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: I_{C_1}, I_{C_2}, V_{C_1}, V_{C_2}, V_{CE_1}, V_{CE_2}, differential voltage gain: A_d, common mode gain: A_{cm} and CMRR in dB. Assume $\beta_1 = \beta_2 = 100$

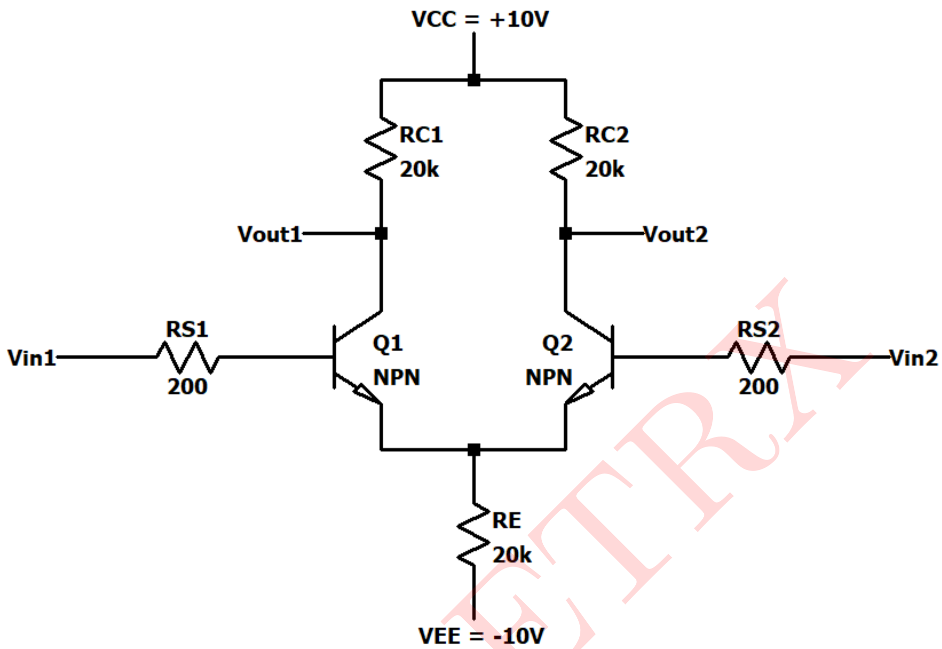

Figure 1: Circuit 1

Solution:

The given circuit 1 is a dual input balanced output (DIBO) configuration differential amplifier.

For DC Analysis, consider only one transistor as both the transistors are identical.

DC Analysis:

Applying KVL at the B-E loop,

$R_{S_1}I_{B_1} - V_{BE} - 2R_EI_E - V_{EE} = 0$

$I_{B_1}R_{S_1} + (1+\beta)I_{B_1}2R_E = -V_{EE} - V_{BE}$

$$I_{B_1} = \frac{-V_{EE} - V_{BE}}{R_{S_1} + (1+\beta)2R_E}$$

$$I_B = \frac{10 - 0.7}{200 + (1+100) \times 2 \times 20 \times 10^3} = \mathbf{2.3\ \mu A}$$

