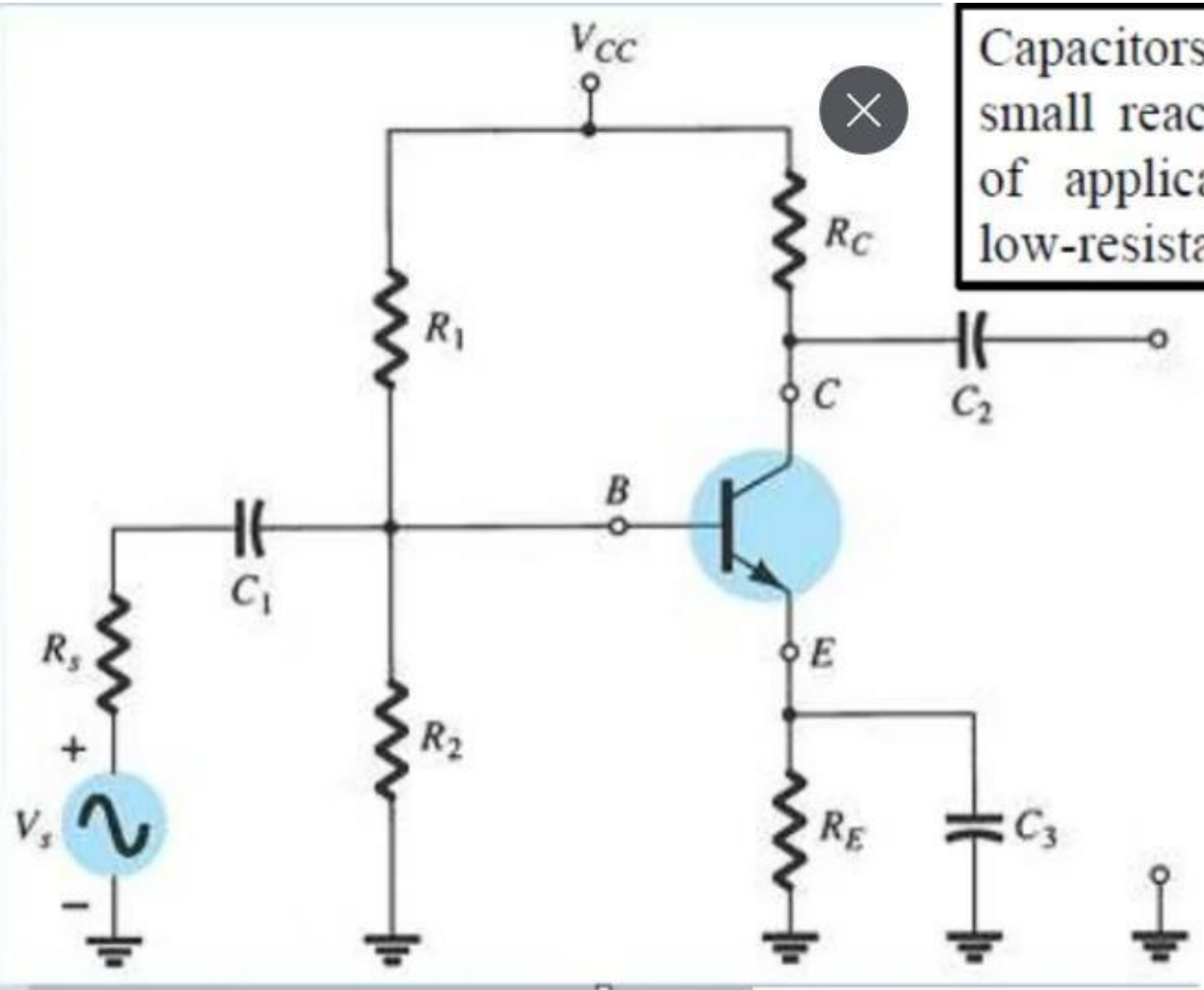
Collector current IC = IB *(2**β+β^2.)**

Hence Darlington pair is regarded as super beta transistor.

It offers very high input impedance, uses few components and hence can be used for easy circuit designs, can amplify signal to larger extent.

