UNIT-1

Multistage Amplifiers:

Classification of Amplifiers:

1. Based on the Transistor configurations, the amplifiers are classified as,
   → Common Emitter amplifier
   → Common Base Amplifier
   → Common Collector Amplifier
2. Based on the Frequency range
   → Audio Frequency range amplifier (20 to 20 KHz)
   → Video Frequency range Amplifier | Pulse amplifier (Hz to few MHz)
   → Radio Frequency range Amplifier / High frequency range Amplifier (Hundreds to MHz)
   → Ultra high Frequency range Amplifier (UHF) (100s to 1000 MHz)
3. Based on the type of coupling
   → RC coupled Amplifier
   → Transformer coupled Amplifier
   → Direct Coupled Amplifier
4. Based on the method of operation | Power amplifiers
   → Class A power Amplifier
   → Class B power Amplifier
   → Class C power Amplifier
   → Class AB power Amplifier

5. Based on the type of signal

→ Small signal Amplifiers

→ Large signal Amplifiers Eg: Power amplifiers

→ Input signal have large amplitude

6. Based on Application

→ Voltage Amplifiers

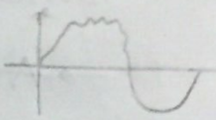
→ Current Amplifiers

→ Power Amplifier

→ Tuned Amplifier

Distortions in Amplifiers

1. Nonlinear Distortion/Amplitude distortion:

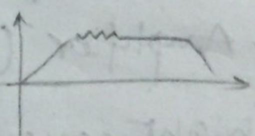


In this type of distortion some new frequencies are present in output which are not present in input.

2. Frequency Distortion: It occurs due to some reactive components.

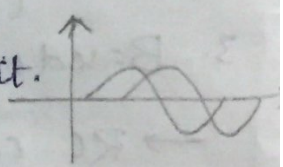
Harmonic distortion

They are identified in frequency response



3. Phase shift Distortion: It occurs due to complex conjugate components present in the circuit.

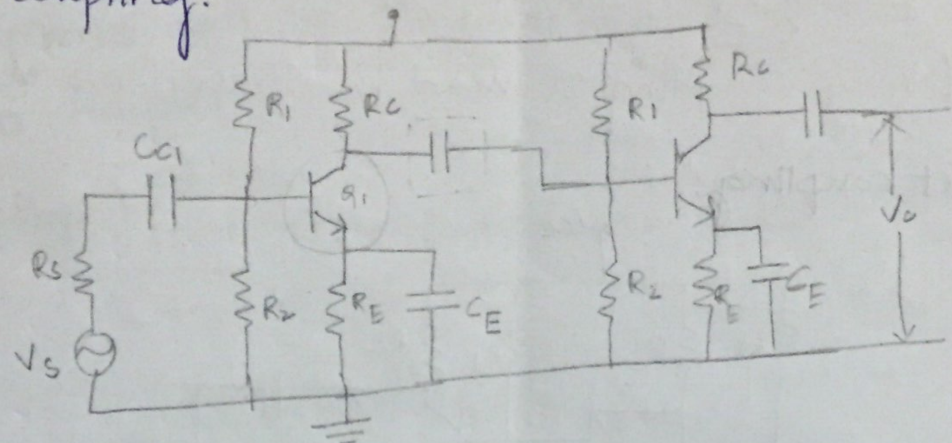
(Delay Distortion)



Different types of coupling schemes: 27|12|19

1. RC coupling
2. Transformer coupling
3. Direct coupling

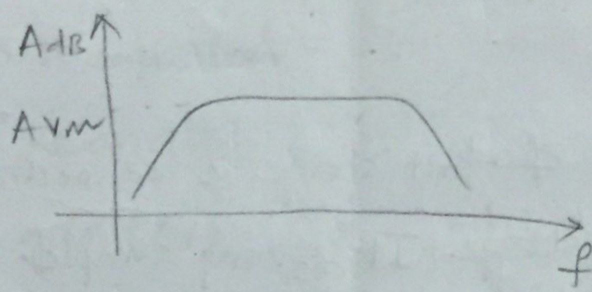
1. RC coupling:



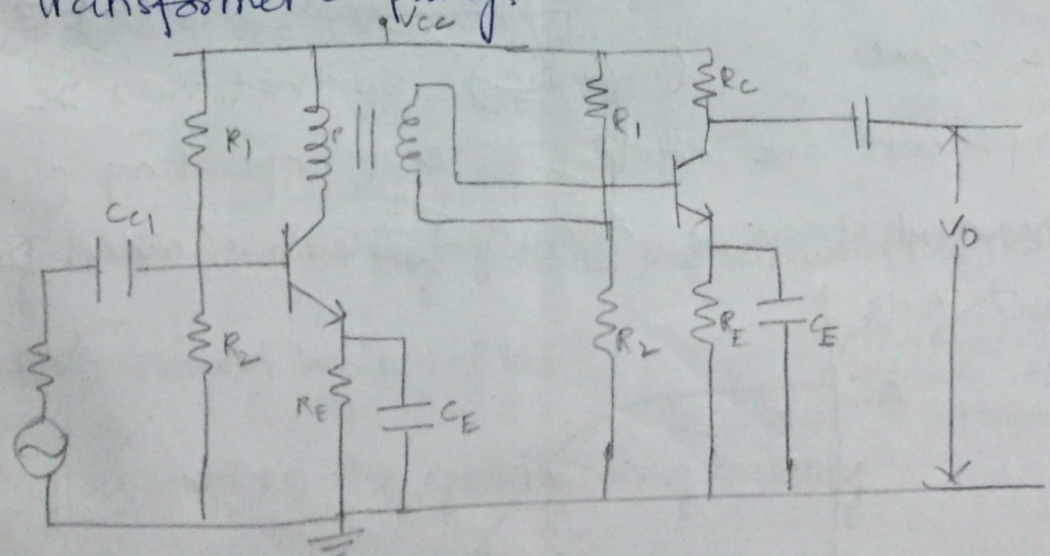
(Two stage RC coupled Amplifier)

There are no disturbances in the operating point due to RC coupling.
↓
fixed.

capacitor allows only AC signal to the next level by blocking the DC signal so the response will be as expected.



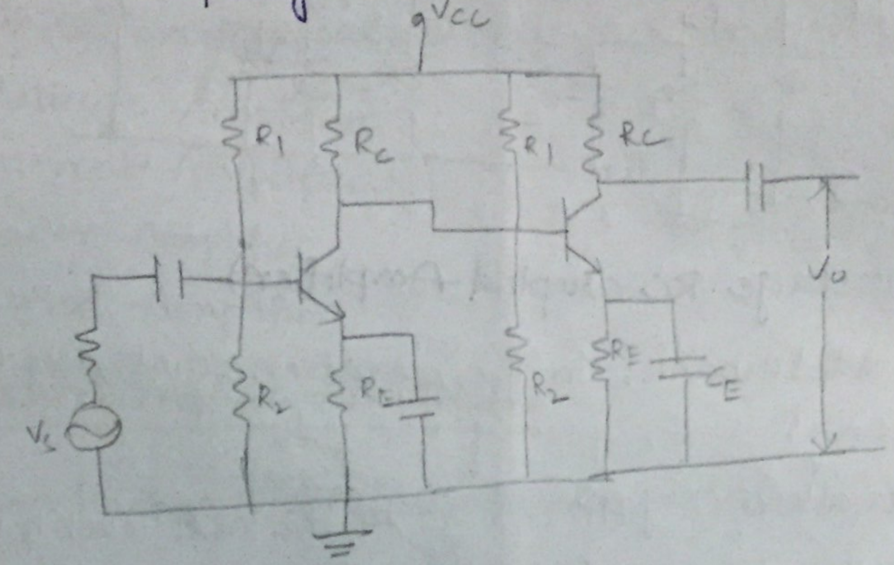
2. Transformer coupling:



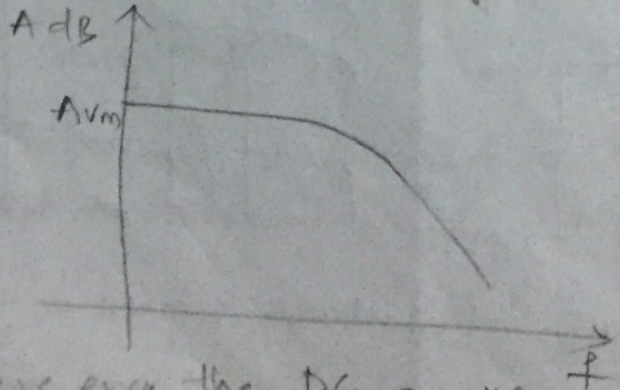
The output of the first stage is given as the input of the next stage through transformer. As the inductive elements are present, there will be some leakage so the frequency response is distorted. Circuit is also complex

Transformer coupling is used in Impedance matching

3. Direct coupling:



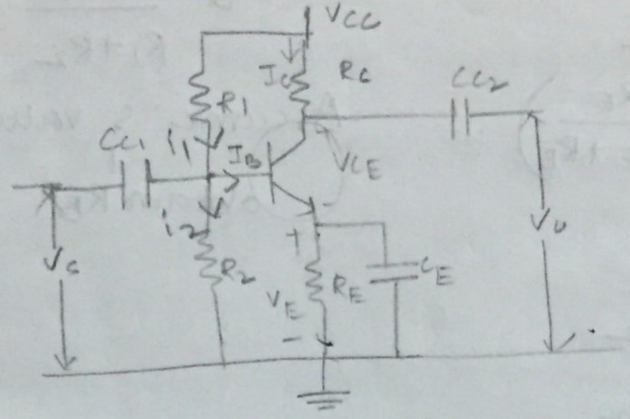
The output is of first stage is connected directly to the next stage. It is very simple. By R1, Rc and Vcc some DC components are added to the signal.
(new DC) so that new DC components are added so that operating point of the next stage is changed which is called Drift.



where ever the DC amplification is required the Direct coupled Amplifier is used.

RC coupled Amplifier is preferred because the frequency response will be similar to ideal response. Circuit is also simple.

Design & Analysis of CE Amplifier Circuit:



R_1 & R_2 — Biasing Resistors ; R_C — Collector Resistance

R_E — Emitter Resistance ; C_{c_1}, C_{c_2} — Coupling capacitors

C_E — Bypass capacitor.