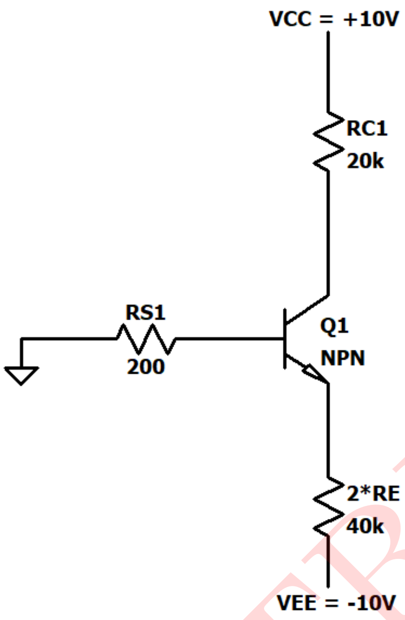

Figure 2: DC Equivalent Circuit

$I_{C_1} = \beta I_{B_1}$

$I_{CQ} = 100 \times 2.3 \times 10^{-6} = \mathbf{0.23\ mA}$

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

$I_E = (1+100) \times 2.3 \times 10^{-6} = \mathbf{0.23\ mA}$

As both the transistors are identical,

$I_{C_1} = I_{C_2} = \mathbf{0.23\ mA}$

$I_{E_1} = I_{E_2} = \mathbf{0.23\ mA}$

$V_{C_1} = V_{CC} - I_{C_1} R_{C_1} = 0$

$V_{C_1} = 10 - 0.23 \times 10^{-3} \times 20 \times 10^3 = \mathbf{5.4\ V}$

Applying KVL at C-E loop,

$V_{CC} - I_C R_{C_1} - V_{CE_1} - I_{E_1} 2R_{E_1} - V_{EE} = 0$

$V_{CE_1} = V_{CC} - I_{C_1} R_{C_1} - I_{E_1} 2R_{E_1} - V_{EE}$

$V_{CE_1} = 10 - 0.23 \times 10^{-3} \times 20 \times 10^3 - 0.23 \times 10^{-3} \times 20 \times 10^3 \times 2 + 10 = \mathbf{6.2\ V}$

As both the transistors are identical,

$V_{C_1} = V_{C_2} = \mathbf{5.4\ V}$

$V_{CE_1} = V_{CE_2} = \mathbf{6.2\ V}$

AC Analysis:

$$r_\pi = \frac{\beta V_T}{I_C}$$

$$r_o = \frac{100 \times 26 \times 10^{-3}}{0.23 \times 10^{-3}} = \mathbf{11.304\ k\Omega}$$

$$|A_d| = \frac{\beta R_C}{(r_\pi + R_S)}$$

$$|A_d| = \frac{100 \times 20 \times 10^3}{(11.304 \times 10^3 + 200)} = \mathbf{173.85}$$

$$A_{cm} = \left|\frac{R_C}{2R_E}\right| = \frac{20 \times 10^3}{2 \times 20 \times 10^3} = \mathbf{0.5}$$

$$\text{CMRR} = \left|\frac{A_d}{A_{cm}}\right| = \frac{173.85}{0.5} = \mathbf{347.7}$$

CMRR in dB $= 20log_{10}(347.7) = \mathbf{50.824\ dB}$

SIMULATED RESULTS:

Above circuit is simulated in LTspice. The results are presented below:

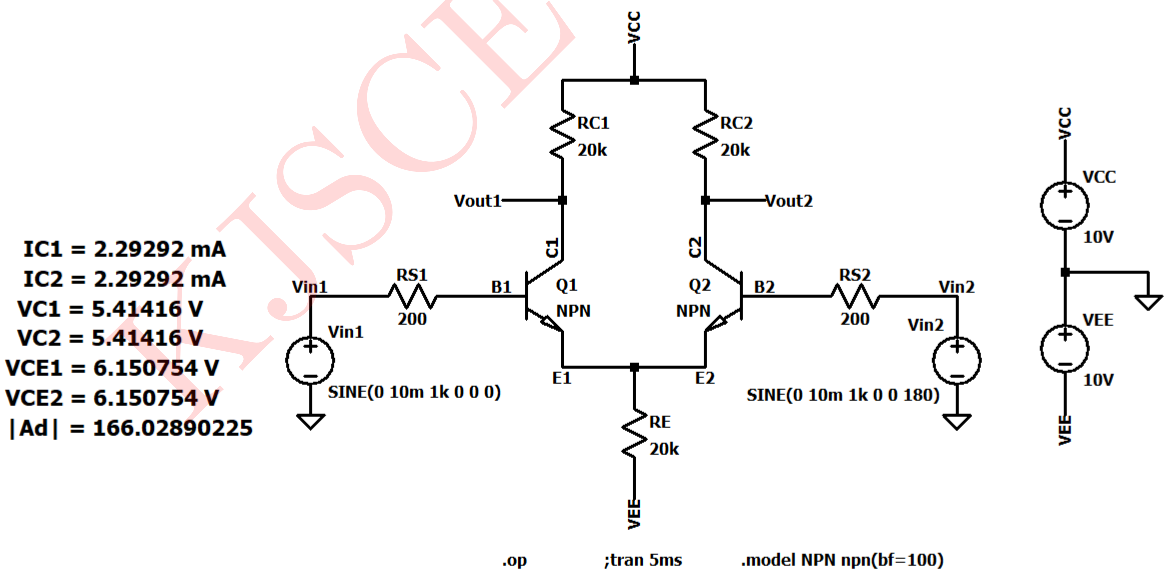

Figure 3: Circuit Schematic 1: Results

The input and output waveforms are shown in figure 4.

