K. J. SOMAIYA COLLEGE OF ENGINEERING
DEPARTMENT OF ELECTRONICS ENGINEERING
ELECTRONIC CIRCUITS
Multi Transistor Circuits

Numerical 1:

For the circuit shown in figure 1, Determine I_{C_1}, I_{C_2}, V_{CE_1}, V_{CE_2}, A_{V_1}, A_{V_2}, A_{V_T}, Input impedance of 1^{st} stage, Output impedance of 2^{nd} stage

Given: $\beta_1 = \beta_2 = 200$

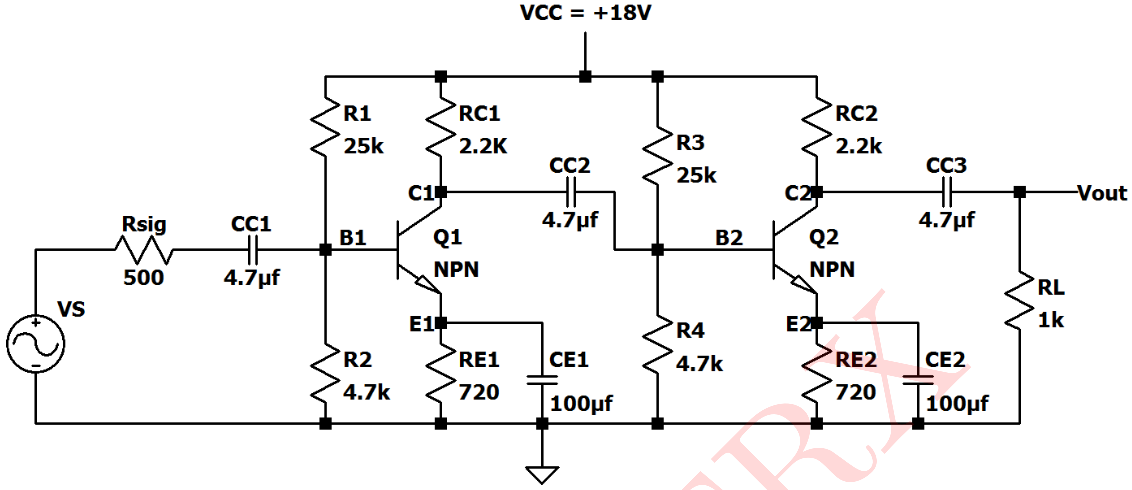

Figure 1: Circuit 1

Solution:

Above given circuit 1 is 2-stage RC coupled CE-CE amplifier

$V_{BE_1} = V_{BE_2} = 0.7V$ (Assumption)

→ Due to R-C coupling, both the stages Q-point are isolated

→ Since, both the stage are symmetric in parameter and resistor values, DC analysis of one stage is sufficient

DC Analysis:-

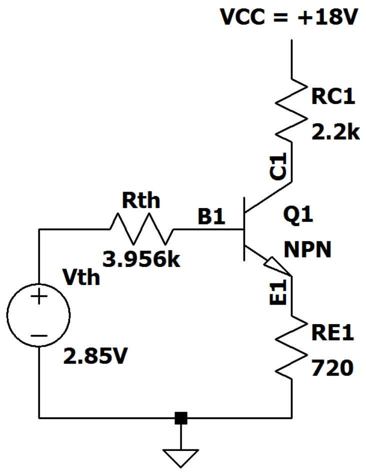

Figure 2: DC Equivalent circuit

$$V_B = V_{th} = \frac{R_2}{R_1 + R_2} \times V_{CC} = \frac{4.7k\Omega}{25k\Omega + 4.7k\Omega} \times 18 = 2.85V$$

$\boldsymbol{V_{th} = 2.85V}$

$R_{th} = R1 \; || \; R2 = 25k \; || \; 4.7k = 3.956k\Omega$

$\boldsymbol{R_{th} = 3.956k\Omega}$

Applying KVL to the base-emitter loop:-

$V_{th} - I_B R_{th} - V_{BE(ON)} - I_E R_E = 0$

$I_E = I_C + I_B = (\beta + 1) I_B$

Assume $V_{BE(ON)} = 0.7V$

$V_{th} - I_B R_{th} - 0.7V - (\beta + 1) I_B R_E = 0$

$$I_B = \frac{V_{th} - 0.7V}{R_{th} + ((\beta + 1) R_E)} = \frac{2.85 - 0.7}{2.956k\Omega + (201 \times 0.72k\Omega)} = 14.46\mu A$$

$\therefore \boldsymbol{I_{B1} = I_{B2} = 14.46\mu A}$

$I_C = \beta I_B = 200 \times 14.46\mu A = 2.89mA$

$\therefore \boldsymbol{I_{C_1} = I_{C_2} = 2.89mA}$

Applying KVL to the collector-emitter loop:-

$V_{CE} = V_{CC} - I_C R_C - (\beta + 1) I_B R_E$

$V_{CE} = 19 - (2.89mA \times 2.2k\Omega) - (201 \times 720\Omega \times 14.46\mu A) = 9.549$

$\boldsymbol{V_{CE_1} = V_{CE_2} = 9.549V}$

Small-Signal parameters:-

$$g_{m_1} = \frac{I_C}{V_T} = \frac{2.89mA}{26mV} = 111.15 \; mA/V$$

$\boldsymbol{g_{m_1} = g_{m_2} = 111.15 \; mA/V}$

$$r_{\pi_1} = \frac{V_T}{I_B} = \frac{26mV}{14.46\mu A} = 1.8k\Omega$$

$\boldsymbol{r_{\pi_1} = r_{\pi_2} = 1.8k\Omega}$

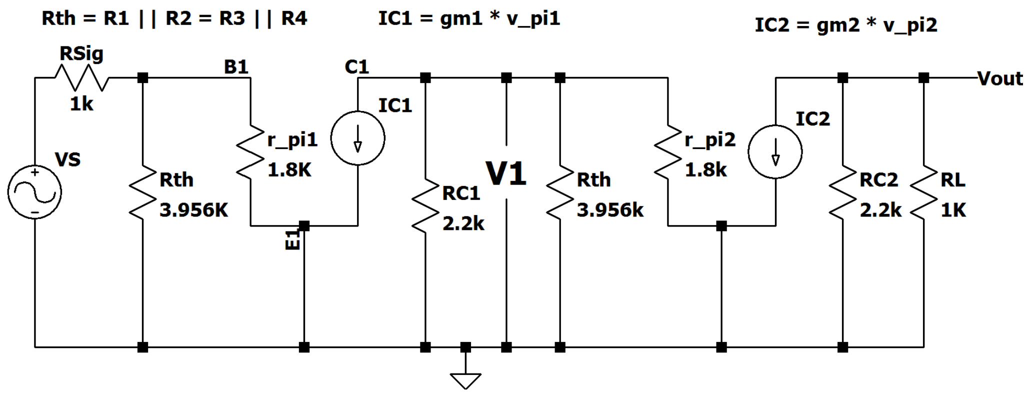

Figure 3: Small Signal Equivalent Circuit

Input Impedance:-

$Z_i = R_1 \mid\mid R_2 \mid\mid r_{\pi_1} = R_{th} \mid\mid r_{\pi_1} = 3.956k \mid\mid 1.8k = 1.237k\Omega$