Design of R_C and R_E

Voltage gain $(A_V) = \frac{A_i R_L}{Z_i} = \frac{-h_{fe} R_L}{h_{ie}} = \frac{-h_{fe} R_C}{h_{ie}}$

$V_{CC} = I_C R_C + V_{CE} + V_E$

$$\boxed{R_C = \frac{V_{CC} - V_{CE} - V_E}{I_C}} \quad \text{--- (1)}$$

→ V_{CE} should by 50% of Vcc to avoid the Thermal Runaway (Self destruction of Transistor)

→ V_E should be 10% of Vcc

↓

to maintain the good biasing stability

→ $V_E = I_E R_E$

Assumptions to find Rc

$$\boxed{R_E = \frac{V_E}{I_E}} \quad (I_C \simeq I_E) \quad \text{--- (2)}$$

Design of R_1 & R_2

$$V_B = V_{CC}\frac{R_2}{R_1+R_2} \quad \text{--- (3)}$$

$$R_B = \frac{R_1R_2}{R_1+R_2} \quad \text{--- (4)}$$

$$S = \frac{1+\beta}{1+\beta\left(\frac{R_E}{R_E+R_B}\right)}$$

Assume 'S' value and obtain R_B

$$\frac{V_B}{V_{CC}} = \frac{R_2}{R_1+R_2}$$

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

(Alternature method)

$I_B \equiv$ negligeble $\Rightarrow i_1 = i_2$; $R_1 = \dfrac{V_{CC}-V_B}{i_2}$

i_2 value is taken as 10% of I_C

Design of coupling capacitors

For designing coupling capacitors, consider the lower cutoff frequeny, as it effects the f_L value

C_{C1}

$$X_{C_1} = \frac{1}{2\pi f_L C_{C_1}}$$

For good biasing, choose X_{C_1} such that it should be equal to 10% of R_i

$$\boxed{f_L = \frac{1}{2\pi R_i C_{C_1}}}$$

$(R_i = R_1 \| R_2 \| h_{ie})$

C_{C2}

$$X_{C_2} = \frac{1}{2\pi f_L C_{C_2}}$$

$X_{C_2} = 10\%$ of R_0 $\quad (R_0 = R_C \| R_L)$

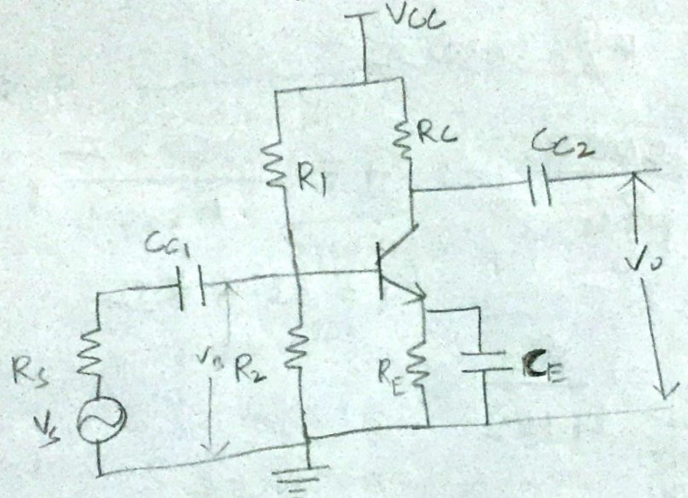
Design of Bypass capacitor

(C_E) X_{CE} value should be equal to 10% of R_E

$$\boxed{X_{CE} = \frac{1}{2\pi f_L C_E}}$$

→ Design a single stage RC coupled Amplifier. Assume $V_{CC} = 12V$, $I_C = 1mA$; $\beta = 100$; $R_L = 1K\Omega$; $h_{ie} = 1K\Omega$

$f_L = 100Hz$. Stability factor ($S = 5$).



$$\beta = \frac{I_C}{I_B} \Rightarrow \frac{10^{-3}}{I_B} = 100$$

$$I_B = 10^{-5}$$

$$R_C = \frac{12 - 6 - 1.2}{1 \times 10^{-3}} \Rightarrow \frac{4.8}{10^{-3}} \Rightarrow 4.8\,K\Omega$$

$$R_E = \frac{1.2}{1 \times 10^{-3}} \Rightarrow 1.2 \times 10^{3}$$

$$V_B = 12\left(\frac{R_2}{R_1 + R_2}\right)$$

$$V_B = V_{BE} + V_E \Rightarrow 0.6 + 1.2$$

$$\Rightarrow 1.8$$

$$5 = \frac{1+100}{1+100\left(\frac{1.2\times10^3}{1.2\times10^3 + R_B}\right)}$$

$$\frac{1.8}{12} = \frac{R_B}{R_1}$$

$$5 + 500\left(\frac{1.2\times10^3}{1.2\times10^3 + R_B}\right) = 101$$

$$500\left(\frac{1.2\times10^3}{1.2\times10^3+R_B}\right)=96$$

$$\frac{1.2\times10^3}{1.2\times10^3+R_B}=0.192$$

$$\frac{1.2\times10^3}{0.192}=1.2\times10^3+R_B$$

$$6.25\times10^3=1.2\times10^3+R_B$$

$$R_B=5.05\times10^3$$

$$R_B=5050\,\Omega$$

$$\frac{1.8}{12}=\frac{5050}{R_1} \qquad R_1=\frac{5050\times12}{1.8}$$

$$R_1=33.6\,K\Omega$$

$$\frac{5050}{33.6\times10^3}=\frac{R_2}{R_1+R_2}$$

$$\frac{33.6\times10^3}{5050}=1+\frac{R_1}{R_2}$$

$$6.65-1=\frac{R_1}{R_2}$$

$$5.65=\frac{R_1}{R_2} \Rightarrow R_2=\frac{33.6\times10^3}{5.65}$$

$$R_2=5.9\times10^3\,\Omega$$

$$X_{C1}=\frac{1}{2\pi f_L C_{C1}}$$

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

$$\frac{1}{R_i}=\frac{1}{33.6\times10^3}+\frac{1}{5.9\times10^3}+\frac{1}{10^3}$$

$$\frac{1}{R_i}=\frac{1}{10^3}\left(\frac{1}{33.6}+\frac{1}{5.9}+1\right)$$

$$\frac{1}{R_i}=\frac{1}{10^3}(0.02+0.16+1)$$

$$\frac{1}{R_i}=\frac{(1.18)}{10^3}$$

$$R_i=\frac{10^3}{1.18}$$

$$R_i=0.849\times10^3\Rightarrow847\,\Omega$$

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$$C_{C_1} = \frac{1}{100 \times 2 \times 3.14 \times 847}$$

$$C_{C_1} = \frac{1}{531916} = 1.87 \times 10^{-6} F$$

$$C_{C_1} = 1.87 \mu F$$

$$R_0 = R_C \| R_L$$

$$\frac{1}{R_0} = \frac{1}{4.8 \times 10^3} + \frac{1}{10^3} = \left(\frac{1}{4.8} + 1\right) \times \frac{1}{10^3} = \frac{1}{R_0}$$

$$(1.2) \times \frac{1}{10^3} = \frac{1}{R_0},$$

$$R_0 = 0.83 \times 10^3$$

$$X_{C2} = 0.83 \times 10^2$$
$$= 83$$

$$83 = \frac{1}{2 \times 3.14 \times 100 \times C_{C2}}$$

$$C_{C_2} = \frac{1}{314 \times 166} = \frac{1}{52124} = 19.1 \times 10^{-6} F$$
$$= 19.1 \mu F$$

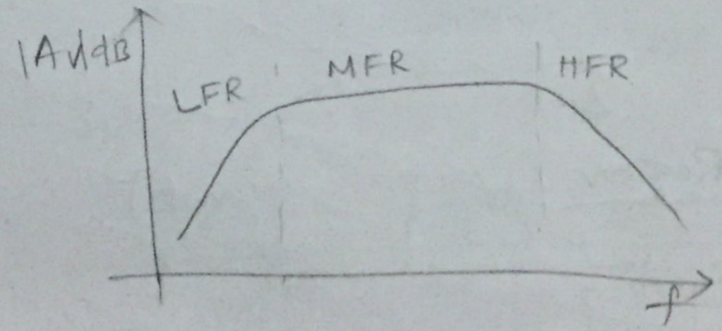
$$X_{CE} = 1.2 \times 10^2$$

$$120 = \frac{1}{2 \times 314 \times C_E}$$

$$C_E = \frac{1}{314 \times 240} = \frac{1}{75360}$$

$$C_E = 13.2 \times 10^{-6} F$$
$$C_E = 13.2 \mu F$$

Frequency response of CE Amplifier



Low-frequency Region (High pass circuit)

In low frequency region, it acts as High pass filter.

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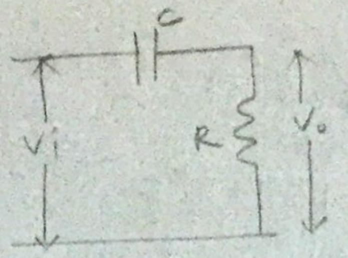
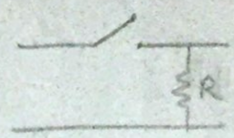


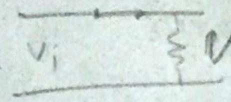
$$X_C = \frac{1}{2\pi f C}$$

$f = 0 \quad X_C = \frac{1}{0} = \infty$



$V_0 = 0$

$f = \infty \quad X_C = \frac{1}{\infty} = 0$



$V_0 = V_i$

$$V_0 = V_i \frac{R}{R + X_C}$$

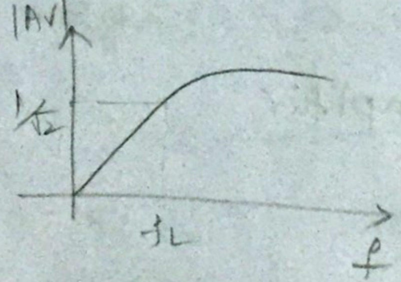
$$A = \frac{V_0}{V_i} = \frac{R}{R + X_C} = \frac{1}{1 + \frac{X_C}{R}} = \frac{1}{1 - \frac{j}{\omega C R}} = \frac{1}{1 - \frac{j}{2\pi f R_C}}$$

$$\boxed{|A_V| = \frac{1}{\sqrt{1 + \left(\frac{f_L}{f}\right)^2}}}$$

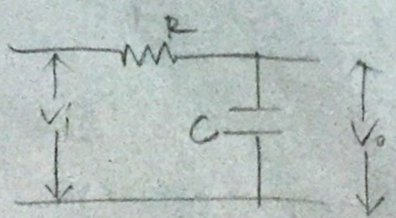
where $f_L = \frac{1}{2\pi R C}$

$f = 0; \quad |A_V| = 0 \quad ; f > f_L \quad |A_V| \approx 1$

$f = f_L \quad |A_V| = 1/\sqrt{2} \quad ; f >> f_L \quad |A_V| = 1$

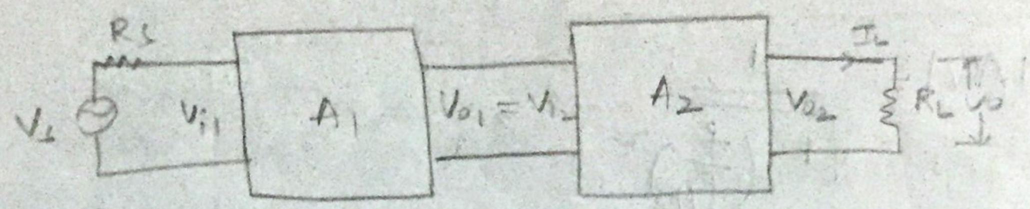


High frequency Region (Lowpass circuit)



$$\frac{V_0}{V_i} = \frac{X_C}{R + X_C} \Rightarrow \frac{\frac{1}{j\omega C}}{R + \frac{1}{j\omega C}}$$

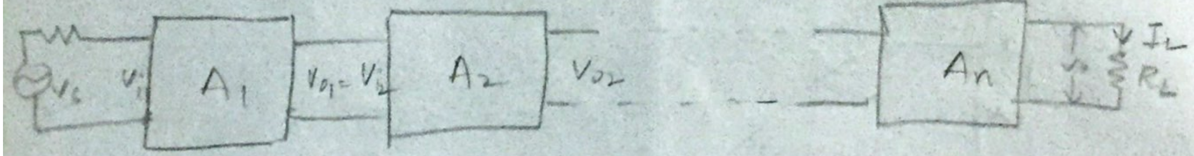
Analysis of Multistage Amplifiers



Two stage amplifier

$$A_V = \frac{V_{O2}}{V_{O1}} = \frac{V_{O2}}{V_{i2}} \times \frac{V_{i2}}{V_{i1}} = A_{V_2} \times A_{V_1}$$

The gain of two stage amplifier is equal to product of individual stage gains.