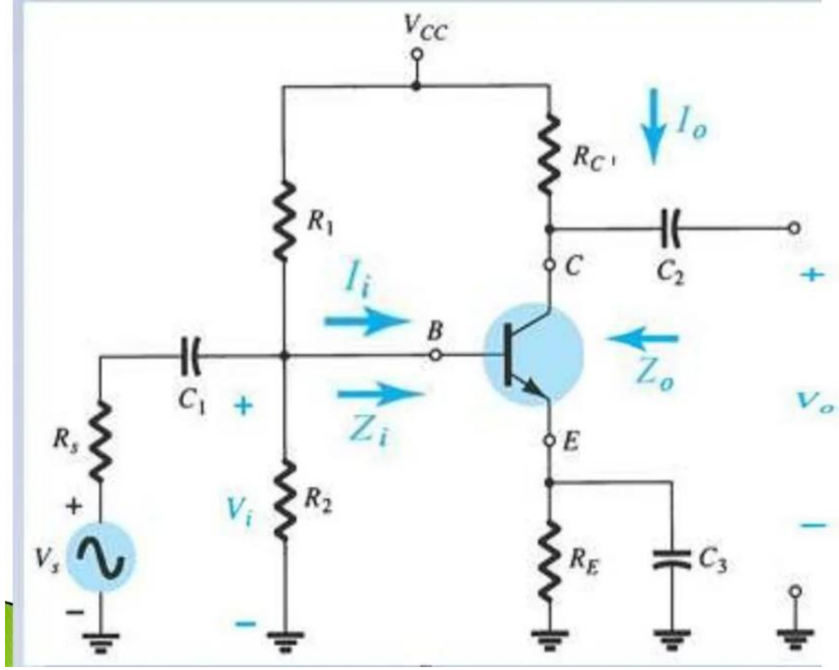
Model

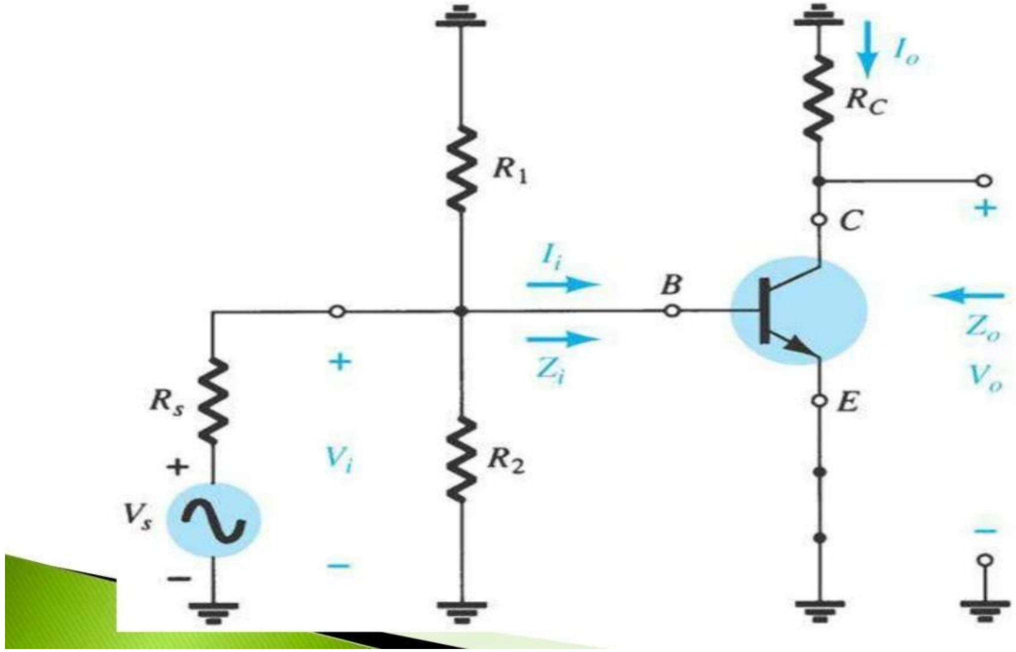
- an equivalent circuit that represents the AC characteristics of the transistor
- uses circuit elements that approximate the behaviour of the transistor.

