K. J. SOMAIYA COLLEGE OF ENGINEERING
DEPARTMENT OF ELECTRONICS ENGINEERING
ELECTRONIC CIRCUITS
Differential Amplifier Circuits

Numerical 1:

Determine the following for the circuit shown in figure 1. Assume $\beta_1 = \beta_2 = 100$

a. Name of the Circuit

b. Current flowing through resistor R_{S_1}, R_{S_2}, R_{C_1}, R_{C_2} & R_E

c. V_{C_1}, V_{C_2}, V_{CE_1}, V_{CE_2}

d. Differential Voltage Gain

e. Commin Mode Gain

f. CMRR in dB

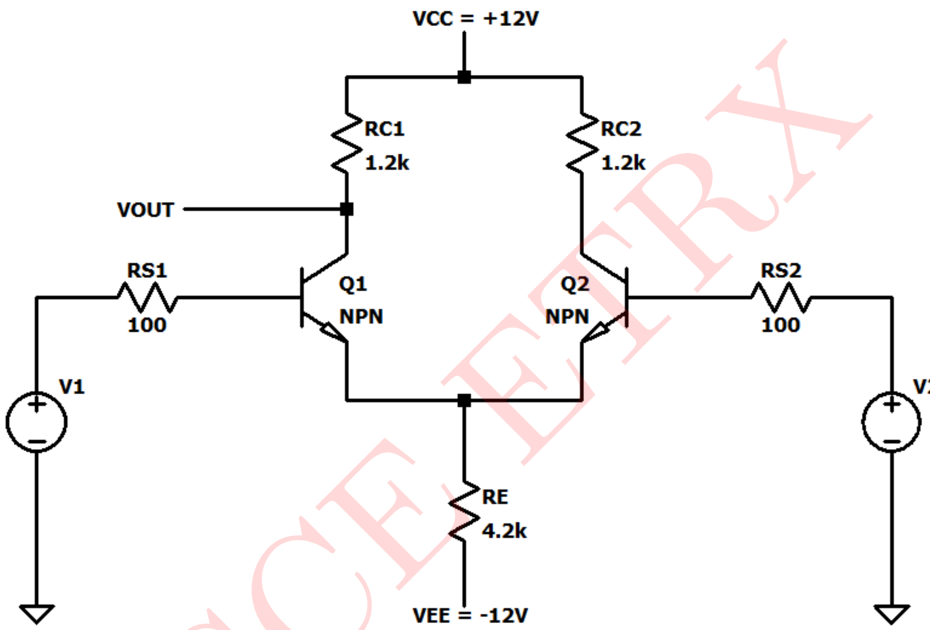

Figure 1: Circuit 1

Solution: Above circuit 1 is a Dual input unbalanced output(DIUO) differential amplifier.

DC Analysis:

$$I_{BQ} = \frac{-V_{EE} - V_{BE}}{R_S + 2(1+\beta)R_E}$$
$$= \frac{-(-12) - 0.7}{100\Omega + 2(101) \times (4.2k\Omega)}$$
$$= \mathbf{13.317\mu A}$$

Thus the current flowing through R_{S_1} & R_{S_2} is $I_{BQ} = 13.317\mu A$

$I_{CQ} = \beta I_{BQ} = 100 \times 13.317\mu A = \mathbf{1.3317mA}$

Thus the current flowing through R_{C_1} & R_{C_2} is $I_{CQ} = 1.3317mA$

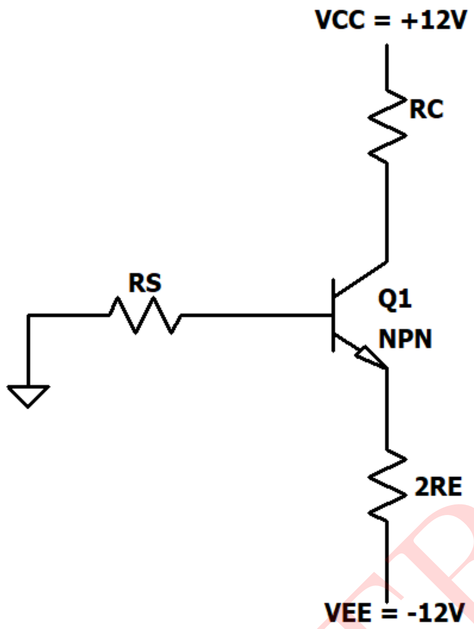

Figure 2: DC Equivalent Circuit

$$
\begin{aligned}
V_{C_1} = V_{C_2} &= V_{CC} - I_{CQ}R_C \\
&= 12 - (1.3317mA \times 1.2k\Omega) \\
&= 10.4V
\end{aligned}
$$