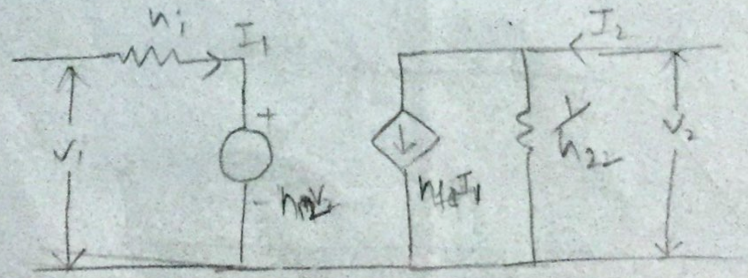


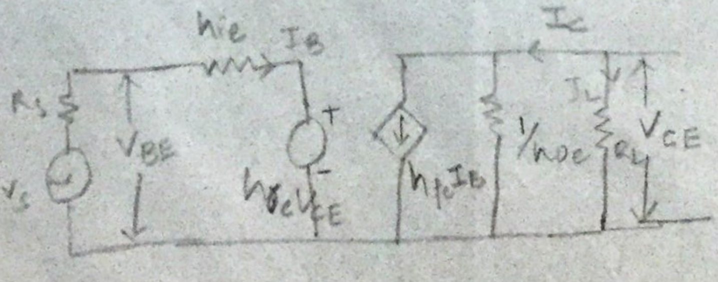
$$A_V = A_{V_1} \times A_{V_2} \cdots A_{Vn}$$

H-parameter model

$$V_1 = h_{11}I_1 + h_{12}V_2$$

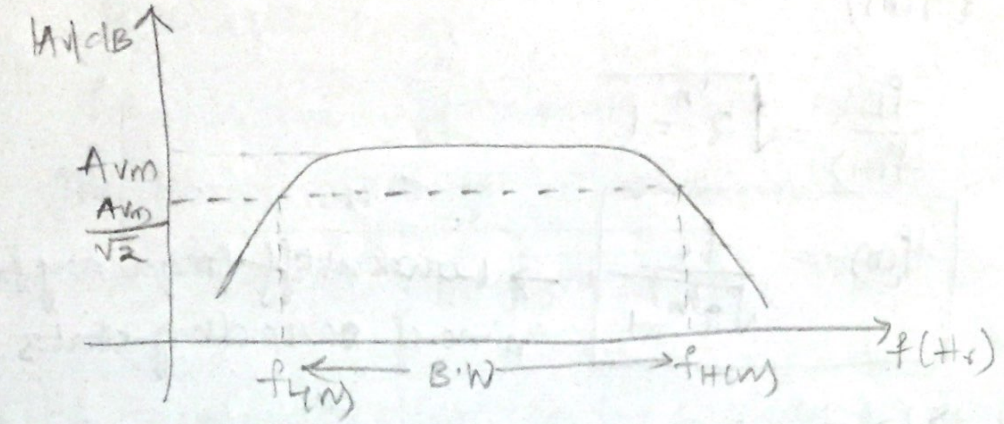
$$I_2 = h_{21}I_1 + h_{22}V_2$$





→ H-parameter model of Amplifier

Effect of bandwidth on Multistage Amplifier 2|1|2020



Overall gain, $A_{v(n)} = A_{v_1} \times A_{v_2} \times \dots \times A_{v_n}$

Bandwidth, $B.W(n) = f_{H(n)} - f_{L(n)}$

The voltage gain at low frequency region is,

$$|A_{vL}| = \frac{1}{\sqrt{1+\left(\frac{f_L}{f}\right)^2}}$$

The voltage gain at high frequency region is,

$$|A_{vH}| = \frac{1}{\sqrt{1+\left(\frac{f}{f_H}\right)^2}}$$

(identical stages)

At lower cutoff frequency the gain of 'n' no. of stages is

$$\frac{1}{\sqrt{2}} = \left[\frac{1}{\sqrt{1+\left(\frac{f_L}{f_{(n)}}\right)^2}}\right]^n$$

$$\sqrt{2} = \left(\sqrt{1+\left(\frac{f_L}{f_{(n)}}\right)^2}\right)^n$$

$$2 = \left(1+\left(\frac{f_L}{f_{(n)}}\right)^2\right)^n$$

$$2^{1/n} = 1+\left(\frac{f_L}{f_{(n)}}\right)^2$$

$$\left(\frac{f_L}{f_{(n)}}\right)^2 = 2^{1/n}-1$$

$$\frac{f_L}{f_{(n)}} = \sqrt{2^{1/n}-1}$$

$$\boxed{f_{L(n)} = \frac{f_L}{\sqrt{2^{1/n}-1}}}$$ → Lower cutoff frequency for 'n' no. of cascading states

f_L → Lower cutoff frequency of single stage / 3dB frequency

n → no. of cascading stages.

At high frequency region

$$\frac{1}{\sqrt{2}} = \left(\frac{1}{\sqrt{1+\left(\frac{f}{f_H}\right)^2}}\right)^n$$

$$\sqrt{2} = \left(\sqrt{1+\left(\frac{f}{f_H}\right)^2}\right)^n$$

$$\Rightarrow 2 = \left(1+\left(\frac{f}{f_H}\right)^2\right)^n$$

$$2^{1/n} = 1+\left(\frac{f}{f_H}\right)^2$$

$$\left(\frac{f_{(n)}}{f_H}\right)^2 = 2^{1/n}-1$$

$$\frac{f_{(n)}}{f_H} = \sqrt{2^{1/n}-1}$$

$$\boxed{f_{H(n)} = f_H\sqrt{2^{1/n}-1}}$$

$f_{H(n)}$ – upper cutoff frequency of n no. of cascading stages → (identical stages)

f_H → upper cutoff frequency of single stage

n → no. of cascading stages.

$B\cdot W_{(n)} = f_{H(n)} - f_{L(n)}$

$B\cdot W_{(n)} \simeq f_{H(n)}$

$f_{H(n)}$ is the approximate bandwidth.

The Band width of 'n' no. of cascading stages is

$$\boxed{B\cdot W_{(n)} = f_H\sqrt{2^{1/n}-1}}$$

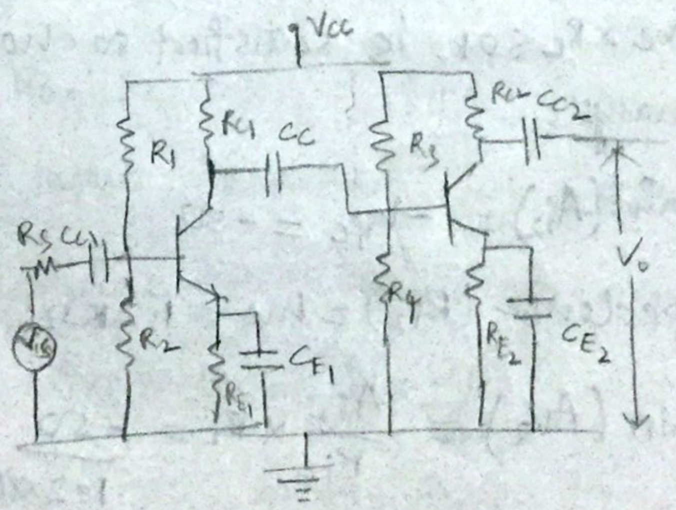
→ The Bandwidth decreases by cascading no. of stages, and the gain increases. [Gain × Bandwidth = constant]

→ In multistage amplifiers $f_{L(n)}$ is always greater than f_L and $f_{H(n)}$ is always less than f_H. Therefore we can say that bandwidth of multistage amplifier is less than the single stage.

→ If the stages are not identical then f_H, the bandwidth is approximately equal to f_H

i.e, $$\boxed{\frac{1}{f_H} = 1.1\sqrt{\frac{1}{f_1^2}+\frac{1}{f_2^2}+\dots+\frac{1}{f_n^2}}}$$

Analysis of two stage RC coupled CE-CE cascade Amplifier.

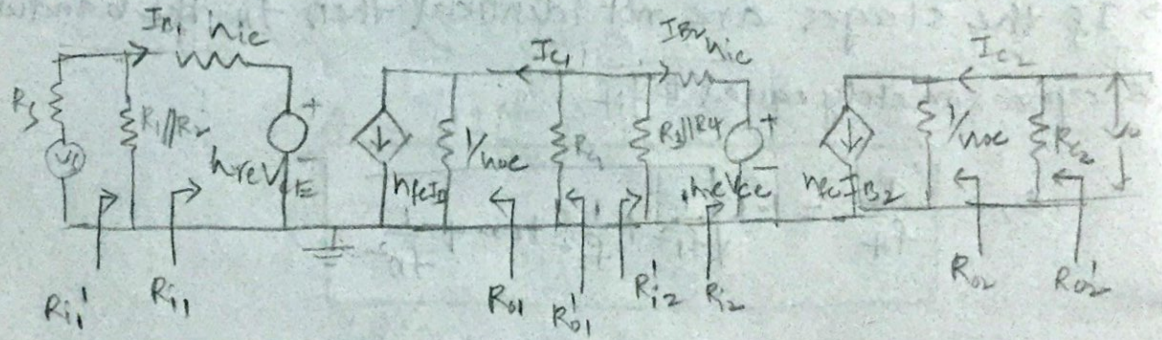


Assume all the external capacitors are short circuited.