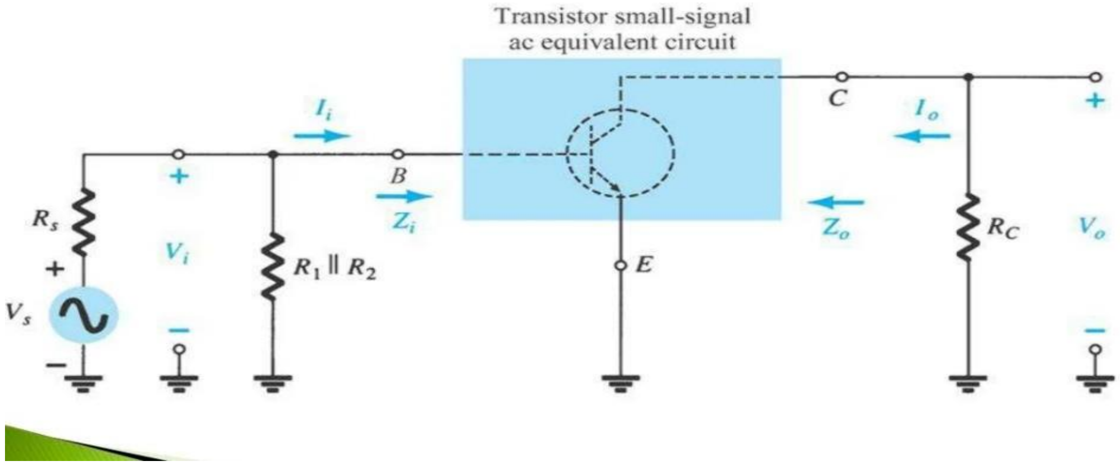


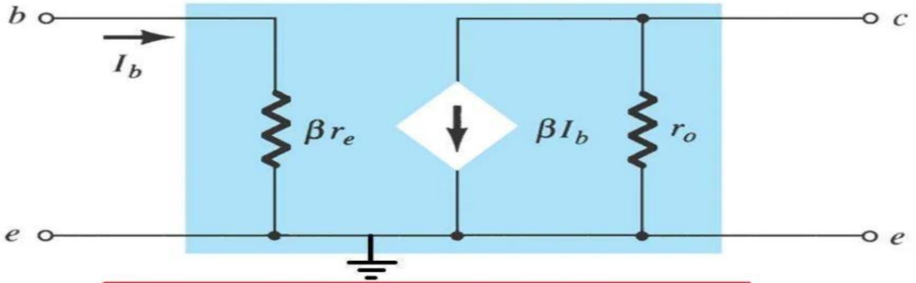
Capacitors chosen with very small reactance at the frequency of application → replaced by low-resistance or short circuit.

Removal of the dc supply and insertion of the short-circuit equivalent for the capacitors.



