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DEPARTMENT OF ELECTRONICS ENGINEERING
ELECTRONIC CIRCUITS
DIFFERENTIAL AMPLIFIER CIRCUITS

16^{th} **July, 2020** **Numerical**

1. Determine the following for the circuit shown in Figure 1
   Assume $\beta_1 = \beta_2 = 100$
   a) Name the circuit
   b) Current flowing through resistors R_{S_1}, R_{S_2} and R_{C_2}
   c) Find V_{C_1}, V_{C_2}, V_{CE_1} and V_{CE_2}
   d) Differential voltage gain
   e) Common mode gain
   f) CMRR in dB

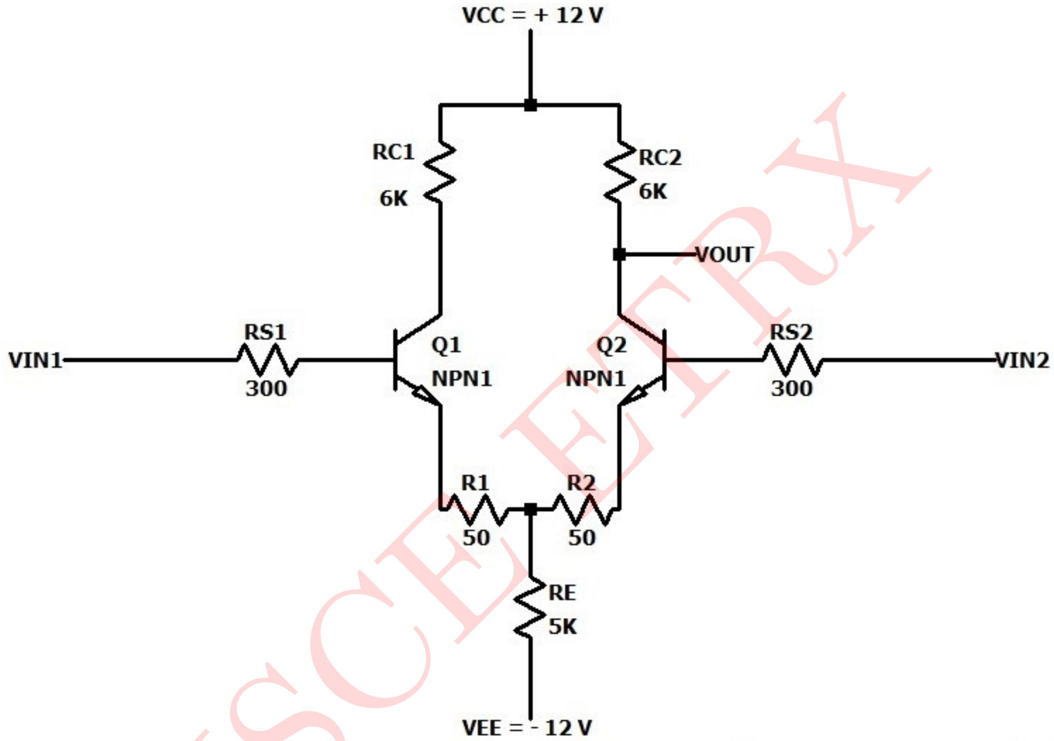

Figure 1: Circuit 1

Solution:

a) The above circuit is a DIUO differential amplifier.