1) Calculate R_i, A_V, A_i, R_o, and A_{is}, A_{vs} if circuit parameters are $R_S = 1K$, $R_{C_1} = 15K\Omega$; $R_{E_1} = 100\Omega$, $R_{C_2} = 4K\Omega$, $R_{E_2} = 330\Omega$ with $R_1 = 200K\Omega$ and $R_2 = 20K\Omega$ for first stage.
$R_1 = 47K\Omega$ and $R_2 = 4.7K\Omega$ for second stage. Assume that $h_{ie} = 1.2K\Omega$, $h_{fe} = 50$, $h_{re} = 2.5\times10^{-4}$ and $h_{oe} = 25\times10^{-6}$

The condition for approximate model is $h_{oe} \cdot R_L \leq 0.1$

$$h_{oe} \times R_L = 25\times10^{-6} \times 4\times10^{3}$$
$$= 100\times10^{-3}$$
$$= 0.1$$



Second stage Analysis 3/12/2020

The condition $h_{oe} \times R_L \leq 0.1$, is satisfied so choose the approximate analysis

1. Current gain $(A_{i_2}) = -h_{fe} = -50$

2. Input impedence $(R_{i_2}) = h_{ie} = 1.2K\Omega$

3. Voltage gain $(A_{V_2}) = \frac{A_{i_2}}{R_{i_2}} \times R_L = \frac{-50}{1.2\times10^{3}} \times 4\times10^{3}$

$$\Rightarrow \frac{-500}{3} = -166.6$$

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First stage analysis

$h_{oe} \cdot R_L' \leq 0.1$

$R_L' = R_{C1} \| R_{i2}' = R_{C1} \| R_1 \| R_2 \| R_{i2}$

$$\frac{1}{R_L'} = \frac{1}{15\times10^3} + \frac{1}{47\times10^3} + \frac{1}{4.7\times10^3} + \frac{1}{1.2\times10^3}$$

$$\frac{1}{R_L'} = \left(\frac{1}{15} + \frac{1}{47} + \frac{1}{4.7} + \frac{1}{1.2}\right)\frac{1}{10^3}$$

$$\frac{1}{R_L'} = (0.06 + 0.02 + 0.21 + 0.83) \times \frac{1}{10^3}$$

$$R_L' = \frac{1000}{1.12} = 892.85 \Rightarrow 0.89\,K\Omega$$

$$892.9 \times 25 = 0.02$$

1. current gain $(A_{i1}) = -h_{fe} = -50$

2. $R_{i1} = h_{ie} = 1.2K\Omega$

3. Voltage gain $A_{v1} = \frac{-50}{1.2\times10^3} \times 892 = -37$

Overall voltage gain $\Rightarrow A_V = A_{V1} \times A_{V2} = 6164.2$

overall current gain $\Rightarrow A_i = 2500$

overall output impedence

$R_{o2} = \infty$

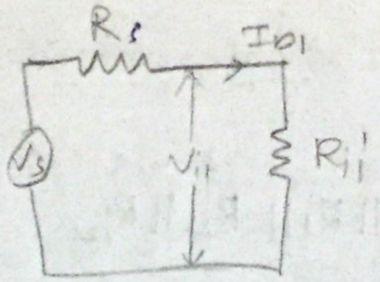
$R_{o2}' = R_{o2} \| R_{C2} = R_{C2} = 4K\Omega$

overall input impedence $= R_{i1}' = R_1 \| R_2$

~~overall~~ Voltage gain including source

$$A_{VS} = \frac{V_o}{V_S} = \frac{V_o}{V_{i1}} \times \frac{V_{i1}}{V_S}$$

$$= A_V \times \frac{V_{i1}}{V_S}$$



$$V_{i1} = \frac{V_s \cdot R_{i1}'}{R_{i1}' + R_s}$$

$$\frac{1}{R_{i1}'} = \left(\frac{1}{200} + \frac{1}{20}\right)\frac{1}{10^3}$$

$$\frac{V_{i1}}{V_s} = \frac{0.018}{1000.018} = 1.8\times10^{-5}$$

$$\frac{1}{R_{i1}} = (5 + 50)$$

$$R_{i1}' = \frac{200\times20\times10^6\ 10^3}{(200+20)10^3}$$

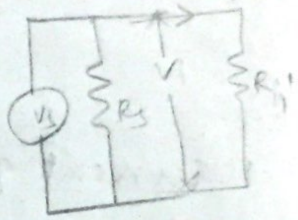
$$R_{i1}' = \frac{1}{55} = 0.018$$

$$\Rightarrow \frac{4000\times10^3}{220} \Rightarrow \frac{40}{22}\times10^5$$

$$\Rightarrow 1.8\times10^5$$

$$I_{b1} \Rightarrow 4K$$

$$A_{vs} = A_v \times \frac{V_{i1}}{V_s}$$



$$A_{is} = \frac{I_2}{I_s} = \frac{I_2}{I_{b1}} \times \frac{I_{b1}}{I_s} = A_1 \times \frac{I_{b1}}{I_s}$$

$$I_{b1} = \frac{I_s \cdot R_s}{R_s + R_{i1}'}$$

$$\frac{I_{b1}}{I_s} = \frac{R_s}{R_s + R_{i1}'} = \left(\frac{1}{1+18}\right)\frac{\times10^3}{10^3}$$

$$\frac{I_{b1}}{I_s} = 0.052$$

$$A_{is} = 2500 \times 0.052$$

$$= 130$$

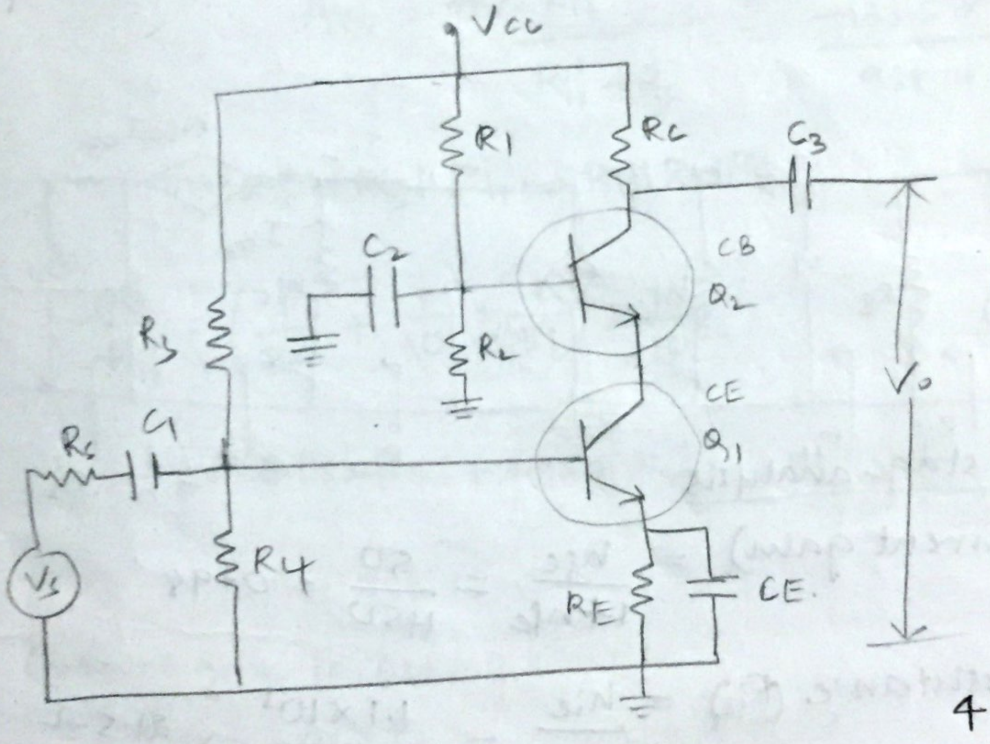
Cascode Amplifier:- (CE + CB) amplifier.

cascading of CE amplifier with CB amplifier is called as cascode amplifier.

The uses of cascode amplifier is ~~high~~ input impedence moderate output impedence, high voltage gain, high bandwidth.

It is used in high frequency and high voltage applications

Cascode amplifier is CS+CG in case of FETs



4/1/2020

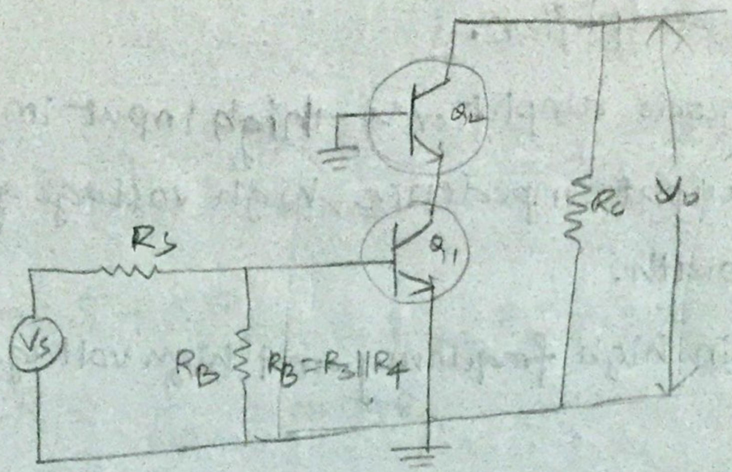
Cascode Analysis

Second stage analysis [CB Amplifier)

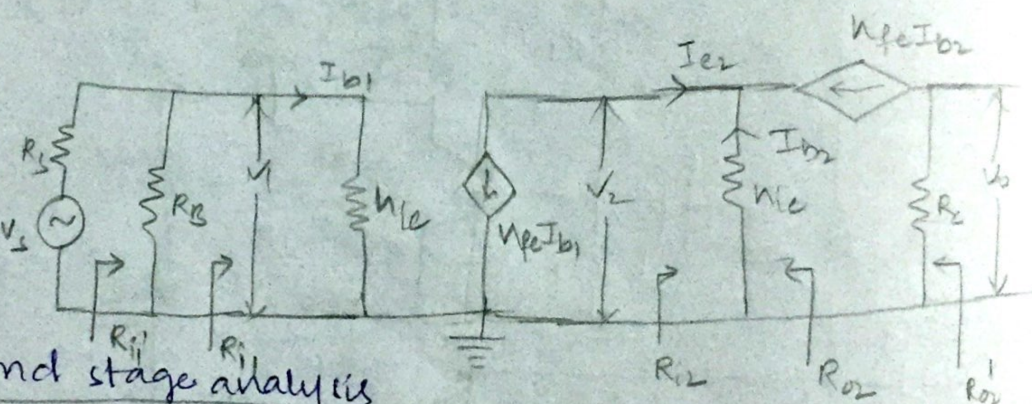
Let us consider the circuit parameters are $R_S = 1K\Omega$, $R_3 = 300K\Omega$; $R_4 = 10K\Omega$ and $R_L = 3K\Omega$

The transistor parameters for both the transistors are $h_{ie} = 1.1K$ and $h_{fe} = 50$

For AC analysis, short all the capacitors, connect the DC power supplies to the ground



$h_{oe} \cdot R_L \leq 0.1$ so the approximate analysis is considered.



Second stage analysis

A_{i2} (current gain) $= \frac{h_{fe}}{1+h_{fe}} = \frac{50}{1+50} = 0.98$

Input resistance (R_{i2}) $= \frac{h_{ie}}{1+h_{fe}} = \frac{1.1\times10^3}{51} \Rightarrow 21.5\,\Omega$

Voltage gain (A_{v2}) $= \frac{0.98}{21.5} \times 3\times10^3 = 136.7$

$h_{oe} \cdot R_L \Rightarrow 25\times10^{-4} \times 21.5 < 0.1$

$R_L \rightarrow R_{i2}$

$h_{oe} \cdot R_L$ value is less than also consider the approximate model for first stage analysis also

First stage analysis (CE amp)

1. $A_{i_1} = -h_{fe} = -50$

2. $R_{i_1} = h_{ie} = 1.1 \times 10^3$

3. $A_{V_1} = \frac{A_{i_1} R_{i_2}}{R_{i_1}} = \frac{-50 \times 21.5}{1.1 \times 10^3} = -0.977$

overall voltage gain $\Rightarrow A_V = A_{V_1} \times A_{V_2} \Rightarrow -133.5$

overall current gain $\Rightarrow A_i = A_{i_1} \times A_{i_2} \Rightarrow -49$

Voltage gain including source:

$$A_{VS} = \frac{A_V \cdot R_{i_1}'}{R_{i_1}' + R_s} = \frac{-133.5 \times 988.14}{988.14 + 1000}$$

$$R_{i_1}' = R_B \| R_{i_1} = R_1 \| R_2 \| R_{i_1}$$

$$\frac{1}{R_{i_1}'} = \left(\frac{1}{300} + \frac{1}{10} + \frac{1}{1.1}\right) \times \frac{1}{10^3}$$

$$\frac{1}{R_{i_1}'} = (0.003 + 0.1 + 0.909) \times \frac{1}{10^3} = \frac{1.012}{10^3}$$

$$R_{i_1}' = 988.14$$

Current gain including source

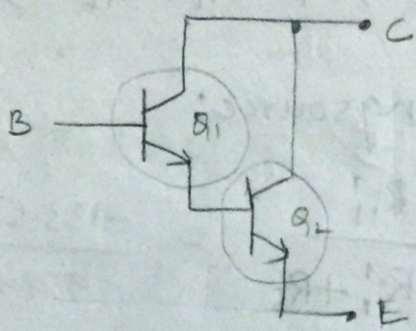
$$A_{V_1} = \frac{A_i \times R_s}{R_{i_1}' + R_s} = \frac{-49 \times 1000}{988.14 + 1000}$$