$Z_{in} = Z_i + R_{sig} = 1.237k + 0.5k = 1.737k\Omega$

$\boldsymbol{Z_{in} = 1.737k\Omega}$

Output Impedance:-

$Z_o = R_{C_2} \mid\mid R_L$

$Z_o = 2.2k \mid\mid 1k = 687.5\Omega$

$\boldsymbol{Z_o = 687.5\Omega}$

Voltage Gain of Stage 1(A_{V_1})

$$A_{V_1} = \frac{V_1}{V_{in}}$$

$V_1 = -g_{m_1}V_{\pi_1}(R_{C1} \mid\mid R_3 \mid\mid R_4 \mid\mid r_{\pi_2})$

$V_1 = -g_{m_1}V_{\pi_1}(R_{C1} \mid\mid R_{th} \mid\mid r_{\pi_2})$

$V_{in} = V_{\pi_1}$

$$A_{V_1} = \frac{V_1}{V_{in}} = -g_m(R_{C1} \mid\mid R_{th} \mid\mid r_{\pi_2})$$

$$A_{V_1} = \frac{V_1}{V_{in}} = -111.15mA/V(2.2k \mid\mid 3.956k \mid\mid 1.8k)$$

$$A_{V_1} = \frac{V_1}{V_{in}} = -111.15mA/V(721.82)$$

$$A_{V_1} = \frac{V_1}{V_{in}} = -88.01$$

$\boldsymbol{A_{V_1} = -88.01}$

$$A_{V1_S} = \frac{V_1}{V_S} = \frac{V_1}{V_{in}} \times \frac{V_{in}}{V_S}$$

$$\frac{V_{in}}{V_S} = \frac{Z_i}{Z_i + R_{sig}} = \frac{1.237k}{1.237k + 0.5k} = 0.71215$$

$A_{V1_S} = -88.01 \times 0.71215 = -62.676$

$\boldsymbol{A_{V1_S} = -62.676}$

Voltage gain for Stage 2:-

$$A_{V_2} = \frac{V_{out}}{V_1}$$

$V_o = -g_{m_2}V_{\pi_2}(R_{C2} \mid\mid R_2)$

$V_1 = V_{\pi_2}$

$$A_{V_2} = \frac{V_{out}}{V_1} = -111.15mA/V(2.2k \mid\mid 1k) = -26.415$$

$\boldsymbol{A_{V_2} = -26.415}$

Overall mid-band voltage gain $= A_{V1_S} \times A_{V_2} = -62.676 \times -76.415$

$\boldsymbol{A_V = 4789.43}$

$\boldsymbol{A_V}$ **in dB** $\boldsymbol{= 20log_{10}(4789.43) = 73.605dB}$

SIMULATED RESULTS:

Above circuit was simulated in LTSpice and results are presented below:

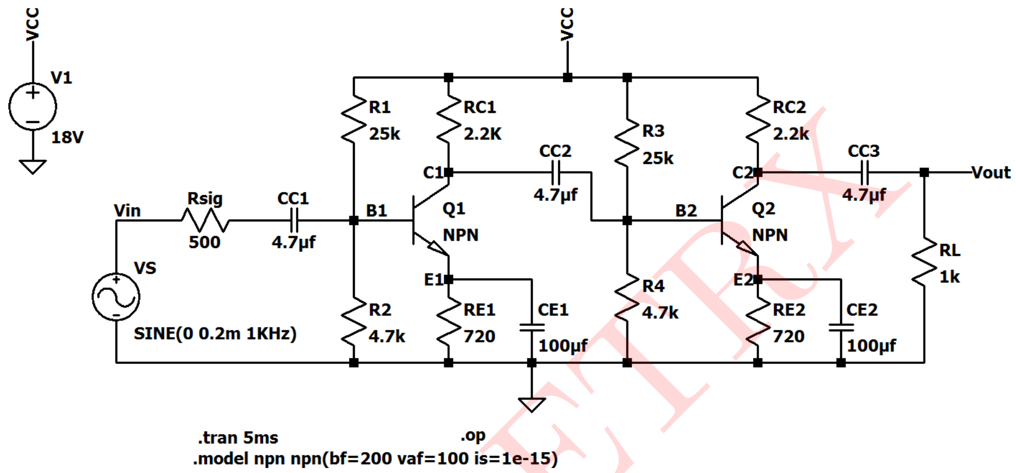

Figure 4: Circuit Schematic 1

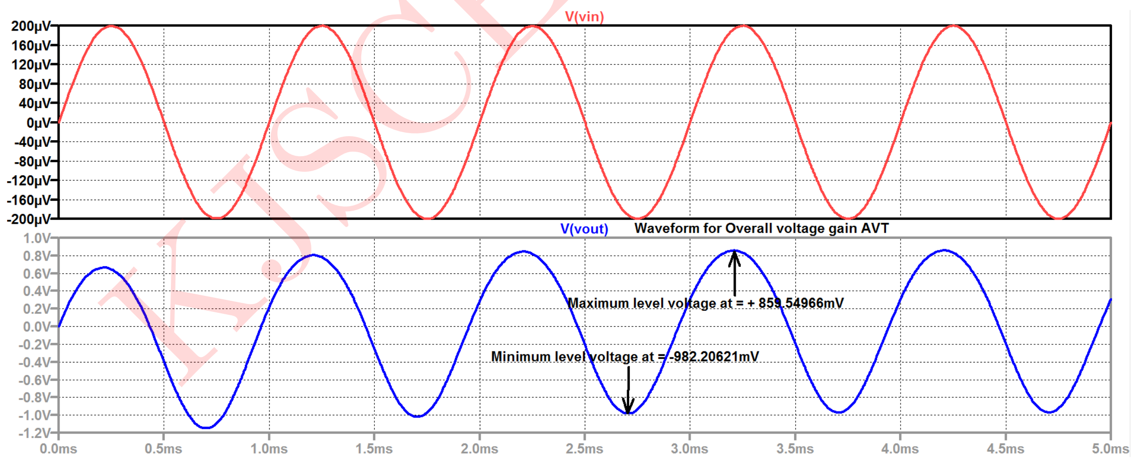

Figure 5: Input and Output waveform for overall voltage gain A_{V_T}

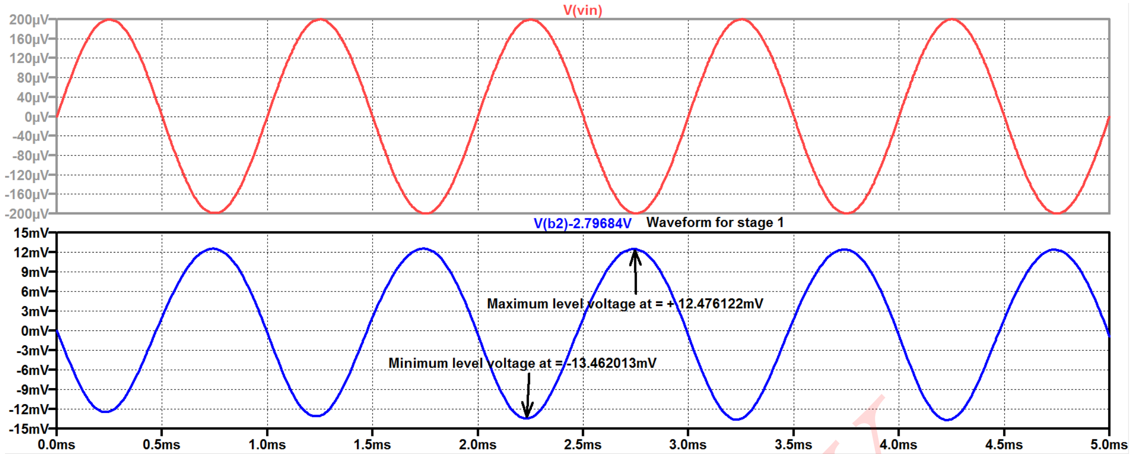

Figure 6: Input and Output waveform for stage 1

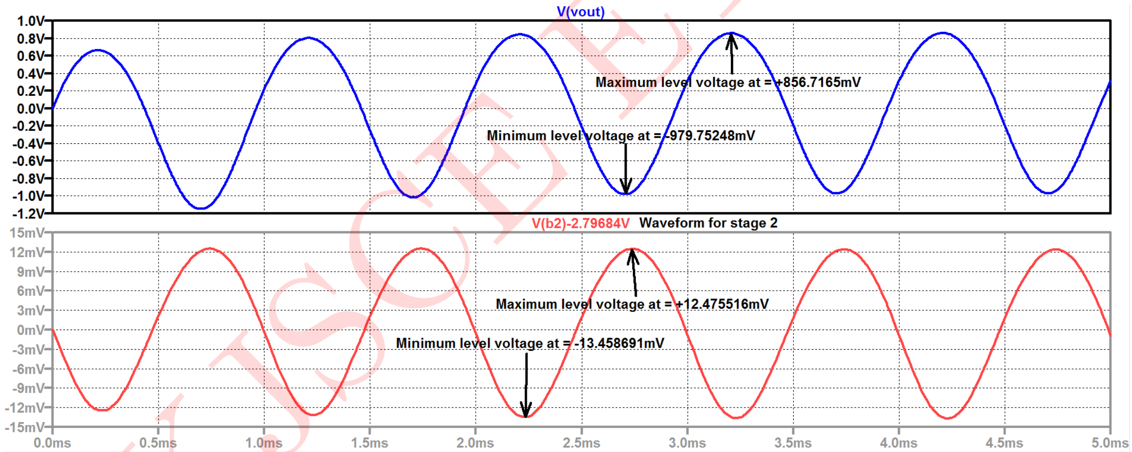

Figure 7: Input and Output waveform for stage 2

Comparison of Theoretical and Simulated Values:

Parameters	Theoretical	Simulated
I_{C_1}, V_{CE_1}	$2.89mA$, $9.549V$	$2.85mA$, $9.685V$
I_{C_2}, V_{CE_2}	$2.89mA$, $9.549V$	$2.85mA$, $9.685V$
A_{V1_S}	-62.676	-63.84
A_{V_2}	-76.415	-73.435
A_{V_T}	$73.605dB$	$73.43dB$
Input Impedance Z_i	$1.237k\Omega$	$-$
Output Impedance Z_o	687.5Ω	$-$

Table 1: Numerical 1

Numerical 2:
For the circuit shown in figure 8, Determine I_D, I_C, V_{GS}, V_{CC}, A_{V_1}, A_{V_2}, A_{V_T}, Input impedance of 1^{st} stage, Output impedance of 2^{nd} stage
Given: $V_S = 2mV$, $I_{DSS} = 6mA$, $V_P = -3V$ and $\beta = 150$

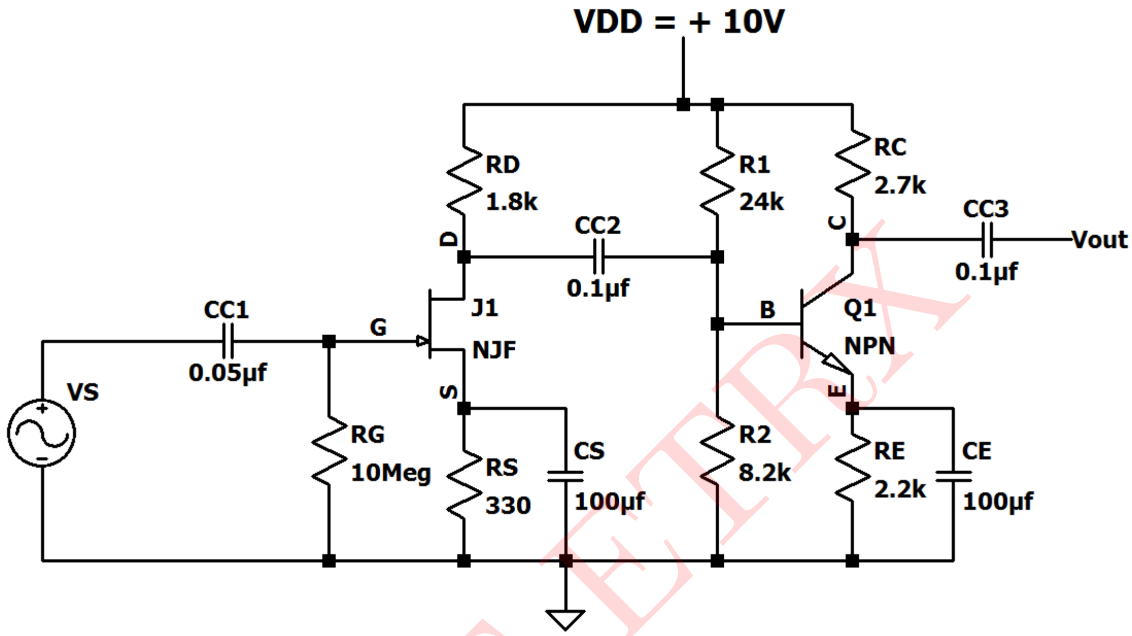

Figure 8: Circuit 1

Solution:

Above given circuit 2 is 2-stage RC coupled circuit, DC Analysis of both stages can be performed individually.