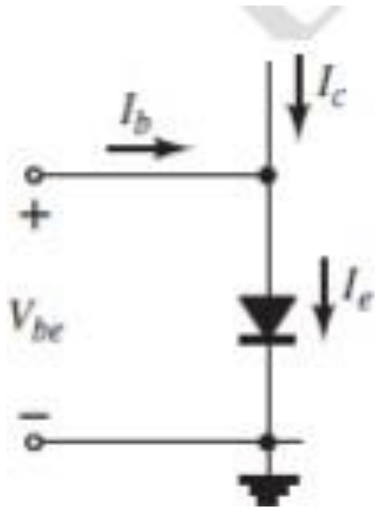




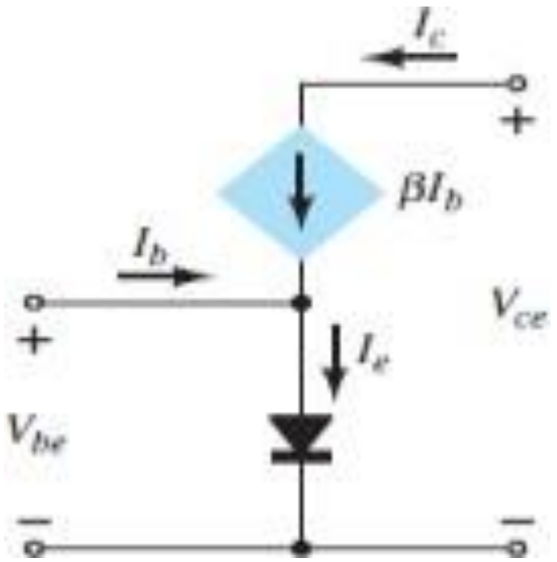


re model for the common emitter transistor configuration

The output resistance r is typically in the range of 40 kΩ to 50 kΩ



I_c
I_b
+
V_{be}
I_e
−

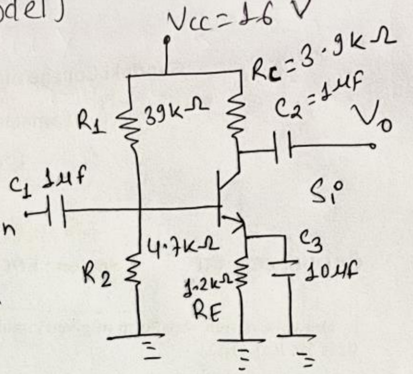


I_c
+
βI_b
I_b
+
V_{ce}
I_e
V_{be}
−
−

Here in numerical, replace all notation of RL by Rc.(if any)

Solved problem (r_e Model)

a) Determine r_e
b) Calculate I/p impedance (Z_{in})
c) " O/p impedance (Z_o)
d) Find Voltage gain (A_v)
e) Find current gain (A_i)
f) Draw ac equivalent circuit



$\beta = 100$

$r_o = 50k\Omega \, (\Rightarrow \infty)$

Here,
AC equivalent circuit for given problem is.

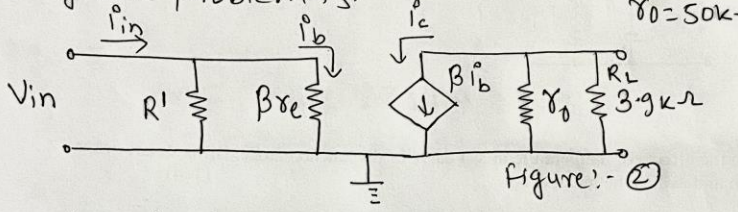


Figure:- 2

Now, $R' = R_1 \| R_2 = \frac{4.7k\Omega \times 39k\Omega}{(4.7+39)k\Omega} = 4.194k\Omega = R_{th}$

a) we have,

$$r_e = \frac{26mV}{I_E}$$

Now solving for I_E, converting given problem into Thevinin's equivalent circuit

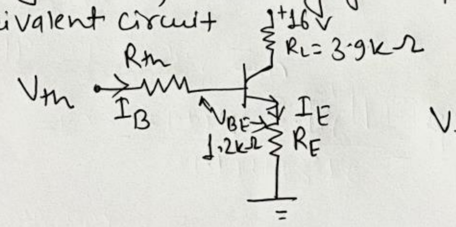


figure:- DC analysis,

$$V_{th} = V_{cc} \times \frac{R_2}{R_1 + R_2}$$

$$= 16 \times \frac{4.7k\Omega}{(39+4.7)k\Omega}$$

$$\therefore V_{th} = 1.720 \, V$$

Applying KVL at I/p,

$$V_{th} = I_B R_{th} + V_{BE} + I_E R_E$$

$[\because I_E \simeq I_c = \beta I_B]$

$$\therefore I_B = \frac{\cancel{16V - 0.7V}\,(1.720-0.7)V}{(4.194k\Omega + \overset{(\beta)}{100} \times 1.2k\Omega)} = \cancel{} = 8.21 \, \mu A$$