Scanned with CamScanner

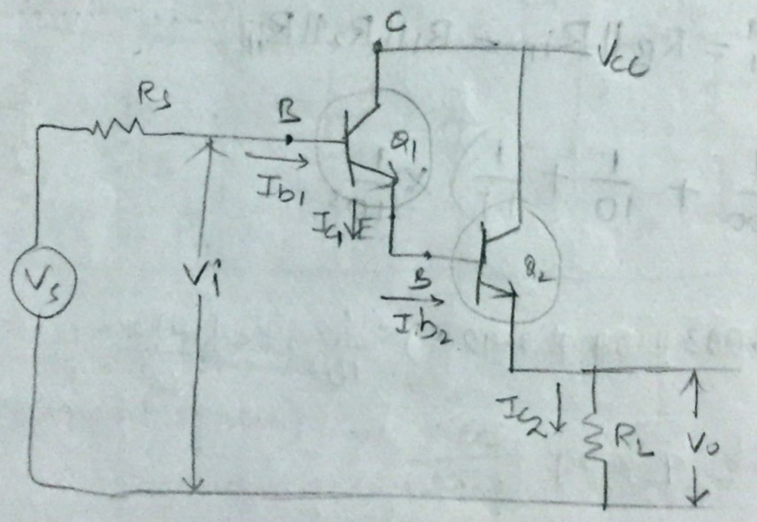
Darlington amplifier

The cascading of two emitter followers is called Darlington pair. To increase the input impedence we are following two techniques, they are

1. Direct coupling (Darlington)
2. Bootstrap technique.



Darlington



cascading of two emitter followers (Darlington pair)

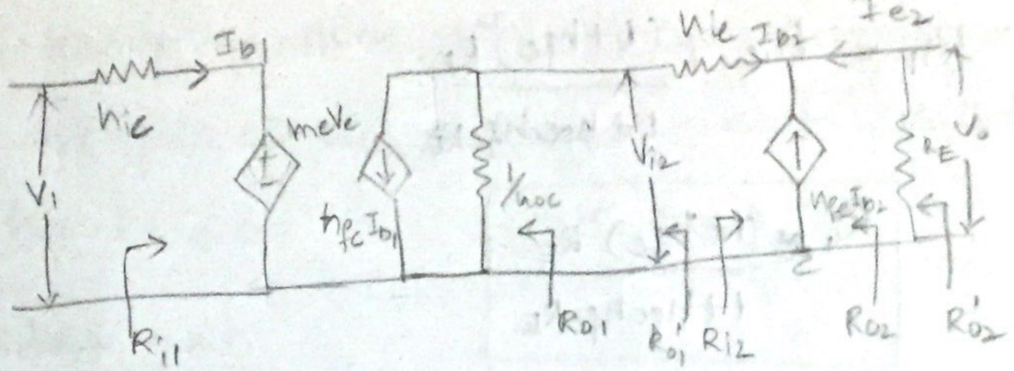
Analysis of Darlington circuit

6/1/2020

Second stage Analysis (CC Amp)

Assume $h_{oe} \cdot R_L \leq 0.1$ i.e, $h_{oe} \cdot R_E \leq 0.1$

So choose the approximate model



1. Current gain $(A_{i2}) = 1+h_{fe}$

2. Inputimpedence $(R_{i2}) = h_{ie} + (1+h_{fe})R_E$

$$R_{i2} \simeq (1+h_{fe})R_E$$

First stage analysis

$h_{oe} \cdot R_{i2} \leq 0.1$ is not satisfied because the value of R_{i2} is very high so the exact model is considered.

conversion formulae

$h_{fc} = -(1+h_{fe})$

$h_{oc} = h_{oe}$

$h_{ic} = h_{ie}$

$h_{rc} = 1$

1) Current gain $(A_{i1}) = \dfrac{-h_{fc}}{1+h_{oc}R_{i2}}$

$$= \frac{(1+h_{fe})}{1+h_{oe}R_{i2}}$$

$$= \frac{(1+h_{fe})}{1+h_{oe}(1+h_{fe})R_E}$$

$$A_{i1} = \frac{(1+h_{fe})}{1+h_{oe}h_{fe}R_E}$$

2) Input resistance $(R_i) = h_{ic} + h_{rc}A_{i1}R_{i2}$

$$= h_{ie} + A_I R_{i2}$$

$$= h_{ie} + \frac{1+h_{fe}}{1+h_{oe}h_{fe}R_E} \times (1+h_{fe})R_E$$

$$R_{i_1} = h_{ie} + \frac{(1+h_{fe})^2 R_E}{1+h_{oe}h_{fe}R_E}$$

$$\boxed{R_{i_1} \simeq \frac{(1+h_{fe})^2 R_E}{1+h_{oe}h_{fe}R_E}}$$

Overall curren gain $A_I = A_{I1} \times A_{I2}$

$$= \frac{1+h_{fe}}{1+h_{oe}h_{fe}R_E} \times (1+h_{fe})$$

$$\boxed{A_I = \frac{(1+h_{fe})^2}{1+h_{oe}h_{fe}R_E}}$$

Now by comparing i/p resistance and current gain of a single stage emitter follower and Darlington circuit with $R_E = 4k\Omega$.

When single stage is considered, the second stage is taken

Single stage (CC)

$A_{i_2} = 1+h_{fe}$

$= 51$

$R_{i2} = (1+h_{fe})R_E$

$= (51)4K$

$\Rightarrow 204K\Omega$

Darlington pair (CC+CC)

$$A_i = \frac{(1+50)^2}{1+50\times 25\times 4\times 10^{3}\times 50} = \frac{26000}{57}$$

$\Rightarrow ~~490~~ \Rightarrow 433.5$

$$R_i = \frac{(51)^2 \times 4\times 10^3}{1+25\times 10^{-6}\times 4\times 50\times 10^3}$$

$$\frac{2500\times 10^3 \times 4}{1+5} \Rightarrow \frac{10^7}{6}$$

$= 1.6 M\Omega$

The above equations of the input resistance and current gain of the darlington circuit is valid for

$h_{oe} \cdot R_E \leq 0.1$

Voltage gain

$$A_v = \frac{A_i R_L}{R_i}$$

$$R_i = h_{ie} + h_{re} A_i R_L$$

$$= h_{ie} + A_i R_L$$

$$A_i R_L = R_i - h_{ie}$$

$$A_v = \frac{A_i R_L}{R_i} = \frac{R_i - h_{ie}}{R_i} = \frac{1 - h_{ie}}{R_{i1}}$$

$$\boxed{A_v = 1 - \frac{h_{ie}}{R_i}}$$

$$A_{v1} = 1 - \frac{h_{ie}}{R_{i1}} \quad ; \quad A_{v2} = 1 - \frac{h_{ie}}{R_{i2}}$$

$$A_v = A_{v1} \times A_{v2} = \left[1 - \frac{h_{ie}}{R_{i1}}\right]\left[1 - \frac{h_{ie}}{R_{i2}}\right]$$

$$= 1 - \frac{h_{ie}}{R_{i2}} - \frac{h_{ie}}{R_{i1}} + \frac{h_{ie}^2}{R_{i1} R_{i2}}$$

$$\boxed{A_v = 1 - \frac{h_{ie}}{R_{i2}}} \quad (R_{i1} >> R_{i2})$$

Output Impedence

7/1/2020

$$R_{o1} = \frac{1}{Y_o}$$

$$Y_o = h_{oe} - \frac{h_{fe} h_{re}}{R_s + h_{ie}}$$

$$Y_o = h_{oe} - \left(\frac{-(1+h_{fe})}{h_{ie}+R_s}\right)$$

$$Y_o = h_{oe} + \frac{1+h_{fe}}{h_{ie}+R_s}$$

$$Y_o = \frac{1+h_{fe}}{h_{ie}+R_s}$$

$$R_{o1} = \frac{1}{Y_{o1}} = \frac{h_{ie}+R_s}{1+h_{fe}}$$

First stage output impedence acts as the source of second stage

$$R_{o2} = \frac{h_{ie}+R_{o1}}{1+h_{fe}}$$

$$R_{o2} = \frac{h_{ie}+\left(\frac{h_{ie}+R_s}{1+h_{fe}}\right)}{1+h_{fe}} \Rightarrow \frac{h_{ie}(1+h_{fe})+h_{ie}+R_s}{(1+h_{fe})^2}$$

~~$R_{o2} = 2h_{ie} + h_{ie}h_{fe}$~~

$$\boxed{R_{o2} = \frac{h_{ie}}{1+h_{fe}} + \frac{h_{ie}+R_s}{(1+h_{fe})^2}.}$$ → output impedence of Darlington pair

overall output impedence of Darlington pair is $R_{o2} \| R_E$

Advantages of Darlington circuit.

1. Very high input resistance (in $M\Omega$)
2. Very large current gain.
3. Very low output resistance
4. Voltage gain is less than 1.

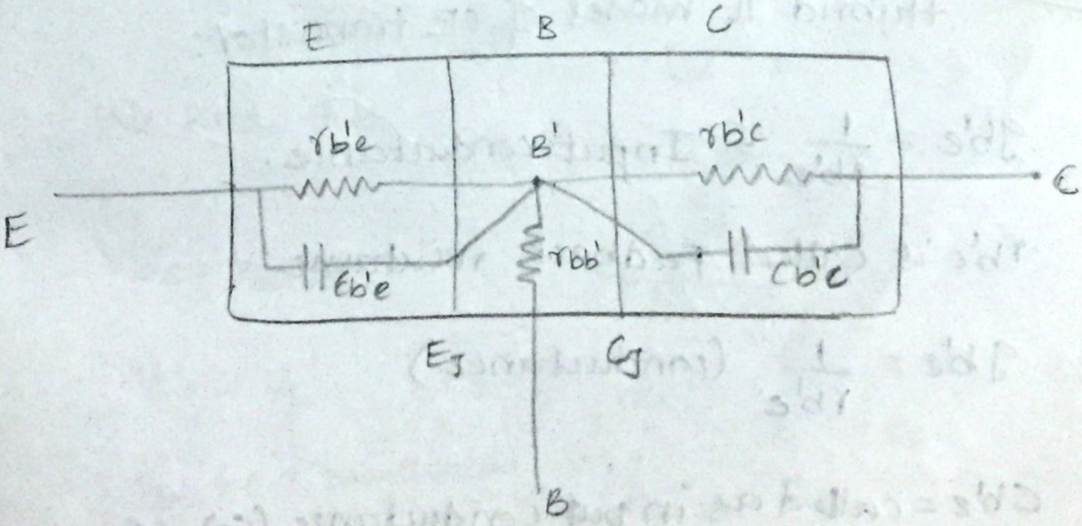
5. Darlington pairs are available in a single package with just 3 leads like a transistor.