DC Analysis for 1^{st}:-

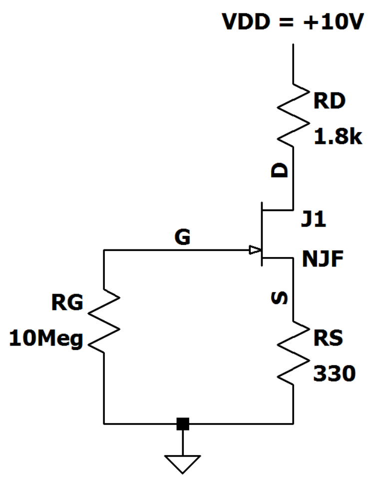

Figure 9: DC Equivalent circuit

Applying KVL to the Gate-Source loop:-

$V_{GS} = -I_D R_S$

$V_{GS} = -I_D(330)$ ....(1)

$$I_D = I_{DSS}\left(1 - \frac{V_{GS}}{V_P}\right)^2$$

$$I_D = 6mA\left(1 + \frac{V_{GS}}{3}\right)^2 \qquad ....(2)$$

Put (2) in (1)

$$V_{GS} = -330\left(\frac{6}{1000}\left(1 + \frac{V_{GS}}{3}\right)^2\right)$$

$$V_{GS} = -1.98\left(1 + \frac{{V_{GS}}^2}{9} + \frac{2 \times V_{GS}}{3}\right)$$

$V_{GS} = -1.98 - 0.22{V_{GS}}^2 - 1.32V_{GS}$

$0.22{V_{GS}}^2 + 2.32V_{GS} + 1.98 = 0$

Solving above quadratic equation we get

$V_{GS} = -0.936639V$

or

$V_{GS} = -9.608V$, We reject this value, as ($V_{GS} > V_P$)

$\therefore \boldsymbol{V_{GS} = -0.936V}$

$$I_D = -\frac{V_{GS}}{R_S} = \frac{0.936V}{330\Omega} = 2.84mA$$

$\boldsymbol{I_D = 2.84mA}$

Small-Signal parameters:-

$$g_{m_1} = \frac{2I_{DSS}}{V_P}\left(1 - \frac{V_{GS}}{V_P}\right) = \frac{2 \times 6 \times 10^{-3}}{3}\left(1 - \frac{0.936}{3}\right) = 2.752\ mA/V$$

$\boldsymbol{g_{m_1} = 2.752\ mA/V}$

DC Analysis for 2^{nd} stage:-

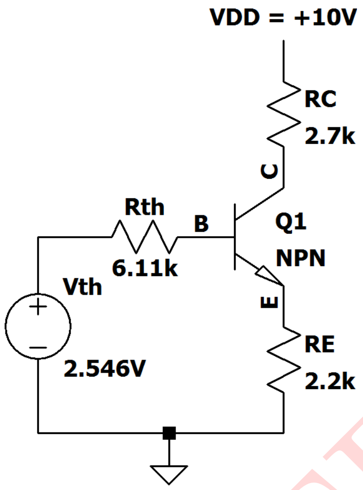

Figure 10: DC Equivalent circuit

$$V_B = V_{th} = \frac{R_2}{R_1 + R_2} \times V_{DD} = \frac{8.2k\Omega}{2.4k\Omega + 8.2k\Omega} \times 10 = 2.546V$$

$\boldsymbol{V_{th} = 2.546V}$

$R_{th} = R1 \ || \ R2 = 2.4k \ || \ 8.2k = 6.11k\Omega$

$\boldsymbol{R_{th} = 6.11k\Omega}$

Applying KVL to the base-emitter loop:-

$V_{th} - I_B R_{th} - V_{BE(ON)} - I_E R_E = 0$

$I_E = I_C + I_B = (\beta + 1) I_B$

Assume $V_{BE(ON)} = 0.7V$

$V_{th} - I_B R_{th} - 0.7V - (\beta + 1) I_B R_E = 0$

$$I_B = \frac{V_{th} - 0.7V}{R_{th} + ((\beta + 1) R_E)} = \frac{2.546 - 0.7}{6.11k\Omega + (151 \times 2.2k\Omega)} = 5.456\mu A$$

$\therefore \boldsymbol{I_B = 5.456\mu A}$

$I_C = \beta I_B = 150 \times 5.456\mu A = 0.818mA$

$\therefore \boldsymbol{I_C = 0.818mA}$

Applying KVL to the collector-emitter loop:-

$V_{CE} = V_{DD} - I_C R_C - (\beta + 1) I_B R_E$

$V_{CE} = 10 - (0.818mA \times 2.7k\Omega) - (151 \times 2.2k\Omega \times 5.456\mu A) = 5.9776V$

$\boldsymbol{V_{CE} = 5.9776V}$

Small-Signal parameters:-

$g_{m_2} = \frac{I_C}{V_T} = \frac{0.818mA}{26mV} = 31.47\ mA/V$

$\boldsymbol{g_{m_2} = 31.47\ mA/V}$

$r_\pi = \frac{V_T}{I_B} = \frac{26mV}{5.456\mu A} = 4.765k\Omega$

$\boldsymbol{r_\pi = 4.765k\Omega}$

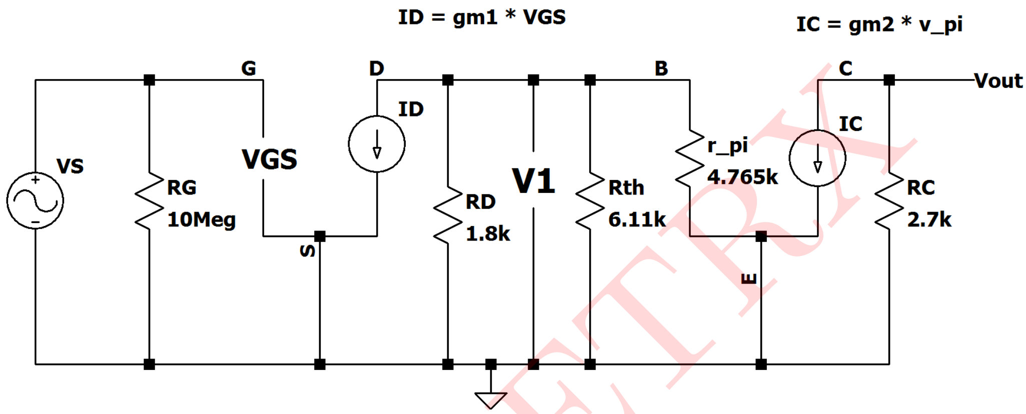

Figure 11: Small Signal Mid-Frequency Equivalent Circuit

Input Impedance:-

$Z_i = R_G = 10M\Omega$

$\boldsymbol{Z_i = 10M\Omega}$

Output Impedance:-

$Z_o = R_C = 2.7k\Omega$

$\boldsymbol{Z_o = 2.7k\Omega}$

Voltage Gain of Stage 1(A_{V_1})