$$\therefore V_{C_1} = V_{C_2} = \mathbf{10.4V}$$

$$
\begin{aligned}
V_{CEQ} &= V_{CC} - V_{EE} - I_{CQ}(R_C + 2R_E) \\
&= 12 - (-12) - (1.3317mA)(1.2k\Omega + 2 \times 4.2k\Omega) \\
&= 24 - 12.784 \\
&= \mathbf{11.216V}
\end{aligned}
$$

$$r_\pi = \frac{\beta V_T}{I_{CQ}} = \frac{100 \times 26mV}{1.3317mA} = \mathbf{1.952k\Omega}$$

$$
\begin{aligned}
|A_d| &= \frac{\beta R_C}{2(r_\pi + R_S)} \\
&= \frac{100 \times 1.2k\Omega}{2(1.952k\Omega + 100\Omega)} \\
&= \mathbf{29.239} && \text{[Differential Voltage Gain]}
\end{aligned}
$$

$$
\begin{aligned}
A_{CM} &= \left|\frac{R_C}{2R_E}\right| \\
&= \left|\frac{1.2k\Omega}{2 \times 4.2k\Omega}\right| \\
&= \mathbf{0.1428} && \text{[Common mode gain]}
\end{aligned}
$$

$$\text{CMRR} = \left|\frac{A_d}{A_{CM}}\right| = \left|\frac{29.239}{0.1428}\right| = 204.754$$

$$\begin{aligned}\text{CMRR in dB} &= 20log_{10}\left(\frac{A_d}{A_{CM}}\right)\\ &= 20log_{10}(204.754)\\ &= \mathbf{46.22}\text{dB}\end{aligned}$$

SIMULATED RESULTS

The above circuit is simulated in LTspice and results are presented below:

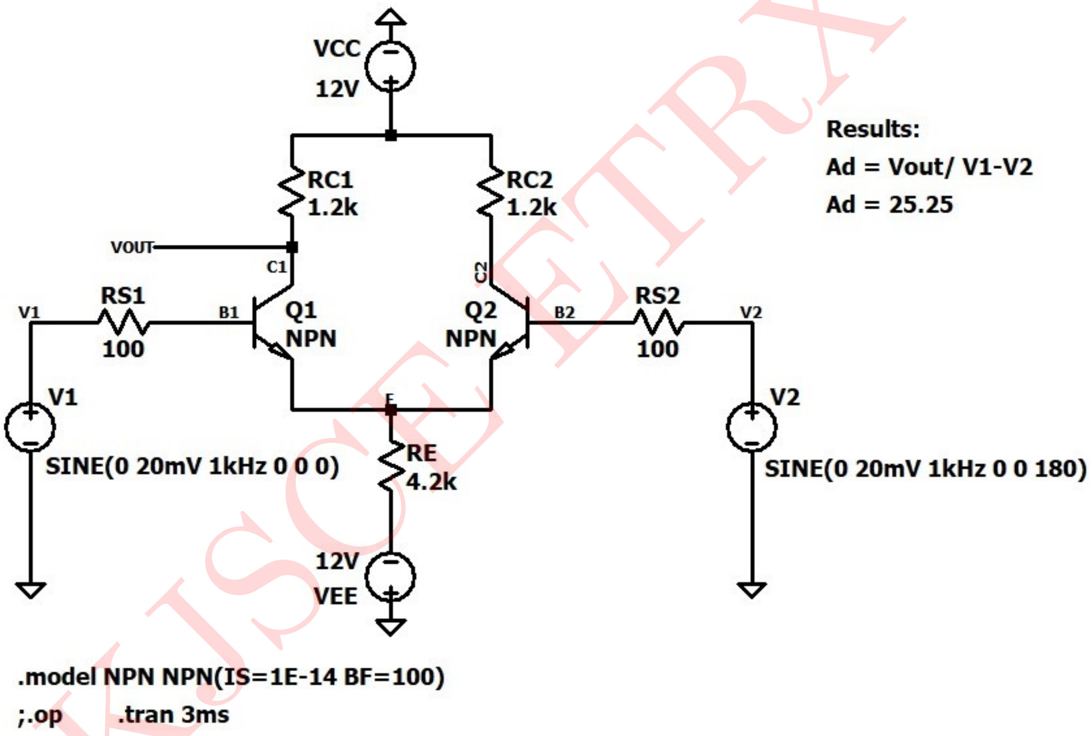

Figure 3: Circuit Schematic

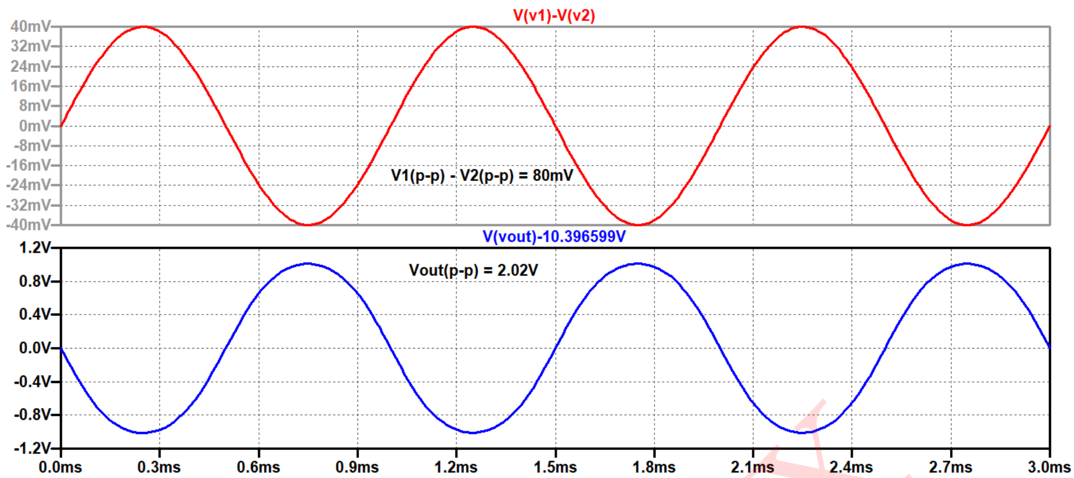

Figure 4: Input and Output waveform

Comparison of Theoretical and Simulated results:

Parameters	Theoretical	Simulated
I_{C_1}, I_{C_2}	$1.3317mA$, $1.3317mA$	$1.3361mA$, $1.3361mA$
V_{C_1}, V_{C_2}	$10.4V$, $10.4V$	$10.3966V$, $10.3966V$
V_{CE_1}, V_{CE_2}	$11.216V$, $11.216V$	$11.06V$, $11.06V$
Differential Voltage gain: $\lvert A_d \rvert$	29.239	25.25
Commom mode Voltage gain: A_{CM}	0.1428	–
CMRR in dB	46.26dB	–

Table 1: Numerical 1

Numerical 2:

Consider the differential amplifier in the figure 5. The transistor parameters are $k_{n_1} = k_{n_2} = 50\mu A/V^2$, $\lambda_1 = \lambda_2 = 0.02V^{-1}$ & $V_{TN_1} = V_{TN_2} = 1V$