Applying KVL at I/P,

$$V_{th} = I_B R_{th} + V_{BE} + I_E R_E$$

$$V_{th} = I_B R_{th} + V_{BE} + (1+\beta) I_B R_E$$

$$I_B = \frac{V_{th} - V_{BE}}{R_{th} + (1+\beta) R_E}$$

on solving, $I_B = 8.13\,\mu A$

Again,

$$I_C = \beta I_B = 821\,\mu A \approx I_E.$$

$\therefore I_E = 821\,\mu A = 0.821\,mA$ //

a) $r_e = \frac{26mV}{I_E} = \frac{26}{0.821} = 31.6\,\Omega$ // (dynamic emitter resistance)

For, calculation of Zin & Zo, we need ac equivalent circuit as in figure 1.2 (Short circuit all the dc voltage sources & all the capacitors). In figure, C_3 is short circuited therefore ~~drop~~ voltage drop across $R_E = 0V$.

b) For I/P impedance, $Z_{in} = R' \| \beta r_e = 4.194k\Omega \| 3.16k\Omega$

$$Z_{in} = \frac{4.194 \times 3.16}{4.194 + 3.16} = 1.802\,k\Omega = 1.802\,k\Omega$$

[or, $1.811k\Omega$ for, $(\beta+1) r_e$]

c) For O/P impedance, $Z_o = r_o \| R_C$

$= 50k\Omega \| 3.9k\Omega$

$Z_o = 3.617\,k\Omega$ //

[normally, $r_o \geq 10R_C$ ~~or 10Rc~~ $\therefore$ ~~Ro = Rc~~.]

d) Voltage gain $(A_v) = -\frac{R_C}{r_e} = -\frac{R_c}{r_e}$ $\left[\cancel{R_{ac} = R_c}\right]$

$$= -\frac{3.9\,k\Omega}{31.6\,\Omega} = -123.417$$

e) Current gain, $(A_i) = \frac{I_c}{I_B} = \beta = 100$

For voltage gain $(A_v) = \frac{V_o}{V_{in}} = -\frac{I_o Z_o}{I_{in} Z_{in}}$

$$= \frac{-I_c Z_o}{I_{in} Z_{in}} = \frac{-\beta I_B * (r_o \| R_c)}{\beta I_B r_e} = -\frac{(r_o \| R_c)}{r_e}$$

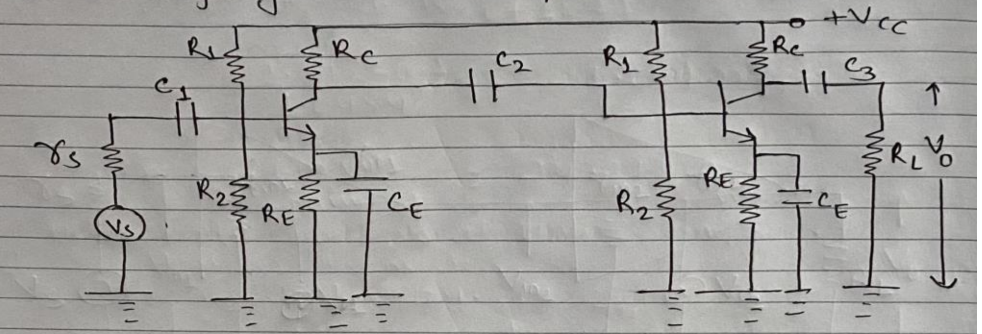
$\left[\text{Here, } r_o >>> R_c, \text{ So } (V_o/V_{in}) \approx -\frac{R_c}{r_e}\right]$

$\left[\text{For } (r_e) = \frac{26\,mV}{I_E}, \text{ We have, } r_d = \frac{\eta V_T}{I_D + I_S}, \begin{cases} \text{For } \eta = 1 \\ V_T = 26\,mV \\ I_D + I_S = I_E \end{cases}\right]$

8.7.1. Principal Performance Characteristics

1. Input resistance, $R_{in} = R_B \| \beta r_e' \cong \beta r_e'$, input resistance of the base
2. AC load resistance, $R_{ac} = R_C \| R_L$
3. Current gain, $A_i = \frac{I_c}{I_b} = \beta$
4. Voltage gain, $A_v = \frac{V_{out}}{V_{in}} = -\frac{I_c R_{ac}}{I_b R_{in}} = -\frac{\beta I_b R_{ac}}{I_b \beta r_e'} = -\frac{R_{ac}}{r_e'}$
5. Power gain, $A_p = A_i\, A_v = \beta \frac{R_{ac}}{r_e'}$