$A_{V_1} = \frac{V_1}{V_{in}}$

$V_1 = -g_{m_1} V_{gs}(R_D \mid\mid R_{th} \mid\mid r_\pi)$

$V_{in} = V_{GS}$

$A_{V_1} = \frac{V_1}{V_{in}} = -g_m(R_D \mid\mid R_{th} \mid\mid r_\pi)$

$A_{V_1} = \frac{V_1}{V_{in}} = -2.752mA/V(1.8k \mid\mid 6.11k \mid\mid 4.765k)$

$A_{V_1} = \frac{V_1}{V_{in}} = -2.752mA/V(1.076k)$

$A_{V_1} = \frac{V_1}{V_{in}} = -2.96$

$\boldsymbol{A_{V_1} = -2.96}$

Voltage gain for Stage 2:-

$A_{V_2} = \frac{V_{out}}{V_1}$

$V_o = -g_{m_2} V_\pi (R_C)$

$V_1 = V_\pi$

$A_{V_2} = \frac{V_{out}}{V_1} = -31.47 \times 10^{-3} \times 2.7 \times 10^3 = -84.969$

$\boldsymbol{A_{V_2} = -84.969}$

Overall mid-band voltage gain $= A_{V_1} \times A_{V_2} = -2.96 \times -84.969 = 251.508$

$\boldsymbol{A_{V_T} = 251.508}$

$\boldsymbol{A_{V_T}}$ **in dB** $\boldsymbol{= 20log_{10}(251.508) = 48.01dB}$

$A_{V_T} = \frac{V_{out}}{V_{in}}$

$\therefore V_{out} = A_{V_T} \times V_{in} = 251.508 \times 4 \times 10^{-3} = 1.006V$

$\boldsymbol{V_{out} = 1.006V}$

SIMULATED RESULTS:

Above circuit was simulated in LTSpice and results are presented below:

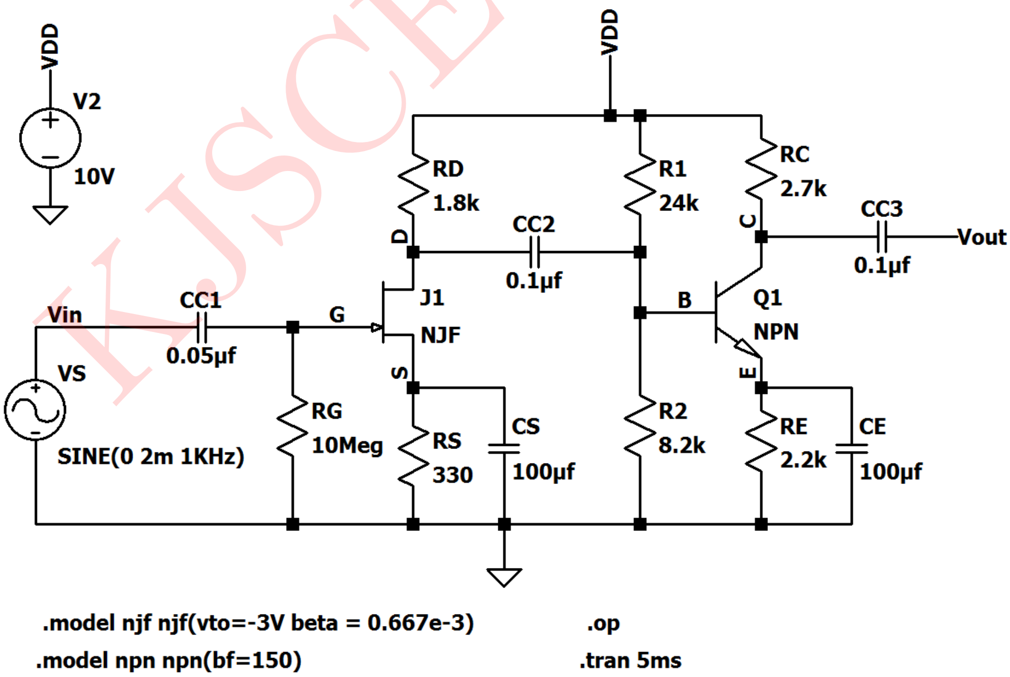

Figure 12: Circuit Schematic 2

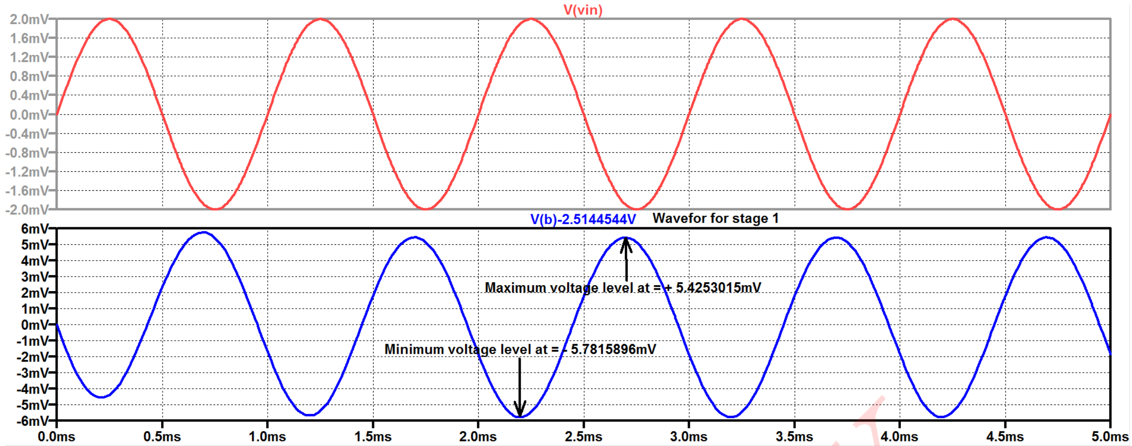

Figure 13: Input and Output waveform for stage 1

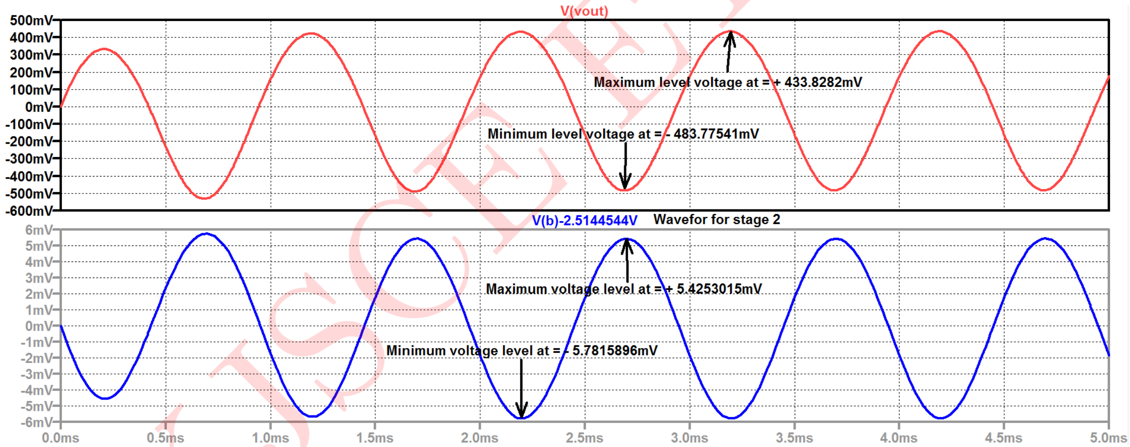

Figure 14: Input and Output waveform for stage 2

Comparison of Theoretical and Simulated Values:

Parameters	Theoretical	Simulated
I_D, V_{GS}	$2.84mA$, $-0.936V$	$2.84mA$, $-0.936V$
I_C, V_{CE}	$0.818mA$, $5.9778V$	$0.79mA$, $6.12V$
A_{V_1}	-2.96	-2.801
A_{V_2}	-84.969	-81.88
A_{V_T}	$48.01dB$	$47.21dB$
Input Impedance Z_i	$10M\Omega$	$-$
Output Impedance Z_o	$2.7k\Omega$	$-$
V_{out}	$1.006V$	$0.92V$

Table 2: Numerical 2

Numerical 3:
For the circuit shown in figure 15, the BJT parameters are $\beta_1 = \beta_2 = 100$, $V_{BE_1} = V_{BE_2} = 0.7V$
a) Determine all node voltage and terminal currents under DC analysis
b) Determine overall voltage gain of the circuit

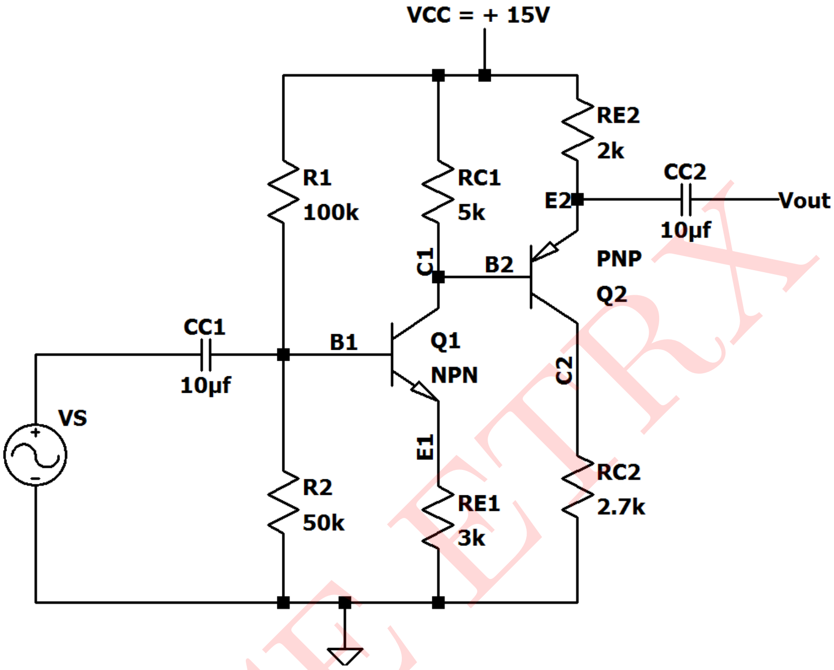

Figure 15: Circuit 3

Solution:

Above given circuit 3 is 2-stage RC coupled amplifier

$\therefore$ DC Analysis will be done for both the stages

DC Analysis:-

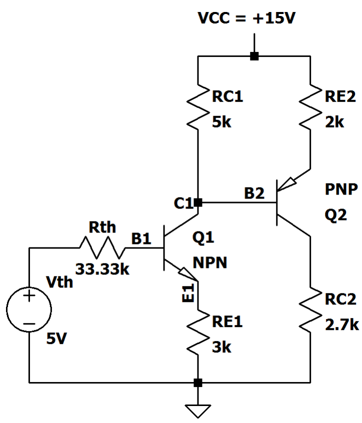

Figure 16: DC Equivalent circuit

$$V_B = V_{th} = \frac{R_2}{R_1 + R_2} \times V_{CC} = \frac{50k\Omega}{100k\Omega + 50k\Omega} \times 15 = 5V$$

$\boldsymbol{V_{th} = 5V}$

$R_{th} = R1 \mid\mid R2 = 100k \mid\mid 50k = 33.33k\Omega$

$\boldsymbol{R_{th} = 33.33k\Omega}$

Applying KVL to the base-emitter loop:-

$V_{th} - I_{B_1}R_{th} - V_{BE(ON)} - I_{E_1}R_{E_1} = 0$

$I_{E_1} = I_{C_1} + I_{B_1} = (\beta_1 + 1)I_{B_1}$

Assume $V_{BE(ON)} = 0.7V$

$V_{th} - I_{B_1}R_{th} - 0.7V - (\beta + 1)I_{B_1}R_{E_1} = 0$

$$I_{B_1} = \frac{V_{th} - 0.7V}{R_{th} + ((\beta + 1)R_{E_1})} = \frac{5 - 0.7}{33.33k\Omega + (101 \times 3k\Omega)} = 12.785\mu A$$

$\therefore \boldsymbol{I_{B_1} = 12.785\mu A}$

$I_{C_1} = \beta_1 I_{B_1} = 100 \times 12.785\mu A = 1.2785mA$

$\therefore \boldsymbol{I_{C_1} = 1.2785mA}$

$I_{E_1} = I_{C_1} + I_{B_1} = 1.2785mA + 12.785\mu A = 1.291mA$

$\therefore \boldsymbol{I_{E_1} = 1.291mA}$

$V_{C_1} = V_{CC} - I_{C_1}R_{C_1}$ [Ignoring I_{B_2} and $I_{RC1} \approx I_{C_1}$] ....(1)

$V_{C_1} = 15 - 1.2785mA \times 5k\Omega = 8.607V$

$\boldsymbol{V_{C_1} = 8.607V}$

$V_{E_2} = V_{B_2} + V_{EB_2}(on) = V_{C_1} + V_{EB_2}(on)$

$V_{E_2} = 8.607 + 0.7 = 9.307V$

$\boldsymbol{V_{E_2} = 9.307V}$

From the circuit:-

$V_{CC} - I_{E_2}R_{E_2} - V_{E_2} = 0$

$$I_{E_2} = \frac{V_{CC} - V_{E_2}}{R_{E_2}} = \frac{15 - 9.037}{2k\Omega} = 2.8465mA$$