a. Determine I_S, I_{D_1}, I_{D_2}, V_{D_1}, V_{D_2}, V_{DS_1}, V_{DS_2}

b. Determine differential mode volatge gain A_d

c. Determine common mode voltage gain A_{CM}

d. Determine CMRR in dB

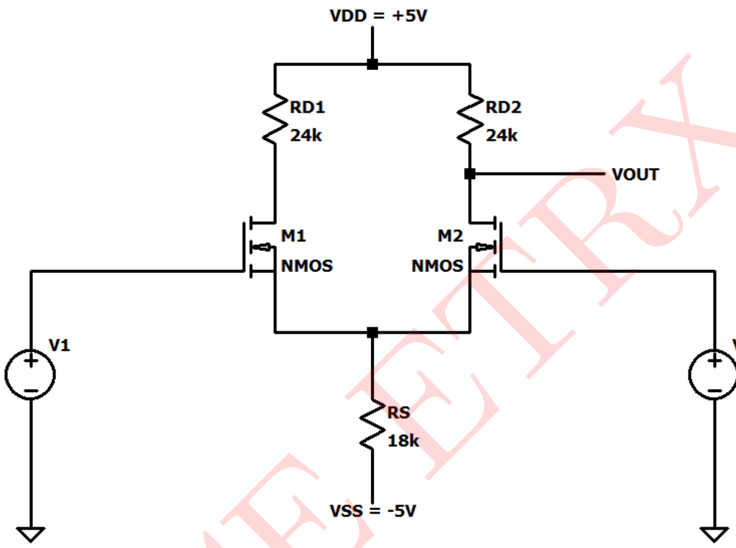

Figure 5: Circuit 2

Solution: The above circuit 2 is a Dual input unbalanced output differential amplifier.

DC Analysis:

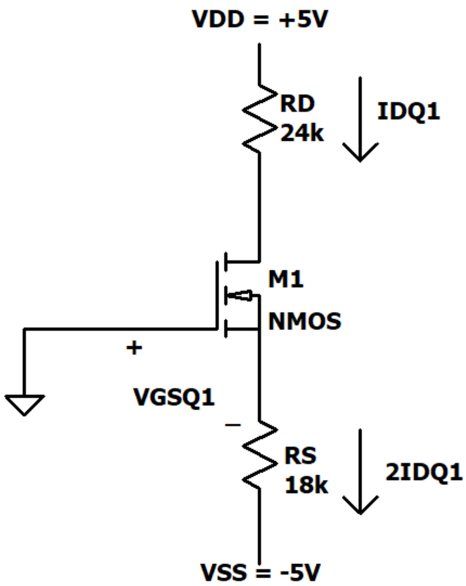

Figure 6: DC Equivalent Circuit

For a symmetrical differential amplifier,

$$V_{GSQ_1} = -V_{SS} - 2I_{DQ_1}R_S$$

$$\text{i.e } V_{GSQ_1} = 5 - 2I_{DQ_1} \times (18k\Omega) \qquad .....(1)$$

$$\begin{aligned} V_{DSQ_1} &= V_{DD} - V_{SS} - I_{DQ_1}(R_D + 2R_S) \\ &= 10 - I_{DQ_1}(24k\Omega + 2 \times (18k\Omega)) \\ &= 10 - I_{DQ_1} \times (60k\Omega) \qquad .....(2) \end{aligned}$$

Now,

$$\begin{aligned} I_{DQ_1} &= k_{n_1}\,(V_{GSQ_1} - V_{TN_1})^2\,(1 + \lambda V_{DS}) \\ &= (50\mu A/V^2)\,(V_{GSQ_1} - 1)^2\,(1 + 0.02(10 - I_{DQ_1} \times 60k\Omega)) \\ &= (50\mu A/V^2)\,(V_{GSQ_1} - 1)^2\,(1.2 - 1200I_{DQ_1}) \qquad .....[\text{From } (2)] \\ &= 6 \times 10^{-5} \times (V_{GSQ_1} - 1)^2 - 0.06I_{DQ_1} \times (V_{GSQ_1} - 1)^2 \end{aligned}$$

$$I_{DQ_1}(1 + 0.06(V_{GSQ_1} - 1)^2) = 6 \times 10^{-5} \times (V_{GSQ_1} - 1)^2$$

$$I_{DQ_1} = \frac{6 \times 10^{-5} \times (V_{GSQ_1} - 1)^2}{1 + 0.06(V_{GSQ_1} - 1)^2} \qquad .....(3)$$

Substituting equation(3) in equation(1),

$$\begin{aligned} V_{GSQ_1} &= 5 - \frac{2 \times 18k\Omega \times 6 \times 10^{-5} \times (V_{GSQ_1} - 1)^2}{1 + 0.06(V_{GSQ_1} - 1)^2} \\ &= \frac{5 + 0.3(V_{GSQ_1} - 1)^2 - 2.16(V_{GSQ_1} - 1)^2}{1 + 0.06(V_{GSQ_1} - 1)^2} \end{aligned}$$

$$V_{GSQ_1} \times (1 + 0.06(V_{GSQ_1} - 1)^2) = 5 + 0.3(V_{GSQ_1} - 1)^2 - 2.16(V_{GSQ_1} - 1)^2$$