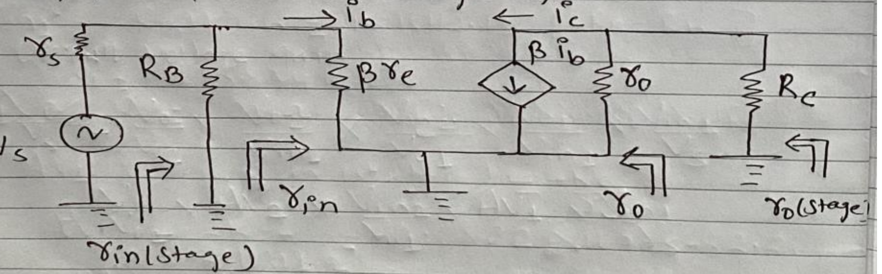
Voltage gain of Two-stage RC coupled Amplifier.



Figure!- Two stage Rc coupled amplifier.

Now,

r_e, model for 1^{st} stage is,



Here, $r_{in} = \beta r_e$ //

(r_{in1}), $r_{in}(stage) = R_B || r_{in}$ //

$r_o(stage)$, (r_{o1}) $= r_o || R_c \simeq R_c$ //

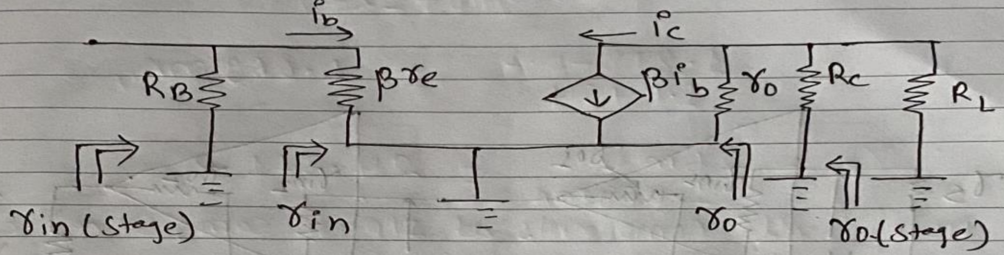
where,
$R_B = R_1 || R_2$

$r_o >>> R_c$

$\therefore$ Voltage gain $= \frac{-R_c}{r_e}$ //

$\therefore$ 1^{st} stage voltage gain (A_{V1}) $= -\frac{R_c}{r_e}$ //

For 2^{nd} stage, r_e model is



Here,

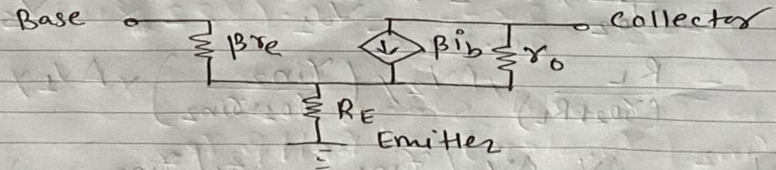
$r_{in} = \beta r_e$

$r_{in}(stage) = r_{in2} = R_B || \beta r_e$

$r_o(stage) = r_{o2} = R_c || r_o \simeq R_c$

$\therefore$ Voltage gain for 2^{nd} stage (A_{V2}) $= -\frac{R_c}{r_e}$

Note:- If there is no capacitor at parallel of R_E or in absence of C_E, R_E is present in the circuit as,