$\boldsymbol{I_{E_2} = 2.8465mA}$

$$I_{C_2} = \frac{\beta_2}{1 + \beta_2} \times I_{E_2} = \frac{100}{101} \times 2.8465mA = 2.818mA$$

$\boldsymbol{I_{C_2} = 2.818mA}$

$I_{B_2} = \frac{I_{E_2}}{1+\beta_2} = \frac{2.8465mA}{101} = 281.8\mu A$

$\boldsymbol{I_{B_2} = 28.18\mu A}$

Rewriting expression for equation (1):-

$V_{C_1} = V_{CC} - I_{RC_1}R_{C_1}$

$I_{RC_1} = I_{C_1} - I_{B_2} = 1.2785mA - 28.18\mu A = 1.25mA$

$V_{C1_{new}} = 15.1.25mA \times 5k\Omega = 8.75V$

$V_{E2_{new}} = V_{C1_{new}} + V_{EB_2} = 8.75 + 0.7 = 9.45V$

$I_{E2_{new}} = \frac{V_{CC} - V_{E2_{new}}}{R_{E_2}} = \frac{15 - 9.45}{2k\Omega} = 2.775mA$

$I_{C2_{new}} = \frac{\beta_2}{1+\beta_2} \times I_{E2_{new}} = \frac{100}{101} \times 2.775mA = 2.743mA$

$I_{B2_{new}} = \frac{I_{E2_{new}}}{1+\beta_2} = \frac{2.775mA}{101} = 27.47\mu A$

$V_{E_1} = I_{E_1}R_{E_1} = 1291mA \times 3k = 3.873V$

$V_{C_2} = I_{C_2}R_{C_2} = 2.743 \times 2.7k\Omega = 7.406V$

$V_{B_1} = V_{BE_1}(on) + V_{E_1} = 4.573V$

Node Voltages:-

$V_{B_1} = 4.573V,\ V_{C_1} = 8.75V,\ V_{E_1} = 3.873V$

$V_{C_2} = 7.406V,\ V_{E_2} = 9.45V,\ V_{B_2} = V_{C_1} = 8.75V$

Terminal Currents:-

$I_{B_1} = 12.785\mu A,\ I_{C_1} = 1.2785mA,\ I_{E_1} = 1.291mA$

$I_{B_2} = 24, 47\mu A,\ I_{C_2} = 2.743mA,\ I_{E_2} = 2.775mA$

Small-Signal parameters:-

$g_{m_1} = \frac{I_{C_1}}{V_T} = \frac{1.2785mA}{26mV} = 491.73\ mA/V$

$\boldsymbol{g_{m_1} = 491.73\ mA/V}$

$r_{\pi_1} = \frac{V_T}{I_{B_1}} = \frac{26mV}{12.785\mu A} = 2.033k\Omega$

$\boldsymbol{r_{\pi_1} = 2.033k\Omega}$

$g_{m_2} = \frac{I_{C_2}}{V_T} = \frac{2.743mA}{26mV} = 105.5\ mA/V$

$\boldsymbol{g_{m_2} = 105.5\ mA/V}$

$r_{\pi_2} = \frac{V_T}{I_{B_2}} = \frac{26mV}{27.43\mu A} = 947.867\Omega$

$\boldsymbol{r_{\pi_2} = 947.687\Omega}$

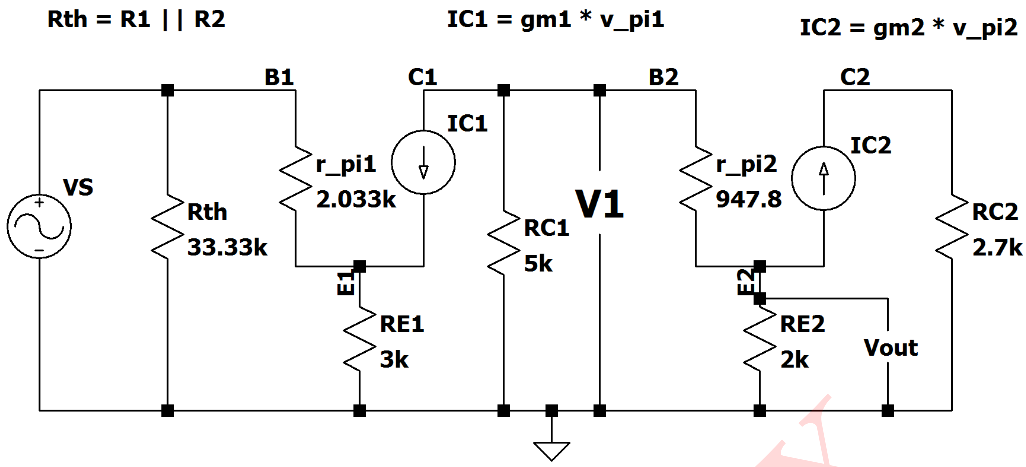

Figure 17: Small Signal Equivalent Circuit

Voltage Gain of Stage 1(A_{V_1})

$A_{V_1} = \frac{V_1}{V_S}$

$V_1 = -g_{m_1} V_{\pi_1}(R_{C_1}) = -(\beta_1 ib_1)R_{C_1}$

$V_S = ib_1[r_{\pi_1} + (1+\beta_1)R_{E_1}]$

$A_{V_1} = \frac{V_1}{V_S} = \frac{-(\beta_1 ib_1)R_{C_1}}{ib_1[r_{\pi_1} + (1+\beta_1)R_{E_1}]} = \frac{-100 \times 5k}{[2.033k\Omega + (101 \times 3k\Omega)]} = -1.639$

$\boldsymbol{A_{V_1} = -1.639}$

Voltage Gain of Stage 2(A_{V_2})

$A_{V_2} = \frac{V_{out}}{V_1}$

$V_{out} = -g_{m_1} V_{\pi_2}(R_{E_2}) = -(\beta_2 ib_2)R_{E_2}$

$V_1 = ib_2[r_{\pi_2} + (1+\beta_2)R_{E_2}]$

$A_{V_2} = \frac{V_{out}}{V_1} = \frac{(\beta_2 ib_2)R_{C_2}}{ib_2[r_{\pi_2} + (1+\beta_2)R_{E_2}]} = \frac{100 \times 2k}{[947.867\Omega + (101 \times 2k\Omega)]} = 0.985$

$\boldsymbol{A_{V_2} = 0.985}$

Overall mid-band voltage gain $= A_{V_1} \times A_{V_2} = -1.639 \times 0.985$

$\boldsymbol{A_{V_T} = -1.614}$

Output voltage:-

$A_{V_T} = \frac{V_{out}}{V_S}$

$V_{out} = A_{V_T} \times V_S = -1.614 \times 40mV = -64.56mV$

$\boldsymbol{V_{out} = -64.56mV}$

SIMULATED RESULTS:
Above circuit was simulated in LTSpice and results are presented below:

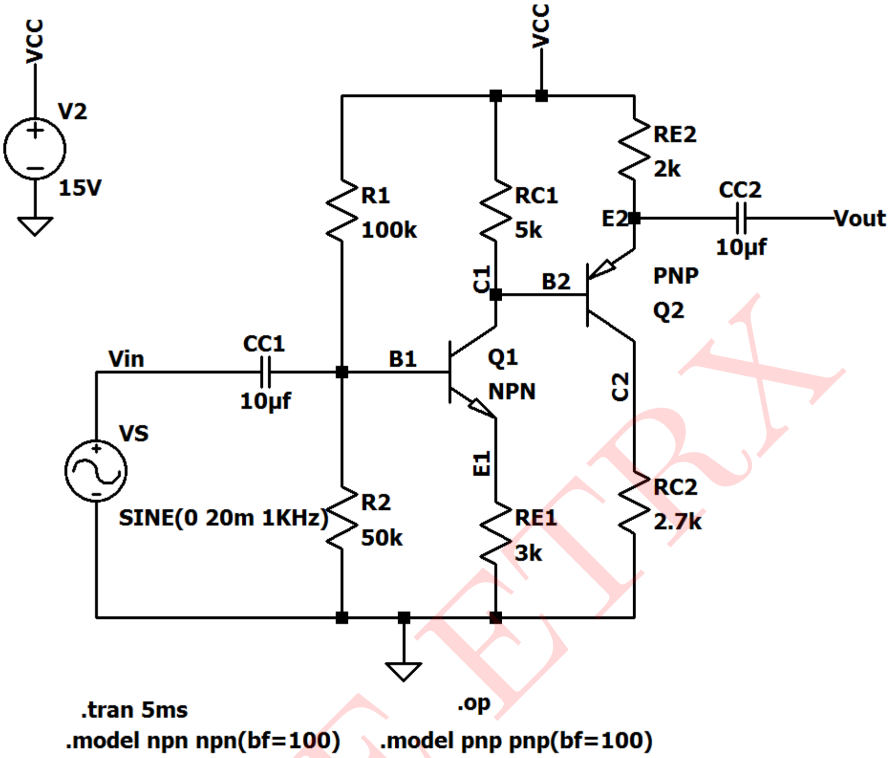

Figure 18: Circuit Schematic 3

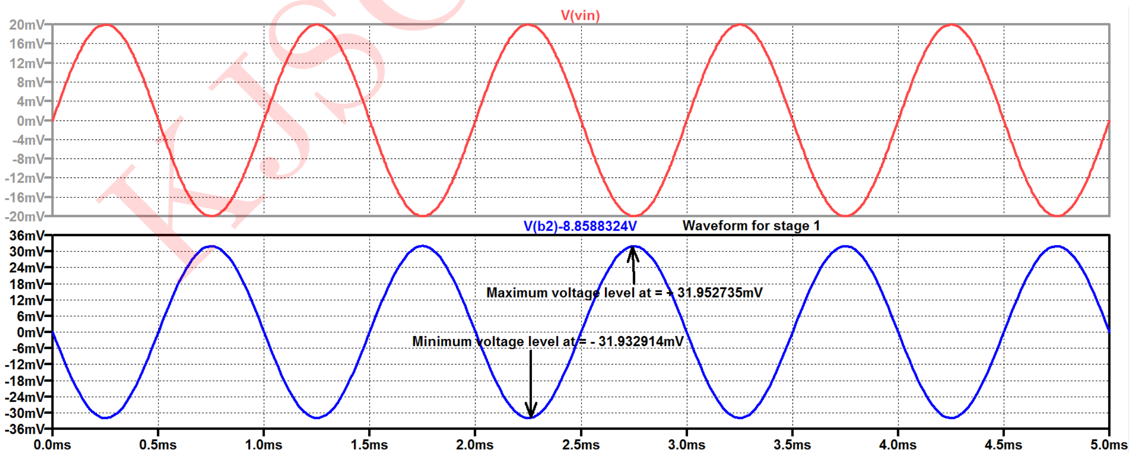

Figure 19: Input and Output waveform for stage 1

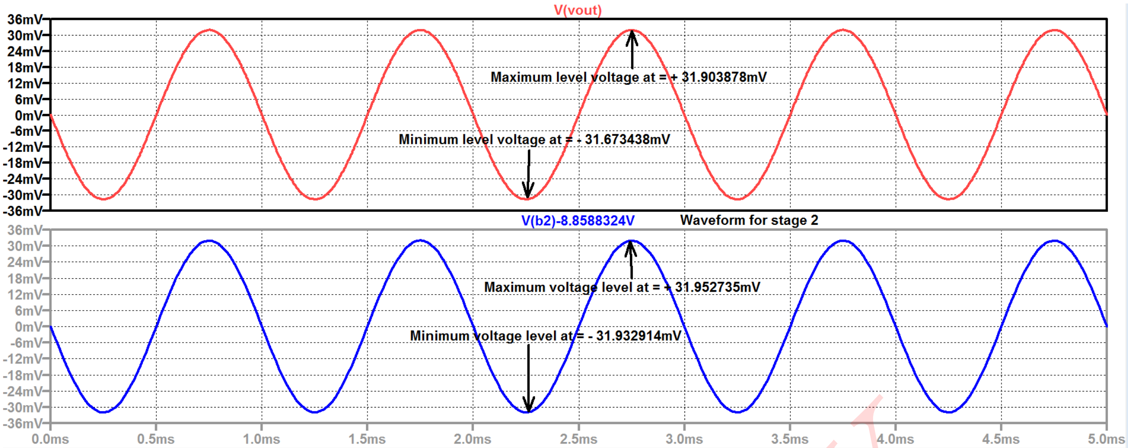

Figure 20: Input and Output waveform for stage 2

Comparison of Theoretical and Simulated Values:

Parameters	Theoretical	Simulated
$I_{C_1}, I_{B_1}, I_{E_1}$	$12.78\mu A$, $1.2785mA$, $1.29mA$	$12.55\mu A$, $1.25mA$, $1.273mA$
$I_{C_2}, I_{B_2}, I_{E_2}$	$27.74\mu A$, $2.47mA$, $2.77mA$	$26.45\mu A$, $2.65mA$, $2.67mA$
V_{C_1}, V_{C_2}	$8.75V$, $7.406V$	$8.85V$, $7.21V$
V_{E_1}, V_{E_2}	$3.873V$, $9.45V$	$3.82V$, $9.65V$
V_{B_1}, V_{B_2}	$4.573V$, $8.75V$	$4.581V$, $8.85V$
A_{V_T}	-1.614	-1.59
V_{out}	$-64.56mV$	$-63.57mV$

Table 3: Numerical 3

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