$$\begin{aligned} \text{LHS} &= V_{GSQ_1} \times (1 + 0.06(V_{GSQ_1} - 1)^2) \\ &= 0.06V_{GSQ_1} + 0.06V_{GSQ_1}(V_{GSQ_1}^2 + 1 - 2V_{GSQ_1}) \\ &= 0.06V_{GSQ_1}^3 + 1.06V_{GSQ_1} - 0.12V_{GSQ_1}^2 \end{aligned}$$

$$\begin{aligned} \text{RHS} &= 5 + 0.3(V_{GSQ_1} - 1)^2 - 2.16(V_{GSQ_1} - 1)^2 \\ &= 5 + 0.3(V_{GSQ_1}^2 + 1 - 2V_{GSQ_1}) - 2.16(V_{GSQ_1}^2 + 1 - 2V_{GSQ_1}) \\ &= -1.86V_{GSQ_1}^2 + 3.14 + 3.72V_{GSQ_1} \end{aligned}$$

$\because$ LHS = RHS

$$0.06V_{GSQ_1}^3 + 1.06V_{GSQ_1} - 0.12V_{GSQ_1}^2 = -1.86V_{GSQ_1}^2 + 3.14 + 3.72V_{GSQ_1}$$

$$0.06V_{GSQ_1}^3 - 2.66V_{GSQ_1} + 1.74V_{GSQ_1}^2 - 3.14 = 0$$

$$V_{GSQ_1} = -30.4V,\ 2.188V,\ -0.786V$$

Now, $\because V_{GSQ_1} > V_{TN_1}$

$\therefore V_{GSQ_1} = \mathbf{2.188V}$

From equation (3),

$$I_{DQ_1} = \frac{6 \times 10^{-5}(V_{GSQ_1} - 1)^2}{1 + 0.06(V_{GSQ_1} - 1)^2}$$

$\therefore I_{DQ_1} = \mathbf{78.15\mu A}$

From equation (2),

$I_{DQ_1} = I_{DQ_2} = I_S = \mathbf{78.15\mu A}$

$V_{DSQ_1} = 10 - I_{DQ_1} \times 60k\Omega = 5.311V$

$V_{DSQ_1} = V_{DSQ_2} = \mathbf{5.311V}$

$$\begin{aligned} V_{D_1} &= V_{DD} - I_{DQ_1} R_D \\ &= 5 - (78.15\mu A) \times 24k\Omega \\ &= \mathbf{3.1244} \end{aligned}$$

$V_{D_1} = V_{D_2} = \mathbf{3.1244V}$

$$\begin{aligned} g_{m_1} &= 2k_n(V_{GSQ_1} - V_{TN_1})\,(1 + \lambda V_{DSQ_1}) \\ &= 2 \times (50\mu A/V^2)\,(2.188 - 1)\,(1 + 0.02 \times 5.311) \\ &= \mathbf{0.1314mA/V} \end{aligned}$$

Differential Voltage Gain:

$$A_d = \frac{g_m R_D}{2} = \frac{0.1314mA/V \times 24k\Omega}{2} = \mathbf{1.5768}$$

Common Mode Voltage Gain:

$$\begin{aligned} A_{CM} &= \left|\frac{g_m R_D}{1 + 2g_m R_S}\right| \\ &= \left|\frac{0.1314mA/V \times 24k\Omega}{1 + 2 \times 0.1314mA/V \times 18k\Omega}\right| \\ &= \mathbf{0.55} \end{aligned}$$

$$\text{CMRR} = \left|\frac{A_d}{A_{CM}}\right| = \mathbf{2.8669}$$

$$\begin{aligned} \text{CMRR in dB} &= 20log_{10}(2.8699) \\ &= \mathbf{9.157}\text{dB} \end{aligned}$$

SIMULATED RESULTS

The above circuit is simulated in LTspice and results are presented below:

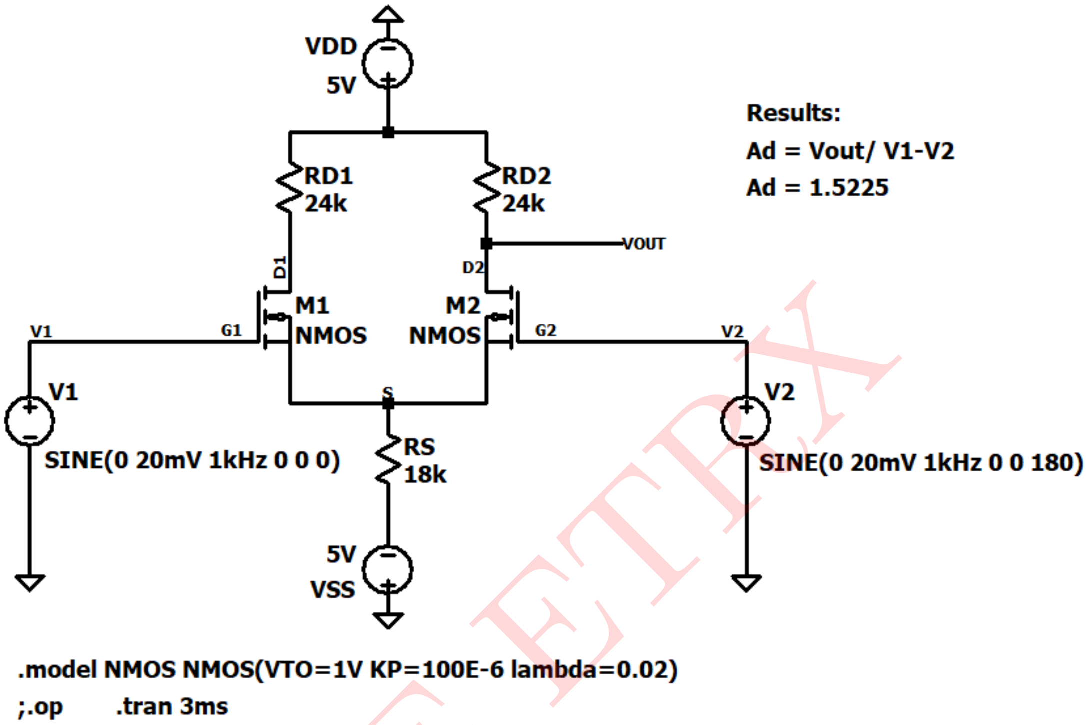

Figure 7: Circuit Schematic

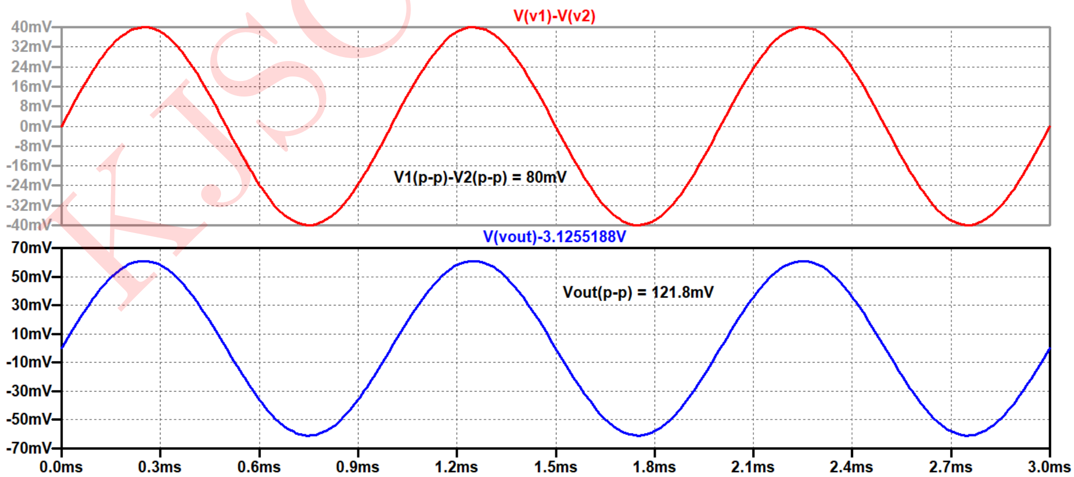

Figure 8: Input and Output waveform

Comparison of Theoretical and Simulated results:

Parameters	Theoretical	Simulated
I_{D_1}, I_{D_2}	$78.15\mu A$, $78.15\mu A$	$78.10\mu A$, $78.10\mu A$
I_S	$78.15\mu A$	$78.10\mu A$
V_{D_1}, V_{D_2}	$3.1244V$, $3.1244V$	$3.1255V$, $3.1255V$
V_{DS_1}, V_{DS_2}	$5.311V$, $5.311V$	$5.313V$, $5.313V$
Differential Voltage gain: A_d	1.5768	1.5225
Commom mode Voltage gain: A_{CM}	0.55	–
CMRR in dB	9.157dB	–