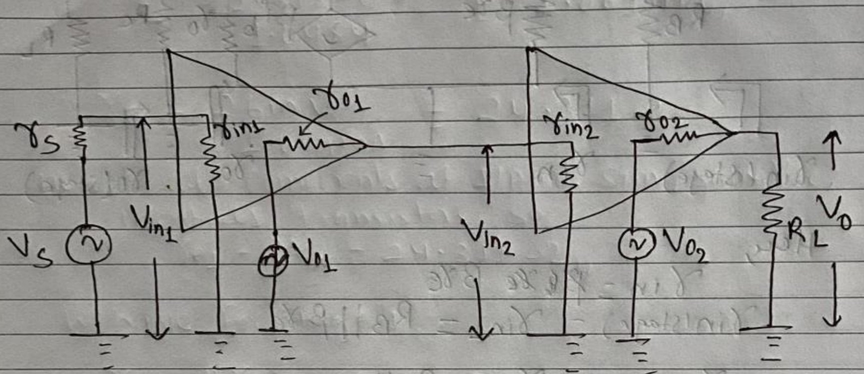


So, you have to consider R_E during modeling, as,

$r_{in} = (\beta r_e + R_E)$

Voltage gain $= -\frac{R_c}{r_e + R_E}$ ... so on

Now the over all circuit is represented as,



∴ Overall voltage gain,

$$\frac{V_o}{V_s} = \frac{V_o}{V_{o2}} \times \frac{V_{o2}}{V_{in2}} \times \frac{V_{in2}}{V_{o1}} \times \frac{V_{o1}}{V_{in1}} \times \frac{V_{in1}}{V_s}$$

$$= \frac{V_o}{V_{o2}} \times AV_2 \times \frac{V_{in2}}{V_{o1}} \times AV_1 \times \frac{V_{in1}}{V_s}$$

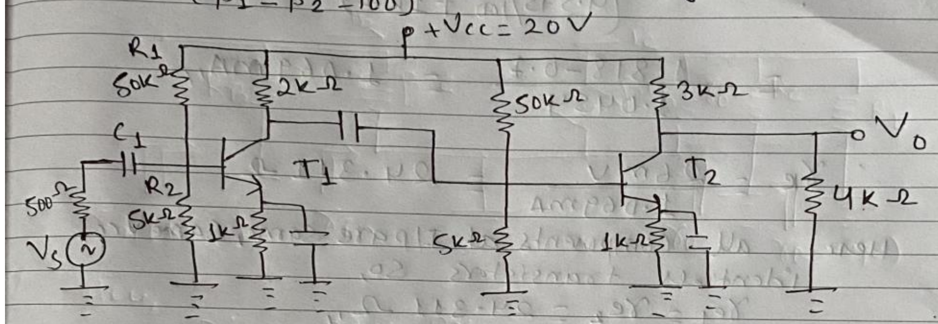
$$= \frac{R_L}{(r_{o2}+R_L)} \times AV_2 \times \left(\frac{r_{in2}}{r_{o1}+r_{in2}}\right) \times AV_1 \times \left(\frac{r_{in1}}{r_s+r_{in1}}\right)$$

$$\therefore \frac{V_o}{V_s} = AV_1 \cdot AV_2 \left(\frac{r_{in1}}{r_s+r_{in1}}\right) \times \left(\frac{r_{in2}}{r_{o1}+r_{in2}}\right) \times \left(\frac{R_L}{R_L+r_{o2}}\right)$$

For current gain,

$$\frac{I_o}{I_s} = \frac{V_o/R_L}{V_s/(r_s+r_{in1})} = \frac{V_o}{V_s} \times \frac{(r_s+r_{in1})}{R_L}$$

Find overall voltage gain for the given circuit. $(\beta_1 = \beta_2 = 100)$



We have, $r_e = \frac{26mV}{I_E}$

To find I_E, we do dc analysis in stage 1 or in T_1.
Converting 1st stage in Thevenin's circuit

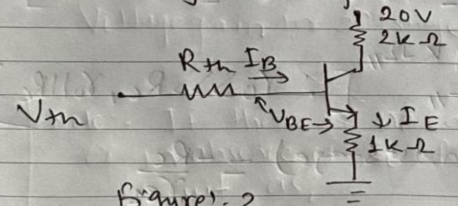


figure: 2

Here,

$$V_{th} = V_{cc} \times \frac{R_2}{R_1+R_2}$$

$$= 20 \times \frac{5}{(50+5)} = 1.818\ V$$

For R_{th},

$$= \frac{R_1 \times R_2}{R_1+R_2}$$

$$= \frac{50 \times 5}{50+5} = 4.545\ k\Omega$$

Now Applying KVL at I/P of figure 2 to find I_E,

$$V_{th} = I_B R_{th} + V_{BE} + I_E R_E \quad \left[I_C \approx I_E \quad \therefore I_B = \frac{I_E}{\beta}\right]$$