Disadvantages

1. In the above analysis we have assumed that the h-parameters of Q_1 and Q_2 are identical but h-parameters for both the transistors will not be same.
2. Leakage current is more, which is not desired
3. It is not possible to use more than two transistors in the Darlington connection.

Hybrid π- Model

~~Hy~~brid π- Model is suitable for high frequencies.
As the internal capacitors are effecting the gain at high frequecies so h-parameter model is not suitable.
Also the diffusion of electrons is faster at high frequencies (diffusion current)
Giacoletto Model is the another name for Hybrid-π model



$r_{bb'}$ - Base spreading Resistance

It is the resistance between base and virtual base terminal

The value of $r_{bb'}$ is 100Ω

$r_{b'e}$

It is the resistance between emitter and virtual base

The value of $r_{b'e}$ is $1K\Omega$

$r_{b'c}$ - Feedback resistance

It is the resistance between collector and virtual base

The value of $r_{b'c}$ is $4M\Omega$

$C_{b'e}$ - Forward Diffusion capacitance

The value of $C_{b'e}$ is 100PF

$C_{b'c}$ - Reverse Transition capacitance.

The value of $C_{b'c}$ is 3PF

The values of above parameters are taken at

$\left.\begin{array}{l} T = 27°C \\ I_c = 1.3mA \end{array}\right\}$ specifications

8/1/2020

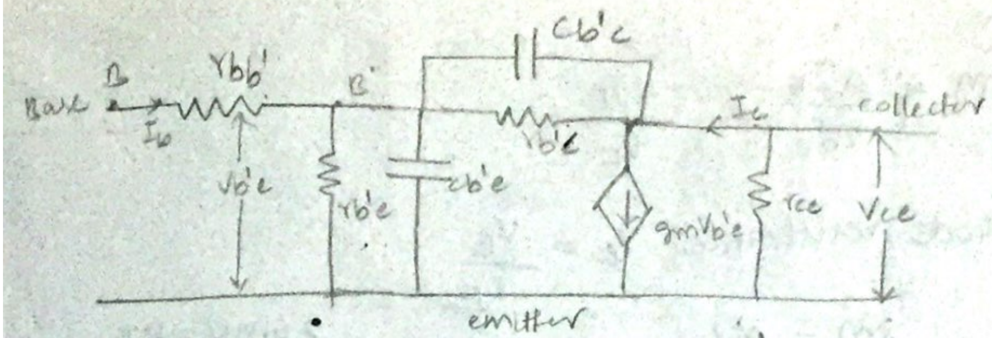
Hybrid π-model of CE transistor:

$g_{b'e} = \frac{1}{r_{b'e}}$ = Input conductance.

$r_{b'e}$ is called Feedback resistance

$g_{b'e} = \frac{1}{r_{b'c}}$ (conductance)

$C_{b'e}$ = called as input conductance (C_e) or C_π



$g_m V_{b'e}$ is a current generator, it is equal to collector current I_c, where g_m is transconductance. It is defined as the ratio of output current to i/p voltage

$$g_m = \frac{I_c}{V_{b'e}}$$

$$I_c = g_m V_{b'e}$$

r_{ce} it is the output resistance b/w the collector and emitter. r_{ce} is very high value $= 80k\Omega$

$$g_m = 50 mA/V$$

Relationship between high frequency π model and low frequency h-parameter model.

1. Transistor Transconductance (g_m)

It is defined as ratio of o/p current to i/p voltage

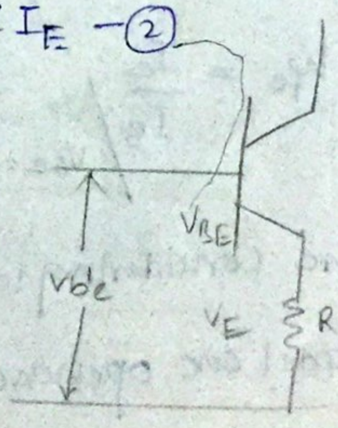
i.e, $g_m = \frac{I_c}{V_{b'e}}$ — ①

We know that, $I_c = \alpha I_E$ —②

$V_{b'e} = V_{BE} + V_E$

$V_{b'e} \simeq V_E$

as $V_{BE} = 0.7$ (small value)



$$g_m = \frac{\alpha I_E}{V_{b'e}} = \frac{\alpha I_E}{V_E}$$

Emitter diode resistance, $r_e = \frac{V_E}{I_E}$

$$g_m = \alpha / r_e$$

$26mV = kT$

V_T = Thermal voltage

Dynamic resistance of forward bias diode:

$$r_e = \frac{V_T}{I_E}$$

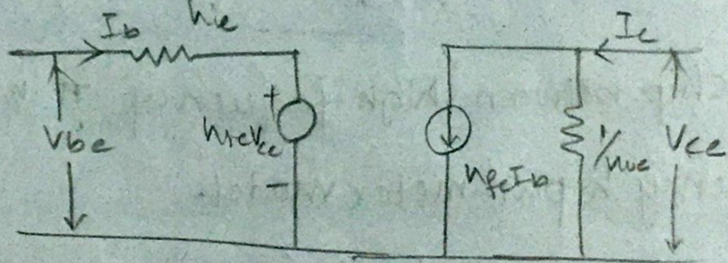
$$g_m = \frac{\alpha I_E}{V_T}$$

$$g_m = \frac{I_E}{V_T} \quad \frac{1.3m}{2.6m} = 50mA/V$$

g_m value

$r_{b'e}/g_{b'e}$:

$V_{bc} = V_{b'c}$

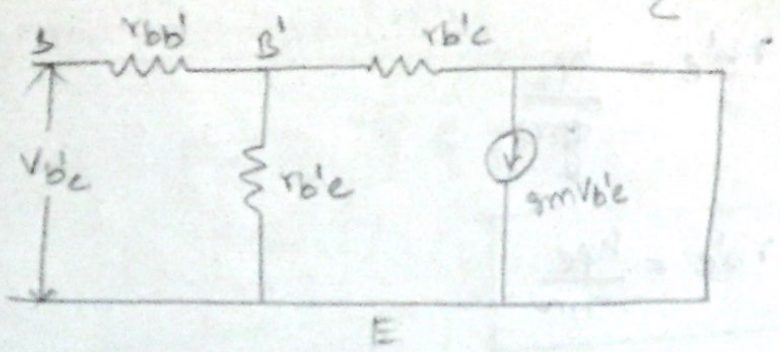


$$V_{b'e} = h_{ie}I_b + h_{re}V_{ce} \quad -(1)$$

$$I_c = h_{fe}I_b + h_{oe}V_{ce} \quad -(2)$$

$$h_{fe} = \frac{I_c}{I_B}\Big/_{V_{ce}=0}$$

as we are considering low frequency, all capacitors in π model are opencircuited, and $V_0 = 0$



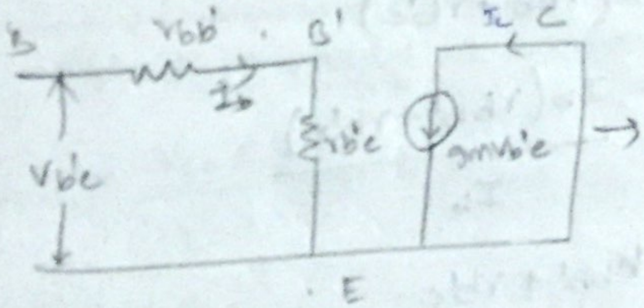
as $r_{b'c} >> r_{b'e}$

$r_{b'c} = \infty \longrightarrow$ open circuit

If output is short circuited, r_{ce} is negligeble in circuit.

$C_{b'e}, C_{b'c}$ internal junction capacitor are open circuited

so the equivalent circuit is at low frequency.



$\rightarrow$ π model at low frequency

$$I_c = g_m V_{b'e}$$

$$V_{b'e} = (r_{bb'} + r_{b'e}) I_b$$

$$r_{bb'} << r_{b'e}$$

$$V_{b'e} = r_{b'e} I_b$$

$$I_c = g_m I_b r_{b'e}$$

$$\frac{I_c}{I_b} = \boxed{g_m r_{b'e} = h_{fe}}$$

$$r_{b'e} = \frac{h_{fe}}{g_m}$$

$$\boxed{r_{b'e} = \frac{h_{fe}}{g_m}}$$

Input conductance $\Rightarrow \boxed{g_{b'e} = \frac{g_m}{h_{fe}}}$

Base spreading Resistance ($r_{bb'}$)

$$h_{ie} = \frac{V_{b'e}}{I_b}$$

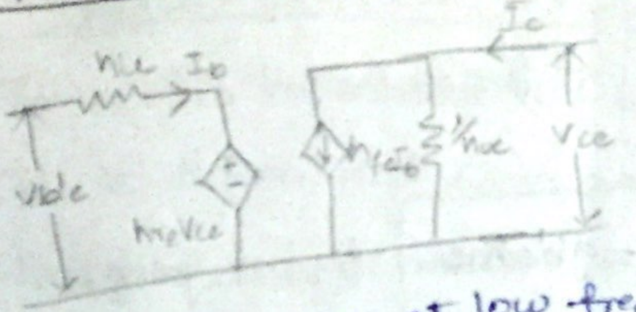
$$V_{b'e} = I_b(r_{bb'} + r_{b'e})$$

$$h_{ie} = \frac{I_b(r_{bb'} + r_{b'e})}{I_b}$$

$$h_{ie} = r_{bb'} + r_{b'e}$$

$$\boxed{r_{bb'} = h_{ie} - r_{b'e}}$$

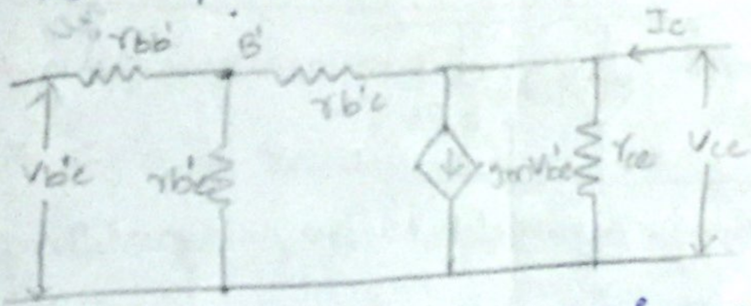
Feedback resistance ($r_{b'c}$) 9/1/2020



h-parameter at low frequency

$$V_{b'e} = h_{ie} I_b + h_{re} V_{ce}$$

$$I_c = h_{fe} I_b + h_{oe} V_{ce}$$



Hybrid-π model at low frequency

$$V_{b'e} = \frac{V_{ce} \times r_{b'e}}{r_{b'e} + r_{b'c}}$$

$$\frac{V_{b'e}}{V_{ce}} = \frac{r_{b'e}}{r_{b'e} + r_{b'c}}$$

$$h_{re} = \frac{r_{b'e}}{r_{b'e} + r_{b'c}}$$

$$h_{re}(r_{b'e} + r_{b'c}) = r_{b'e}$$

$$h_{re} r_{b'e} + h_{re} r_{b'c} = r_{b'e}$$

$$\frac{h_{re} r_{b'e}}{(1 - h_{re})} = r_{b'c}$$

$$r_{b'c} = \frac{r_{b'e}(1 - h_{re})}{h_{re}}$$

$$\Rightarrow \frac{10^3(1 - 2.5 \times 10^{-4})}{2.5 \times 10^{-4}} \Rightarrow \frac{10^3 - 0.25}{2.5 \times 10^{-4}} = 3.99\,M\Omega$$