b) **DC analysis:**

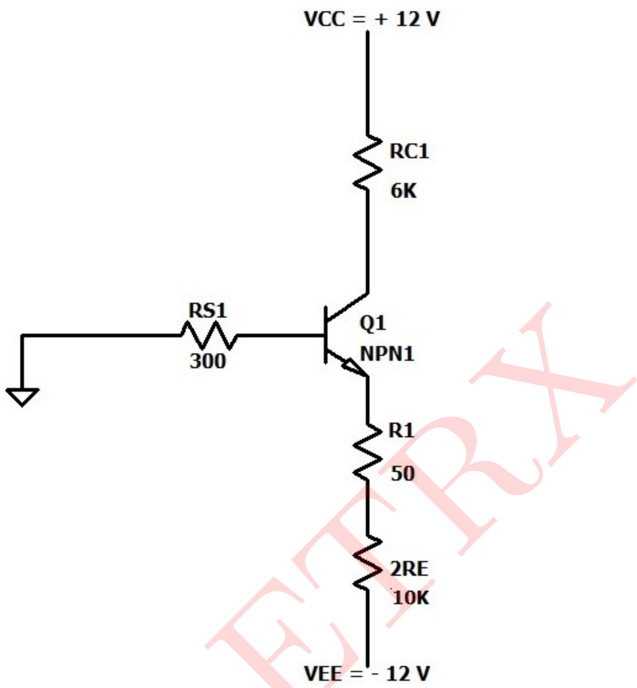

Figure 2: DC equivalent circuit

Applying KVL to the input base-emitter loop, we get

$V_{EE} - I_{BQ}R_{S_1} - V_{BE} - (1+\beta)R_1 I_{BQ} - 2(1+\beta)R_E I_{BQ} = 0$

$I_{BQ} = \dfrac{V_{EE} - V_{BE}}{R_{S_1} + (1+\beta)(R_1 + 2R_E)}$

$\therefore I_{BQ} = 11.129\ \mu\text{A}$

$I_{CQ_1} = I_{CQ_2} = I_{CQ} = \beta \times I_{BQ} = \mathbf{1.112916\ mA}$

c) Applying KVL at output collector-emitter loop, we get

$V_{CEQ} = V_{CC} + V_{EE} - I_{CQ}(R_C + 2R_E + R_1)$

$V_{CEQ} = 12 + 12 - (1.12916 \times 10^{-3}) \times (6k + 10k + 50)$

$\therefore V_{CEQ} = V_{CEQ_1} = V_{CEQ_2} = \mathbf{6.137955\ V}$

Q-point $(I_{CQ_1}, V_{CEQ_1}) = (1.112916\ \text{mA},\ 6.137955\ \text{V})$

$V_C = V_{C_1} = V_{C_2} = V_{CC} - I_C R_C = 12 - (1.12916 \times 10^{-3} \times 6k) = \mathbf{5.3225\ V}$

d) $r_\pi = \dfrac{\beta V_T}{I_{CQ}} = \dfrac{100 \times 26 \times 10^{-3}}{1.112916 \times 10^{-3}} = 2.336205\ \text{k}\Omega$

$$A_d = \frac{\beta R_C}{2(r_\pi + R_S + \beta R_1)} = \mathbf{39.2865}$$

e) $A_{cm} = \left|\frac{R_C}{2R_E}\right| = \left|\frac{6k}{2 \times 5k}\right| = \mathbf{0.6}$

f) $\text{CMRR} = \left|\frac{A_d}{A_{cm}}\right| = 65.4775$

CMRR in dB $= 20\ log_{10}\left(\frac{A_d}{A_{cm}}\right) = 20\ log_{10}(65.4775) = \mathbf{36.32184178\ dB}$

SIMULATED RESULTS:
Above circuit is simulated using LTspice and the results are presented below:

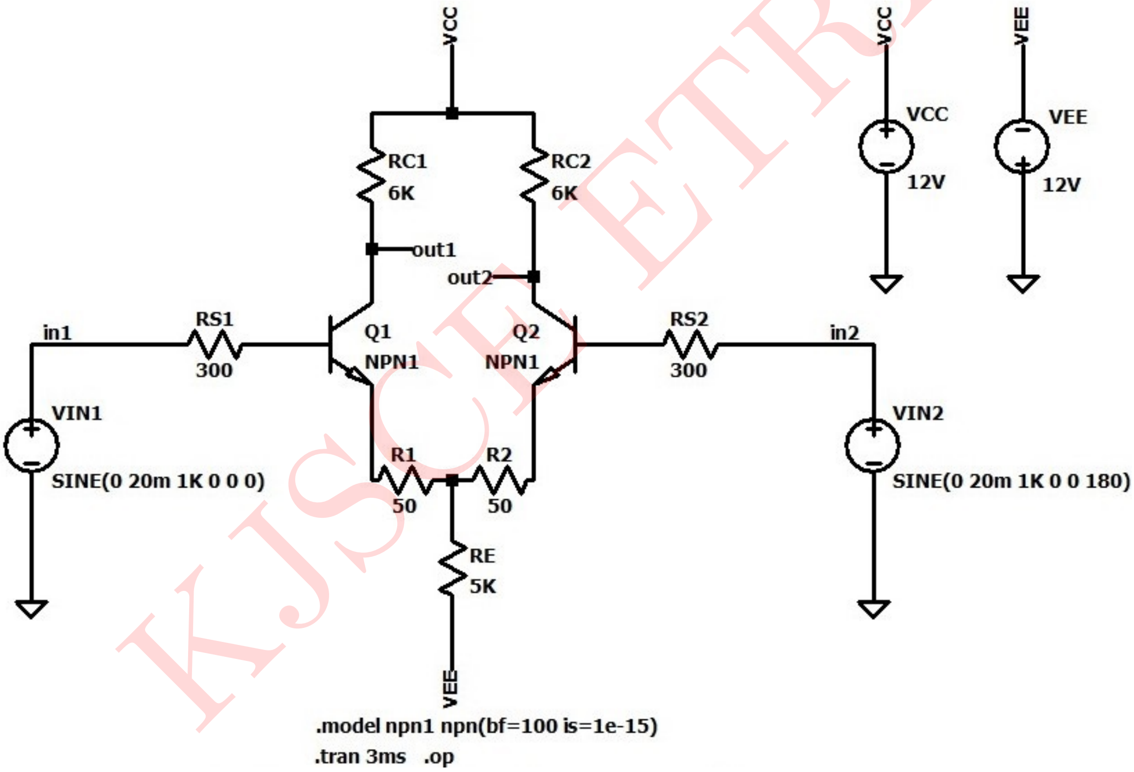

Figure 3: Circuit schematic

The waveforms for input and output voltage are shown in Figure 4

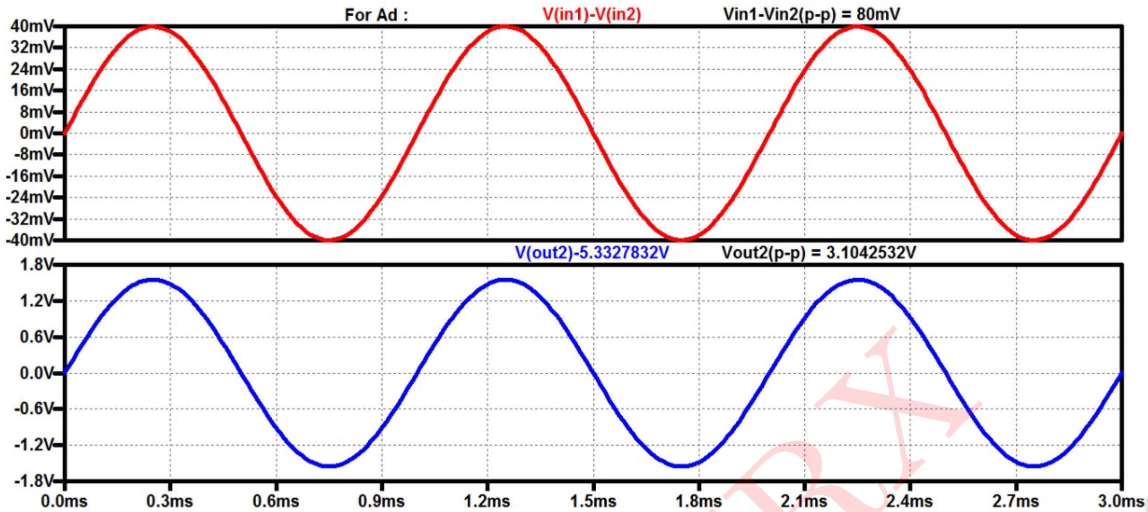

Figure 4: Input and output voltage waveforms

Comparison of theoretical and simulated values:

Parameters	Theoretical	Simulated
I_{C1}, I_{C2}	1.112916 mA	1.1112 mA
V_{C_1}, V_{C_2}	5.3225 V	5.33278 V
V_{CE_1}, V_{CE_2}	6.137955 V	6.053516 V
Differential voltage gain A_d	39.2865	38.803
Common mode voltage gain A_{cm}	0.6	–
CMRR in dB	36.3218 dB	–

Table 1: Numerical 1

2. Consider the differential amplifier in Figure 5.
   The transistor parameters are: $k_{n_1} = k_{n_2} = 40\ \mu A/V^2$, $V_{TN_1} = V_{TN_2} = 0.8$ V, $\lambda = 0.02V^{-1}$
   a) Determine I_S, I_{D_1}, I_{D_2}, V_{D_1}, V_{D_2}, V_{DS_1}, V_{DS_2}
   b) Differential voltage gain A_d
   c) Common mode voltage gain A_{cm}
   d) CMRR in dB