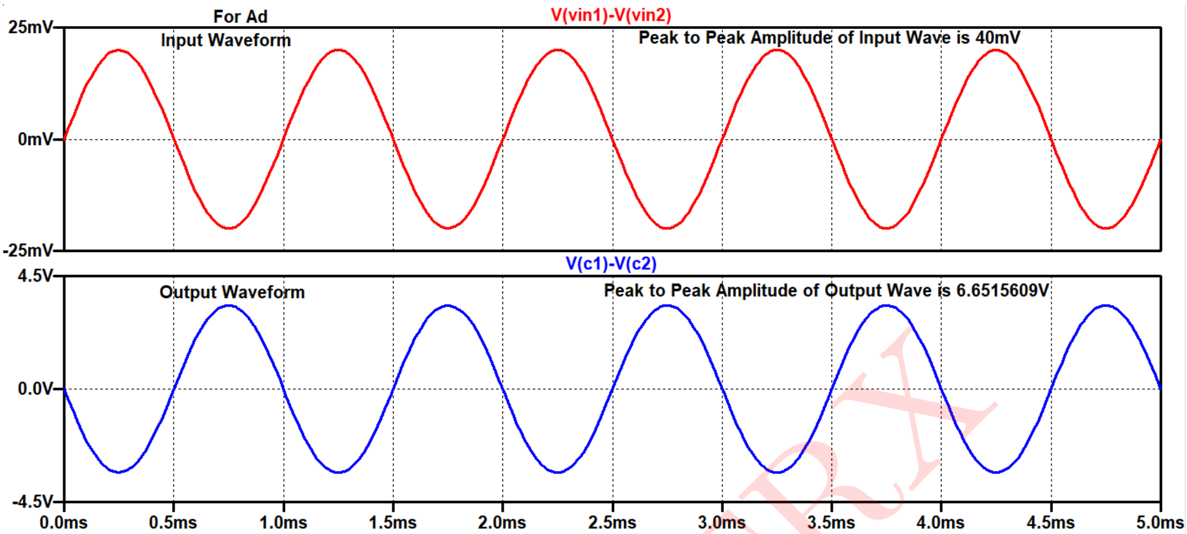

Figure 4: Input & Output waveforms

Comparison of theoretical and simulated values:

Parameters	Theoretical Values	Simulated Values
I_{C_1}	0.23 mA	0.22929 mA
I_{C_2}	0.23 mA	0.22929 mA
V_{C_1}	5.4 V	5.41416 V
V_{C_2}	5.4 V	5.41416 V
V_{CE_1}	6.2 V	6.1507 V
V_{CE_2}	6.2 V	6.1507 V
Differential voltage gain: $\lvert A_d \rvert$	173.85	166.2890
Common mode voktage gain: A_{cm}	0.5	–
CMRR is dB	50.824 dB	–

Table 1: Numerical 1

Numerical 2: Consider the circuit given in figure 5, the transistor parameters are $k_{n_1} = k_{n_2} = 50\ \mu A/V^2$, $\lambda_1 = \lambda_2 = 0.02\ V^{-1}$ & $V_{TN_1} = V_{TN_2} = 1$ V. Determine I_S, I_{D_1}, I_{D_2}, V_{D_1}, V_{D_2}, V_{DS_1}, V_{DS_2}. Calculate differential mode voltage gain: A_{d_1} common mode gain: A_{cm} and CMRR in dB.