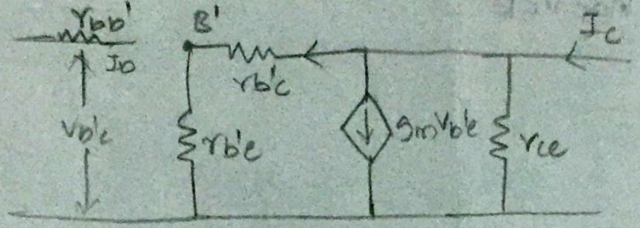
$$\simeq 4\,M\Omega$$

$$\boxed{r_{b'c} = \frac{r_{b'e}}{h_{re}}}$$ – feedback resistance

$$\boxed{g_{b'c} = \frac{h_{re}}{r_{b'e}} = g_{b'e}h_{re}}$$ feed conductance

Output resistance (r_{ce})

$$r_{ce} = \frac{1}{g_{ce}}$$



Hybrid-π model at low frequency

$$I_c = \frac{V_{ce}}{r_{ce}} + g_m V_{b'e} + \frac{V_{ce}}{r_{b'e}+r_{b'c}}$$

$$I_c = V_{ce}\left[\frac{1}{r_{ce}} + \frac{g_m V_{b'e}}{V_{ce}} + \frac{1}{r_{b'e}+r_{b'c}}\right] \quad \left[g_m = \frac{h_{fe}}{r_{b'e}} = h_{fe}g_{b'e}\right]$$

$$I_c = V_{ce}\left[\frac{1}{r_{ce}} + \frac{g_m V_{b'e}}{V_{ce}} + \frac{1}{r_{b'e}+r_{b'c}}\right]$$

$r_{b'c} >> r_{b'e}$

$$\frac{I_c}{V_{ce}} = g_{ce} + h_{fe}g_{b'e}h_{re} + g_{b'c}$$

$$h_{oe} = g_{ce} + h_{fe}g_{b'e}\frac{g_{b'c}}{g_{b'e}} + g_{b'c} \quad \left[h_{re} = \frac{g_{b'c}}{g_{b'e}}\right]$$

$$h_{oe} = g_{ce} + g_{b'c}h_{fe} + g_{b'c}$$

$$\boxed{h_{oe} = g_{ce} + g_{b'c}(1+h_{fe})}$$

$$\boxed{g_{ce} = h_{oe} - g_{b'c}h_{fe}} = \frac{1}{r_{ce}} = \frac{1}{80K\Omega}$$

Diffusion capacitance [$C_{b'e}$]

It is also represented as C_π in hybrid π-model

$C_{b'e}$ is determined from a measurement of f_T, the frequency at which the CE short circuit current gain drops to unity. It is given by $\boxed{C_{b'e} = \frac{g_m}{2\pi f_T} = C_\pi}$

Transition capacitance [$C_{b'c}$]

It is also represented as C_μ in hybrid π model

$C_\mu = C_{b'c}$ is measured as a CB output (collector to base) capacitance with input open and is usually specified by manufacturer as C_{OB} → open circuit-Base capacitance

$$g_m = \frac{I_C}{V_T} = 50\,mA/V$$

$$\frac{1}{g_{b'e}} = r_{b'e} = \frac{h_{fe}}{g_m} = 1K\Omega$$

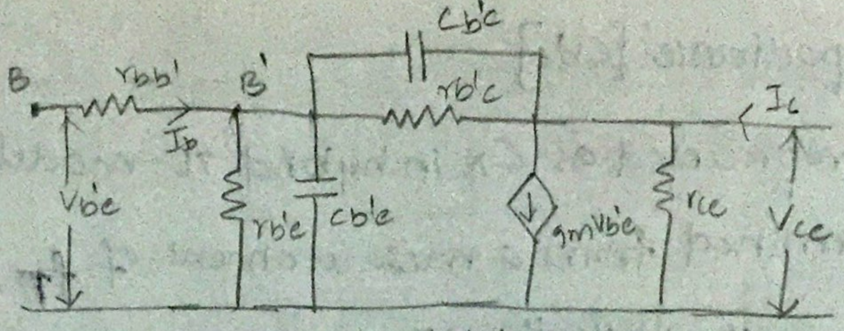
$$r_{bb'} = h_{ie} - r_{b'e} = 100\Omega$$

$$\frac{1}{g_{b'c}} = r_{b'c} = 4M\Omega = \frac{r_{b'e}}{h_{re}}$$

$$g_{ce} = h_{oe} - g_{b'c}h_{fe} = \frac{1}{r_{ce}} = \frac{1}{80K}$$

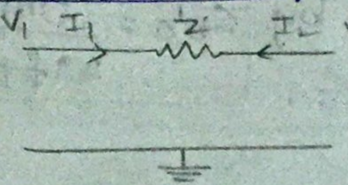
$$C_{b'e} = C_\pi = \frac{g_m}{2\pi f_T}$$

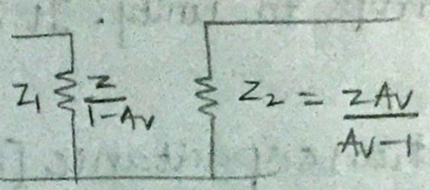
$$C_\mu = C_{b'c}$$



Hybrid - π model

Miller's Theorem:





$$I_1 = \frac{V_1 - V_2}{Z} = \frac{V_1\left(1 - \frac{V_2}{V_1}\right)}{Z}$$

$$\frac{I_1}{V_1} = \frac{1 - A_V}{Z} \Rightarrow Z_1 = \frac{Z}{1 - A_V}$$

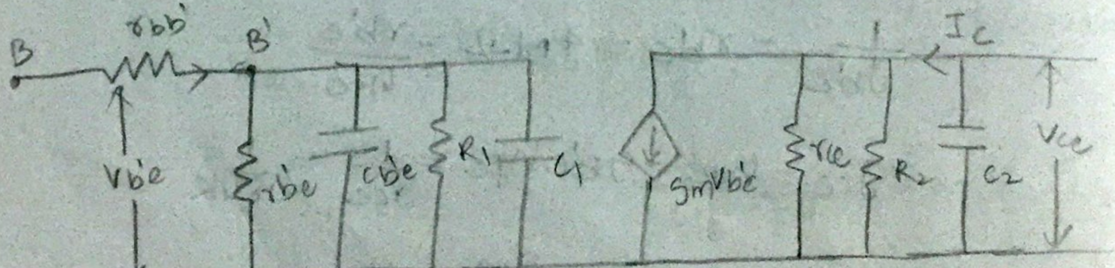
$$I_2 = \frac{V_2 - V_1}{Z} = \frac{V_2\left(1 - \frac{V_1}{V_2}\right)}{Z} = \frac{V_2\left(A_V - 1\right)}{Z A_V}$$

$$Z_2 = \frac{V_2}{I_2} = \frac{Z A_V}{A_V - 1}$$

Assignment

Derive Miller's Theorem, duals of Miller's theorem and Miller effect capacitance, with examples.

- figure can be modified by using Miller's theorem



Hybrid-π model using Miller's Theorem

$$R_1 = \frac{r_{b'c}}{1 - A_V} \qquad C_1 = C_{b'c}(1 - A_V)$$

$$R_2 = \frac{r_{b'c} A_V}{A_V - 1} \qquad C_2 = C_{b'c}\left(1 - \frac{1}{A_V}\right)$$

CE short circuit current gain at high frequencies.

Short circuit current gain means output terminals are short circuited.

If the output terminals are short circuited, r_{ce}, R_2 and C_2 are not considered.

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~~CE short circuit current gain at High frequency:~~

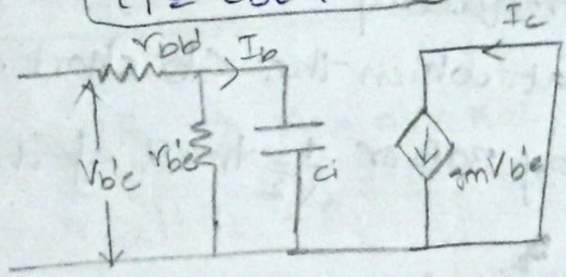
r_{ce} becomes zero so it is neglected because o/p terminals are short circuited

$r_{b'e}$ is parallel to $R_1 \Rightarrow r_{b'e} \| R_1 \simeq r_{b'e}$

$$c_i = C_{b'e} + C_1$$

$$= C_{b'e} + C_{b'c}(1 - A_v)$$

$$\boxed{c_i = C_{b'e} + C_{b'c}}$$



$$A_i = \frac{I_L}{I_b} = \frac{-I_c}{I_b} = \frac{-g_m V_{b'e}}{I_b}$$

$$I_b = V_{b'e}\left[\frac{1}{r_{b'e}} + \frac{1}{1/j\omega c_i}\right]$$

$$I_b = V_{b'e}\left[\frac{1}{r_{b'e}} + j\omega c_i\right]$$

$$A_i = \frac{-g_m V_{b'e}}{I_b} = \frac{-g_m V_{b'e}}{V_{b'e}\left[\frac{1}{r_{b'e}} + j\omega c_i\right]}$$

$$A_i = \frac{-g_m r_{b'e}}{1 + j\omega r_{b'e} c_i}$$

$$A_i = \frac{-\beta}{1+j2\pi f r_{b'e}C_i}$$ $\left[\because h_{fe} = \beta = g_m r_{b'e}\right]$

$$A_i = \frac{-\beta}{1+j\frac{f}{f_\beta}}$$ where $\boxed{f_\beta = \frac{1}{2\pi r_{b'e}C_i}}$

β cutoff frequency

$$|A_i| = \frac{\beta}{\sqrt{1+\left(\frac{f}{f_\beta}\right)^2}}$$

If $f = f_\beta$ then $|A_i| = \frac{\beta}{\sqrt{2}}$

f_β - It is a frequency at which the CE short circuit circuit current gain drops by 3dB or $\frac{1}{\sqrt{2}}$ times of it's value at low frequency.

f_α - α cutoff frequency
It is a frequency at which the CB short circuit current gain drops by 3dB or $\frac{1}{\sqrt{2}}$ times of it's value at low frequency.

$$\boxed{f_\alpha = \frac{1+h_{fe}}{2\pi r_{b'e}C_{b'e}}}$$

Unity gain frequency (f_T)

It is a frequency at which the CE short circuit current gain becomes unity. Hence it is called unity gain frequency (or) Bandwidth

$$\boxed{f_T = \beta f_\beta}$$

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Relation b/w unity gain frequency (f_T) and β-cutoff frequency (f_β)

The unity gain frequency (f_T) is the product of low frequency current gain (β/h_{fe}) and β-cutoff frequency at high frequency.