Table 2: Numerical 2

Numerical 3:

For given differential amplifier in figure 9, find:

a. DC values of V_{o_1} & V_{o_2}

b. Double ended output gain: $\dfrac{V_{o_1} - V_{o_2}}{V_1 - V_2}$

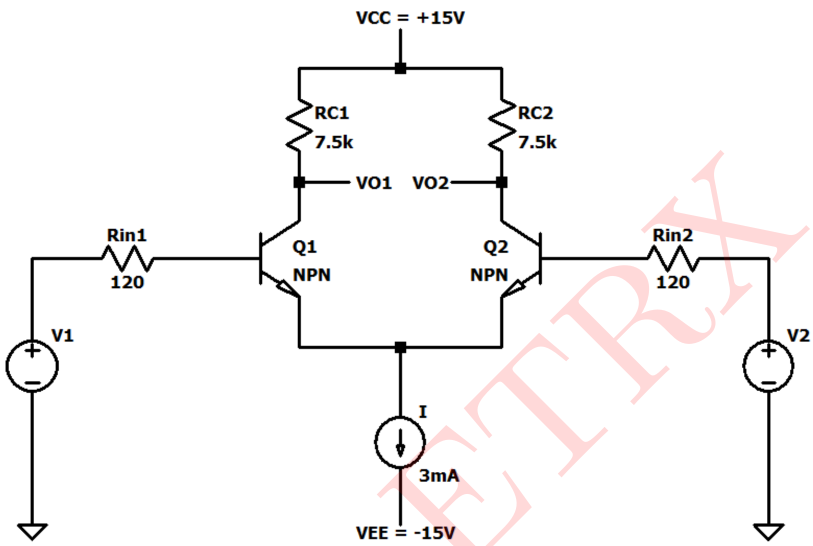

Figure 9: Circuit 3

Solution:

$I_{E_1} = I_{E_2} = \dfrac{I}{2} = \dfrac{3mA}{2} = 1.5mA$

Now, let $I_{C_1} = I_{E_1}$ & $I_{C_2} = I_{E_2}$

$\therefore I_{C_1} = I_{C_2} = \mathbf{1.5mA}$

DC value of $V_{o_1} = V_{CC} - I_{C_1}R_{C_1}$

DC value of $V_{o_2} = V_{CC} - I_{C_2}R_{C_2}$

Since, $R_{C_1} = R_{C_2}$ & $I_{C_1} = I_{C_2}$

$\therefore V_{o_1} = V_{o_2} = 15 - (1.5mA \times 7.5k\Omega)$

$\therefore V_{o_1} = V_{o_2} = \mathbf{3.75V}$

$V_{C_1} = V_{o_1}$ & $V_{C_2} = V_{o_2}$

$\therefore V_{C_1} = V_{C_2} = \mathbf{3.75V}$

Double ended output gain: A_d

$A_d = \dfrac{V_{o_1} - V_{o_2}}{V_1 - V_2}$

means output is between two collectors

[Assuming $V_{o_1} > V_{o_1}$; DIBO]

$$A_d = \frac{V_{o_1} - V_{o_2}}{V_1 - V_2} = \frac{-\beta R_C}{(r_\pi + R_{in})}$$

$$r_\pi = \frac{\beta V_T}{I_{CQ}} = \frac{100 \times 26mV}{1.5mA} = \mathbf{1.733k\Omega}$$

$$A_d = \frac{-100 \times 7.5k\Omega}{(1.733k\Omega + 120\Omega)} = \mathbf{-404.749}$$

SIMULATED RESULTS

The above circuit is simulated in LTspice and results are presented below:

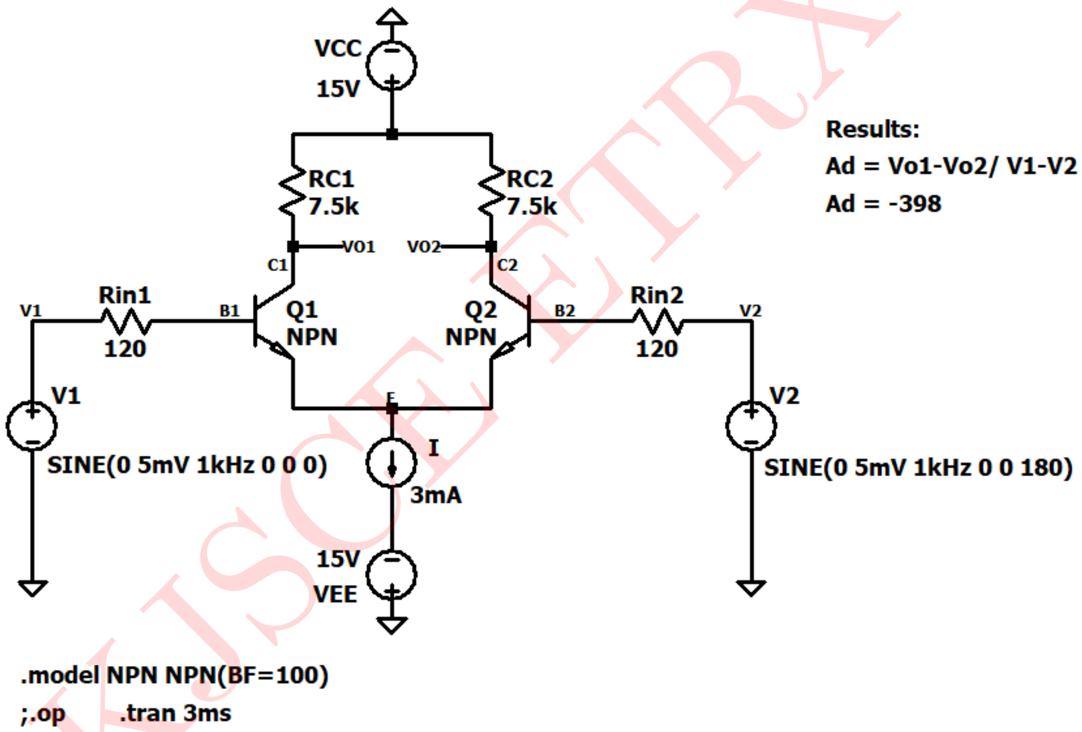

Figure 10: Circuit Schematic

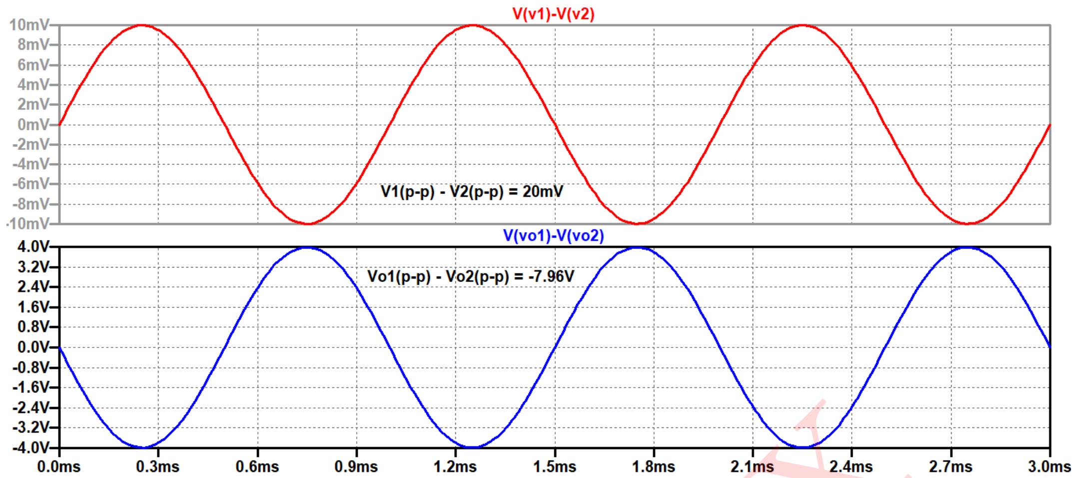

Figure 11: Input and Output waveform

Comparison of Theoretical and Simulated results:

Parameters	Theoretical	Simulated
I_{C_1}, I_{C_2}	$1.5mA$, $1.5mA$	$1.485A$, $1.485\mu A$
V_{C_1}, V_{C_2}	$3.75V$, $3.75V$	$3.86V$, $3.86V$
Differential Voltage gain: A_d	-404.749	-398

Table 3: Numerical 3

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