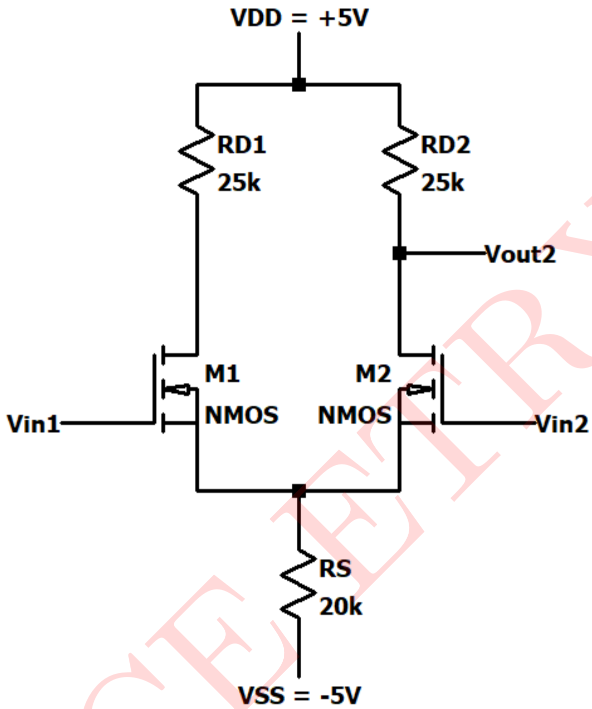

Figure 5: Circuit 2

Solution:

The given circuit 2 is a dual input unbalanced output (DIUO) differential amplifier.

For DC Analysis, consider only one transistor as both the transistors are identical.

DC Analysis:

Applying KVL at the G-S loop,

$-V_{GS_1} - 2I_{D_1}R_S - V_{SS} = 0$

$V_{GS_1} = -V_{SS} - 2I_{D_1}R_S$

$V_{GS_1} = 5 - 2I_{D_1}20 \times 10^3$

$V_{GS_1} = 5 - I_{D_1}40 \times 10^3 \qquad ...(1)$

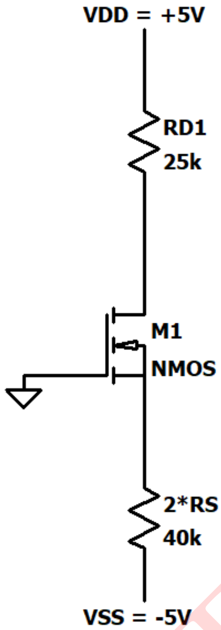

Figure 6: DC Equivalent Circuit

Applying KVL at the D-S loop,

$V_{DD} - I_{D_1}R_{D_1} - V_{DS_1} - I_{D_1}2R_S - V_{SS} = 0$

$V_{DS_1} = V_{DD} - I_{D_1}R_{D_1} - I_{D_1}2R_S - V_{SS}$

$V_{DS_1} = 5 - I_{D_1}25 \times 10^3 - I_{D_1}40 \times 10^3 + 5$

$V_{DS_1} = 10 - I_{D_1}65 \times 10^3$ ...(2)

From current equation,

$I_{D_1} = k_n(V_{GS_1} - V_{TN})^2(1 + \lambda V_{DS_1})$

$I_{D_1} = 50 \times 10^{-6}(5 - I_{D_1}40 \times 10^3 - 1)^2 \times (1 + 0.02(10 - I_{D_1}65 \times 10^3))$

$I_{D_1} = 50 \times 10^{-6}(4 - I_{D_1}40 \times 10^3)^2 \times (1 + 0.2 - I_{D_1}1.3 \times 10^3)$

$I_{D_1} = 50 \times 10^{-6}(4 - I_{D_1}40 \times 10^3)^2 \times (1.2 - I_{D_1}1.3 \times 10^3)$

$I_{D_1} = 50 \times 10^{-6}(16 - I_{D_1}320 \times 10^3 + I_{D_1}^2 1600 \times 10^6) \times (1.2 - I_{D_1}1.3 \times 10^3)$

$I_{D_1} = 50 \times 10^{-6}(19.2 - I_{D_1}384 \times 10^3 + I_{D_1}^2 1920 \times 10^6 - I_{D_1}20.8 \times 10^3 + I_{D_1}^2 416 \times 10^6 - I_{D_1}^3 2080 \times 10^9)$

$I_{D_1} = 50 \times 10^{-6}(19.2 - I_{D_1}404.8 \times 10^3 + I_{D_1}^2 2336 \times 10^6 - I_{D_1}^3 2080 \times 10^9)$

$I_{D_1} = 9.6 \times 10^{-4} - I_{D_1}20.24 + I_{D_1}^2 116.8 \times 10^3 - I_{D_1}^3 104 \times 10^6$

$I_{D_1}^3 104 \times 10^6 - I_{D_1}^2 116.8 \times 10^3 + I_{D_1}21.24 - 9.6 \times 10^{-4} = 0$

$I_{D_1} = \mathbf{9.09 \times 10^{-4}\ A}$ or $I_{D_1} = \mathbf{1.41 \times 10^{-4}\ A}$ or $I_{D_1} = \mathbf{7.15 \times 10^{-5}\ A}$