$$f_T = \beta f_\beta$$

$$= h_{fe} \times \frac{1}{2\pi r_{b'e} C_i}$$

$$= \frac{g_m r_{b'e}}{2\pi r_{b'e} C_i} = \frac{g_m}{2\pi(C_{b'e} + C_{b'c})}$$

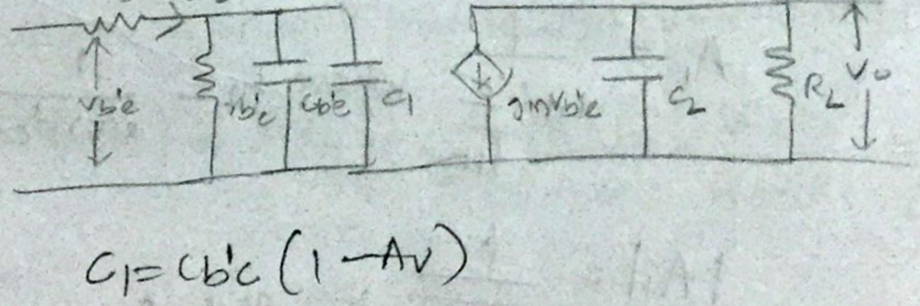
$$\boxed{f_T = \frac{g_m}{2\pi C_{b'e}}} \Rightarrow \boxed{C_{b'e} = \frac{g_m}{2\pi f_T}}$$

High frequency current gain with resistive load

$r_{ce} \| R_L \rightarrow r_{ce} = 80 K\Omega$ neglect r_{ce}

$r_{ce} \| R_L = R_L$

$r_{b'e} \| R_1 = r_{b'c}$



$$C_1 = C_{b'c}(1 - A_V)$$

$$A_V = \frac{V_o}{V_{b'e}} = \frac{-g_m V_{b'e} R_L}{V_{b'e}} = g_m R_L$$

$$C_1 = C_{b'c}(1 + g_m R_L)$$

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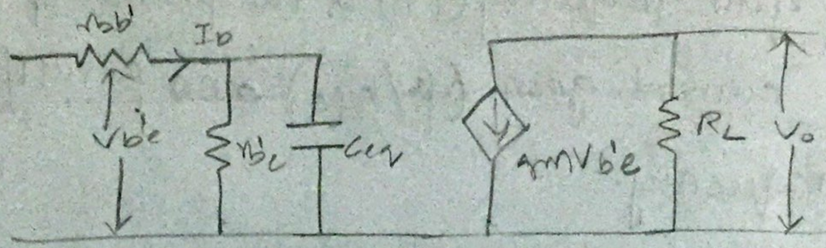
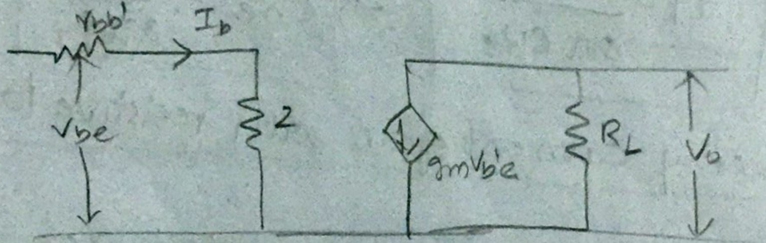
$$C_{eq} = C_{b'e} + C_{b'c}(1 + g_m R_L)$$

$$C_2 = C_{b'c}\left(1 - \frac{1}{A_V}\right) \simeq C_{b'c}$$



$$Z = r_{b'e} \parallel \frac{1}{j\omega C_{eq}} = \frac{r_{b'e} \times \frac{1}{j\omega C_{eq}}}{r_{b'e} + \frac{1}{j\omega C_{eq}}}$$

$$Z = \frac{r_{b'e}}{1 + j\omega r_{b'e} C_{eq}}$$



$$A_i = \frac{-I_c}{I_b} = \frac{-g_m V_{b'e}}{I_b} = -g_m Z$$

$$= -g_m\left(\frac{r_{b'e}}{1 + j\omega r_{b'e} C_{eq}}\right)$$

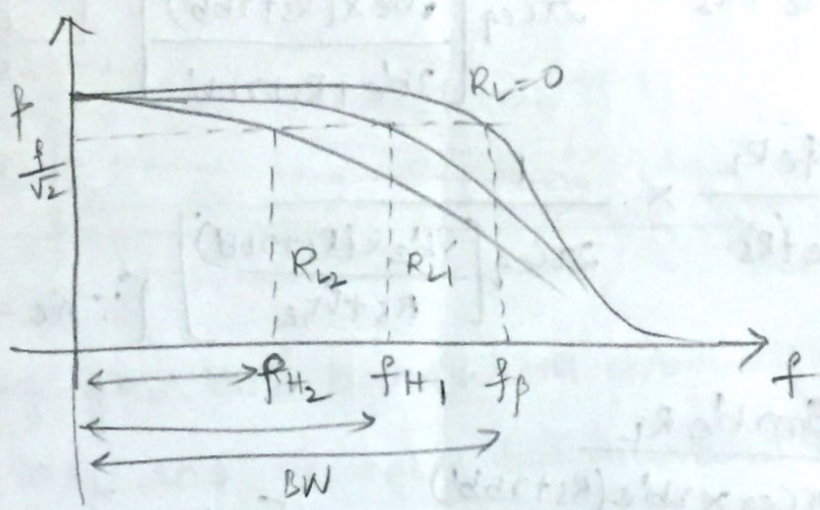
$$A_i = \frac{-\beta}{1 + j\frac{f}{f_H}} \quad \text{where } f_H = \frac{1}{2\pi r_{b'e} C_{eq}}$$

$$|A_i| = \frac{\beta}{\sqrt{1 + \left(\frac{f}{f_H}\right)^2}} \quad \text{if } f = f_H \Rightarrow |A_i| = \frac{\beta}{\sqrt{2}}$$

• f_H is the higher cut off frequency at which the CE current gain drops by $\frac{1}{\sqrt{2}}$ or 3dB from it's value.

$$\boxed{f_H = \frac{1}{2\pi r_{b'e}\left[C_{b'e} + C_{b'c}(1+g_m R_L)\right]}}$$

$$\boxed{f_\beta = \frac{1}{2\pi C_{b'e}(C_{b'e}+C_{b'c})}}$$ with $R_L = 0$



If the load increases, Band width decreases.

The max possibility of f_H (Bandwidth) is f_β as R_L increases the c equivalent capacitance increases so that bandwidth decreases.

Gain and Bandwidth product:

1) Voltage gain with source and Band width product

$$|A_{vs}| = A_v \cdot \frac{R_i'}{R_i'+R_s} = \frac{A_i R_L}{h_{ie}} \times \frac{h_{ie}}{h_{ie}+R_s} = \frac{A_i R_L}{h_{ie}+R_s}$$

$$f_H = \frac{1}{2\pi R_{eq} C_{eq}}$$

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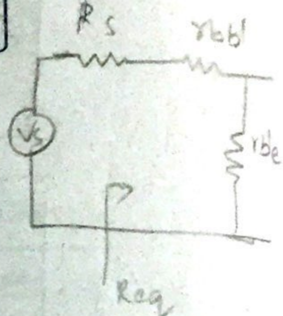
$$|A_{vs} \times BW|$$

$$= |A_{vs} \times F_H| = \frac{A_v \cdot R_i}{R_i + R_s} \times \frac{1}{2\pi R_{eq} C_{eq}}$$

$$= \frac{A_i R_L}{R_i} \times \frac{R_i}{R_i + R_s} \times \frac{1}{2\pi C_{eq}[r_{b'e} \| (R_s + r_{bb'})]}$$



$= r_{b'e} \| (R_s + r_{bb'})$

$$= \frac{h_{fe} R_L}{h_{ie} + R_s} * \frac{1}{2\pi C_{eq}\left[\frac{r_{b'e} \times (R_s + r_{bb'})}{r_{b'e} + R_s + r_{bb'}}\right]}$$

$$= \frac{h_{fe} R_L}{h_{ie} + R_s} \times \frac{1}{2\pi C_{eq}\left[\frac{r_{b'e} \times (R_s + r_{bb'})}{R_s + h_{ie}}\right]}$$

$[\because h_{ie} = r_{b'e} + r_{bb'}]$

$$= \frac{g_m r_{b'e} R_L}{2\pi C_{eq} \times r_{b'e}(R_s + r_{bb'})}$$

$[\because h_{fe} = g_m r_{b'e}]$

$$= \frac{g_m}{2\pi(C_{b'e} + C_{b'c}(1 + g_m R_L))} \times \frac{R_L}{R_s + r_{bb'}}$$

$$= \frac{2\pi f_T C_{b'e}}{2\pi[C_{b'e} + C_{b'c} g_m R_L]} \times \frac{R_L}{R_s + r_{bb'}}$$

$$= \frac{2\pi f_T C_{b'e}}{2\pi[C_{b'e} + C_{b'c}\, 2\pi f_T C_{b'e} R_L]} \times \frac{R_L}{R_s + r_{bb'}}$$

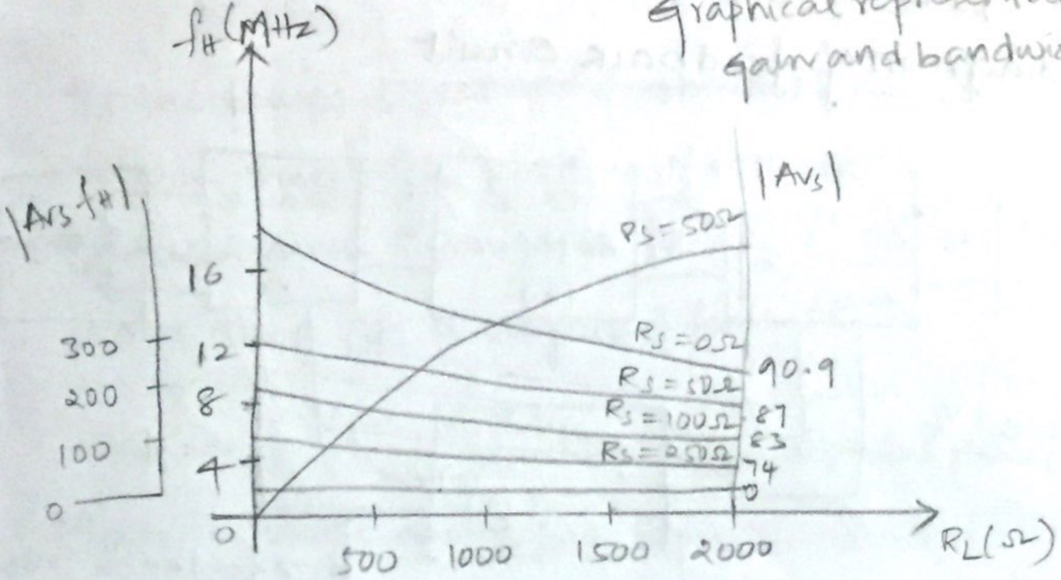
$$|A_{vs} * f_H| = \frac{2\pi f_T C_{b'e}}{2\pi C_{b'e}[1 + 2\pi f_T C_{b'c} R_L]} \times \frac{R_L}{R_s + r_{bb'}}$$

$$\boxed{|A_{vs} * F_H| = \frac{f_T}{1 + 2\pi f_T C_{b'c} R_L} \times \frac{R_L}{R_s + r_{bb'}}}$$

Similarly for, product of current gain and ~~band~~ width

$$\boxed{|A_{IS} \times f_H| = \frac{f_T}{1 + 2\pi f_T C_{b'c} R_L} \times \frac{R_s}{R_s + r_{bb'}}}$$

Graphical representation of gain and bandwidth product



→ The voltage gain and bandwidth product increases with increase in R_L and decreases with increase in R_s.

Therefore we can say that the gain-bandwidth product is not constant but it depends on values of R_L and R_s.