$$\therefore I_E = \frac{V_{th} - V_{BE}}{(R_{th}/\beta + R_E)}$$

$$\therefore I_E = \frac{1.818V - 0.7}{(4.545/100 + 1k\Omega)}$$

$$= \frac{1.818 - 0.7}{1.0454} = 1.069\,mA$$

$$\therefore r_e = \frac{26mV}{1.069mA} = 24.311\,\Omega$$

Here, all components at I/p are same, same Vcc, identicals transsistors so,

$$r_{e_1} = r_{e_2} = 24.311\,\Omega$$

we have for stage 1,

$$r_{in} = \beta r_e = 2.43k\Omega$$

$$r_{in_1} = R_B \| r_{in} = 4.545 \| 2.43 \quad [R_B = R_{th}]$$

$$r_{in_1} = 1.5834\,k\Omega$$

$$r_{o1} \simeq R_c = 2k\Omega \quad [\because r_o >>> R_c, r_o \| R_c]$$

$$\therefore AV_1 \text{ (Voltage gain, 1st stage)} = -\frac{R_c}{r_{e_1}}$$

$$AV_1 = -\frac{2k\Omega}{24.311\Omega} = -0.0822 \times 10^3 = -82.26$$

Now for 2nd stage,

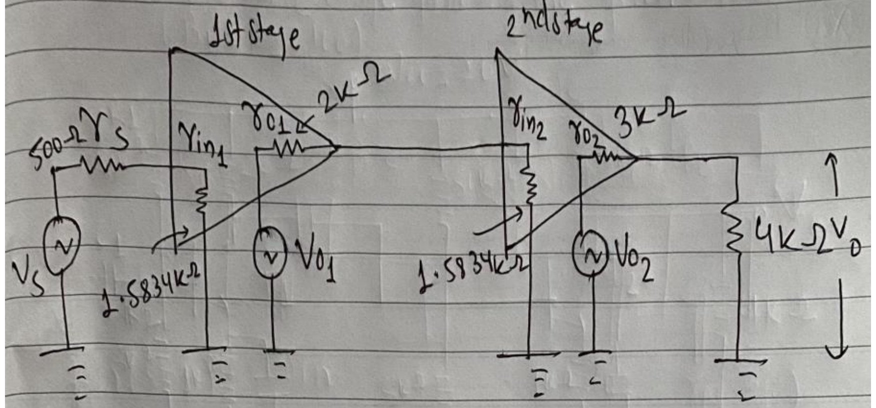
$$r_{in_2} (r_{in}\text{ stage}) = R_B \| \beta_2 r_{e_2}$$

$$= 4.545 \| 2.43 = 1.5834\,k\Omega$$

[Given, $\beta_1 = \beta_2 = 100$, $R_1 = R_2$, r_e same]

$$r_{o\,stage} (r_{o_2}) \simeq R_c \text{ for 2nd stage} = 3k\Omega$$

$$\therefore \text{Voltage gain } (AV_2) = \frac{-R_c}{r_{e2}} = \frac{-3k\Omega}{24.311\Omega} = -123.40$$



∴ Now overall gain is,

$$\frac{V_o}{V_s} = AV_1 \times AV_2 \times \left(\frac{r_{in_1}}{r_{in_1} + r_s}\right) \times \left(\frac{r_{in_2}}{r_{o_1} + r_{in_2}}\right) \times \left(\frac{R_L}{R_L + r_{o_2}}\right)$$

$$= -82.26 \times -123.40 \left(\frac{1.58}{1.58 + 0.5}\right) \times \left(\frac{1.58}{2 + 1.58}\right) \times \left(\frac{4}{4+3}\right)$$

$$= 10150.884 \times 0.759 \times 0.4413 \times 0.5714$$

$$= 1942.86$$

Gain = 20log(1942.86)
= 65.76 dB