Let, $I_{D_1} = 9.09 \times 10^{-4}$ A

$V_{GS_1} = 5 - 9.09 \times 10^{-4} \times 40 \times 10^3 = \mathbf{-31.36\ V}$

Let, $I_{D_1} = 1.41 \times 10^{-4}$ A

$V_{GS_1} = 5 - 1.41 \times 10^{-4} \times 40 \times 10^3 = \mathbf{-0.64\ V}$

Let, $I_{D_1} = 7.15 \times 10^{-5}$ A

$V_{GS_1} = 5 - 7.15 \times 10^{-5} \times 40 \times 10^3 = \mathbf{2.14\ V}$

V_{GS_1} cannot be negative and V_{GS_1} should be greater than V_{TN_1}

$V_{GS_1} = 2.14$ V

$I_{D_1} = 7.15 \times 10^{-5}$ A

$I_{D_1} = \mathbf{0.0715\ mA}$

$V_{DS_1} = 10 - 0.0715 \times 10^{-3} \times 65 \times 10^3 = \mathbf{5.3525\ V}$

$V_{D_1} = V_{DD} - I_{D_1} R_{D_1}$

$V_{D_1} = 5 - 0.0715 \times 10^{-3} \times 25 \times 10^3 = \mathbf{3.2125\ V}$

As both the transistors are identical,

$I_{D_1} = I_{D_2} = \mathbf{0.0715\ mA}$

$V_{DS_1} = V_{DS_2} = \mathbf{5.3525\ V}$

$V_{D_1} = V_{D_2} = \mathbf{3.2125\ V}$

$I_S = 2 \times I_{D_1}$

$I_S = 2 \times 0.0715 \times 10^{-3} = \mathbf{0.143\ mA}$

AC Analysis:

$g_{m_1} = 2k_n(V_{GS_1} - V_{TN_1})(1 + \lambda V_{DS_1})$

$g_{m_1} = 2 \times 50 \times 10^{-6}(2.14 - 1)(1 + 0.02 \times 5.3525) = \mathbf{0.126\ mA/V}$

$$r_{d_1} = \frac{1}{\lambda I_{D_1}}$$

$$r_{d_1} = \frac{1}{0.02 \times 0.0715 \times 10^{-3}} = \mathbf{699.3\ k\Omega}$$

As both the transistors are identical,

$g_{m_1} = g_{m_2} = \mathbf{0.126\ mA/V}$

$r_{d_1} = r_{d_2} = \mathbf{699.3\ k\Omega}$

$$|A_d| = \frac{g_m(r_d \ || \ R_D)}{2}$$

$$|A_d| = \frac{0.126 \times 10^{-3}(699.3 \times 10^3 \ || \ 25 \times 10^3)}{2} = \mathbf{1.52}$$

$$A_{cm} = \frac{g_m(r_d \ || \ R_D)}{1 + 2g_m R_S}$$

$$A_{cm} = \frac{0.126 \times 10^{-3}(699.3 \times 0^3 \ || \ 25 \times 10^3)}{1 + 2 \times 0.126 \times 10^{-3} \times 20 \times 10^3} = \mathbf{0.503}$$

$$\text{CMRR} = \left|\frac{A_d}{A_{cm}}\right| = \frac{1.52}{0.503} = \mathbf{3.02}$$

$$\text{CMRR in dB} = 20log_{10}(3.02) = \mathbf{9.6\ dB}$$

SIMULATED RESULTS:

Above circuit is simulated in LTspice. The results are presented below:

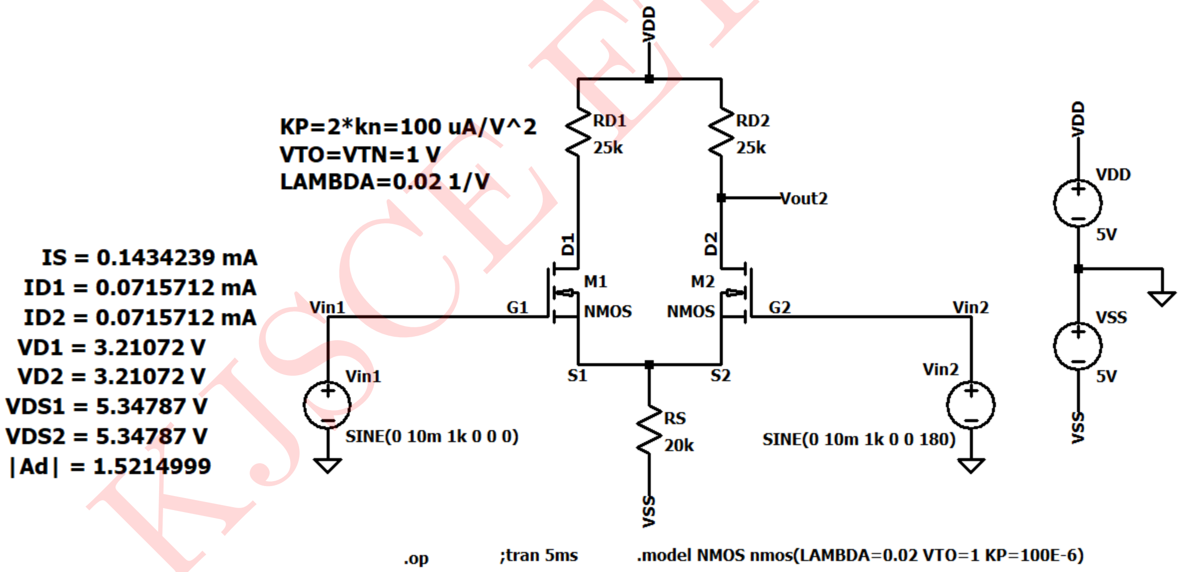

Figure 7: Circuit Schematic 2: Results

The input and output waveforms are shown in figure 8.

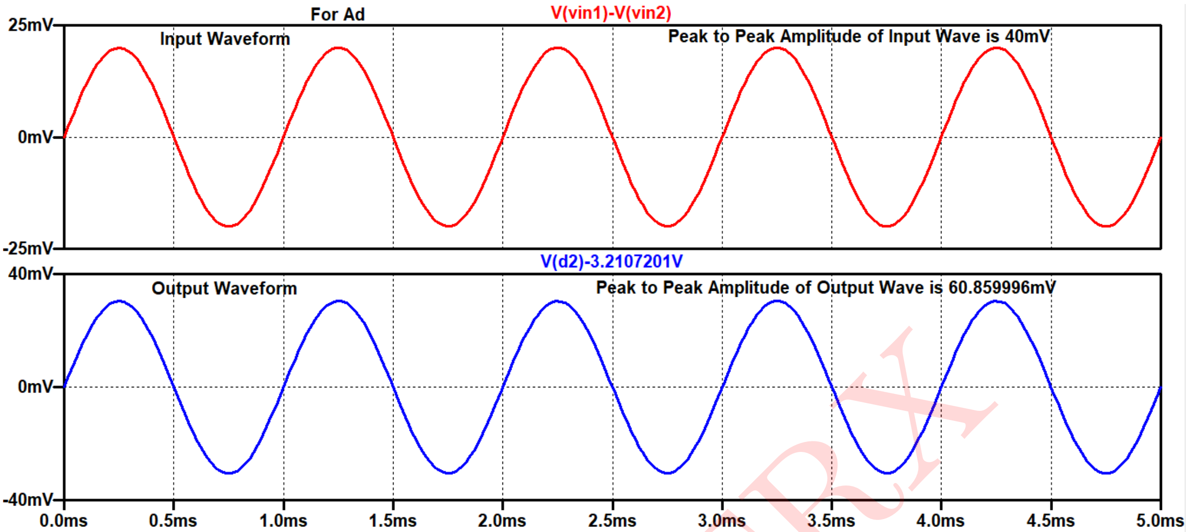

Figure 8: Input & Output waveforms

Comparison of theoretical and simulated values:

Parameters	Theoretical Values	Simulated Values
I_S	0.143 mA	0.1434 mA
I_{D_1}	0.0715 mA	0.0715 mA
I_{D_2}	0.0715 mA	0.715 mA
V_{D_1}	3.2125 V	3.2107 V
V_{D_2}	3.2125 V	3.2107 V
V_{DS_1}	5.3525 V	5.3478 V
V_{DS_2}	5.3525 V	5.3478 V
Differential voltage gain: $\|A_d\|$	1.52	1.5214
Common mode voktage gain: A_{cm}	0.503	–
CMRR is dB	9.6 dB	–

Table 2: Numerical 2

Numerical 3: Determine the following for the differential amplifier shown in figure 9:

a) I_{C_1}, I_{C_2}, V_{C_1}, V_{C_2}

b) Single ended output gain $\left(\dfrac{V_{o_1}}{V_{i_1} - V_{i_2}}\right)$

Given $\beta_1 = \beta_2 = 100$

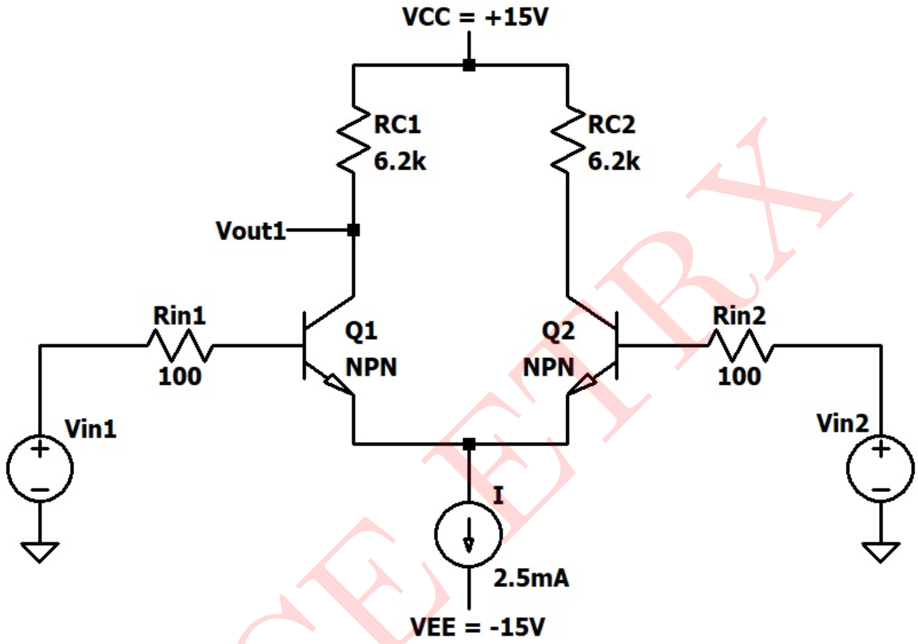

Figure 9: Circuit 3

Solution:

The given circuit 3 is a dual input unbalanced output (DIUO) differential amplifier.

a) As there is a current source at terminal E,

$$I_{E_1} = I_{E_2} = \frac{I}{2} = \frac{2.5 \times 10^{-3}}{2}$$

$I_{E_1} = I_{E_2} = \mathbf{1.25\ mA}$

$$I_{B_1} = \frac{I_{E_1}}{1+\beta} = \frac{1.25 \times 10^{-3}}{101} = \mathbf{12.3\ \mu A}$$

$$I_{C_1} = \beta I_{B_1} = 100 \times 12.3 \times 10^{-6} = \mathbf{1.23\ mA}$$

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

$\therefore I_{C_1} = I_{C_2} = \mathbf{1.23\ mA}$

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

$V_{C_1} = 15 - 1.23 \times 10^{-3} \times 6.2 \times 10^{3} = \mathbf{7.374\ V}$

$V_{C_1} = V_{C_2} = \mathbf{7.374}$

b) $|A_d| = \dfrac{V_{o_1}}{V_{in_1} - V_{in_2}} = \dfrac{\beta R_C}{2(r_\pi + R_{in})}$

where, $r_\pi = \dfrac{\beta V_T}{I_{CQ}} = \dfrac{100 \times 26 \times 10^{-3}}{1.23 \times 10^{-3}} = \mathbf{2.11\ k\Omega}$

$|A_d| = \dfrac{100 \times 6.2 \times 10^{-3}}{2(2.11 \times 10^{3} + 100)} = \mathbf{140.27}$

SIMULATED RESULTS:

Above circuit is simulated in LTspice. The results are presented below:

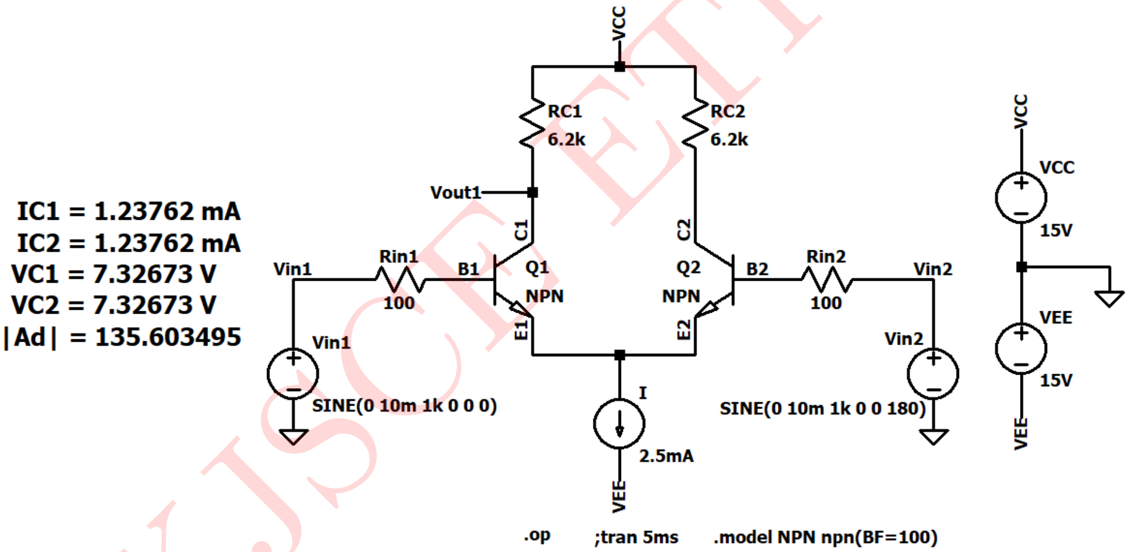

Figure 10: Circuit Schematic 3: Results

The input and output waveforms are shown in figure 11.

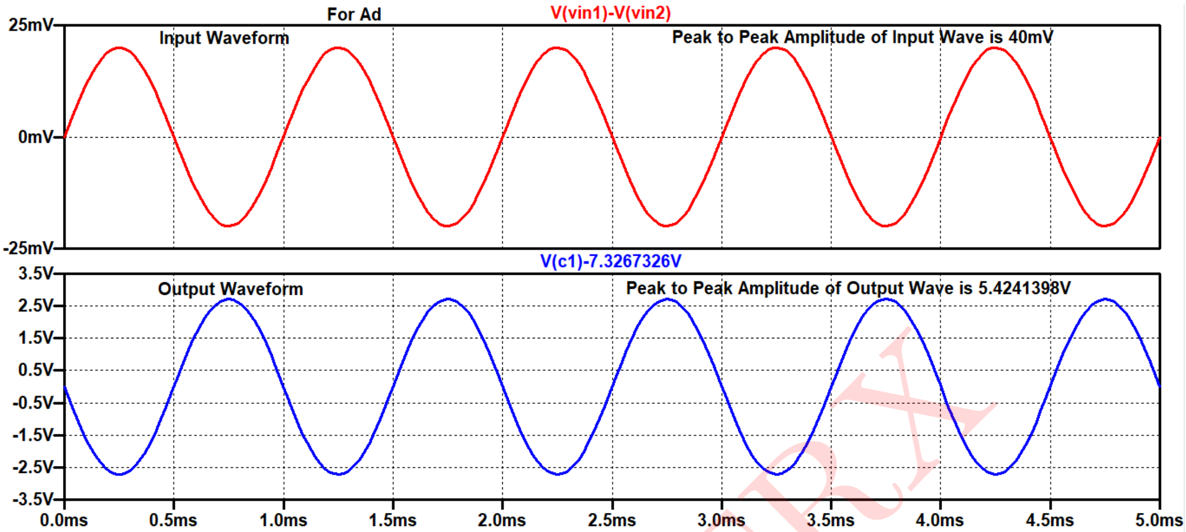

Figure 11: Input & Output waveforms

Comparison of theoretical and simulated values:

Parameters	Theoretical Values	Simulated Values
I_{C_1}	1.23 mA	1.2376 mA
I_{C_2}	1.23 mA	1.2376 mA
V_{C_1}	7.374 V	7.3267 V
V_{C_2}	7.374 V	7.3267 V
Differential voltage gain: $\|A_d\|$	140.27	135.6034

Table 3: Numerical 3

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