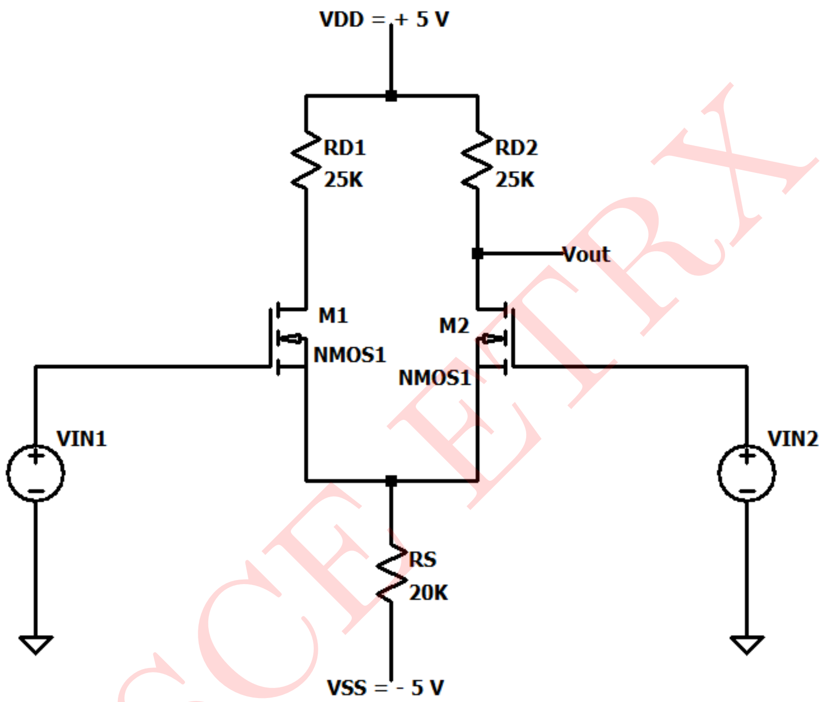

Figure 5: Circuit 2

Solution:

The above circuit is a DIUO mosfet differential amplifier.

For DC analysis, we consider only one transistor, as both transistors are identical.

b) **DC analysis:**

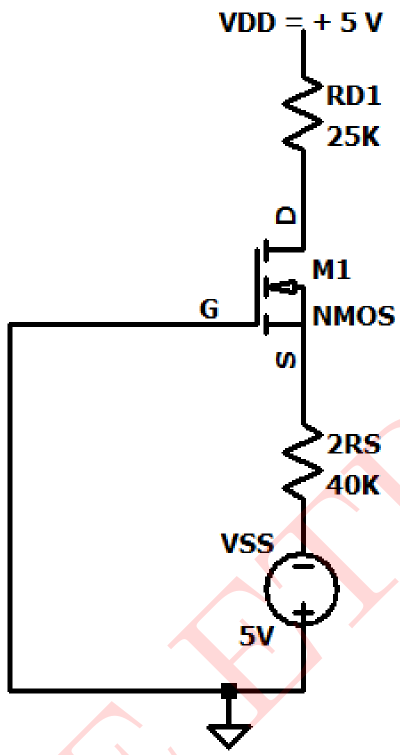

Figure 6: DC equivalent circuit

Applying KVL to the gate-source loop, we get

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

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

$V_{GS_1} = 5 - 2I_{D_1}(20k)$ ....(1)

Applying KVL at drain-source loop

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

$V_{DS_1} = 5 - I_{D_1}(25k) - I_{D_1}(40k) + 5$

$V_{DS_1} = 10 - I_{D_1}(65k)$ ....(2)

$I_{D_1} = k_n(V_{GS_1} - V_{TN_1})^2(1 + \lambda V_{DS_1})$

$I_{D_1} = 40 \times 10^{-6}(5 - I_{D_1}(40k) - 0.8)^2(1 + 0.02(10 - I_{D_1}(65k)))$

$I_{D_1} = 40 \times 10^{-6}[21.168 - 403.2kI_{D_1} + (1920 \times 10^{-6})I_{D_1}^2 - I_{D_1}(22.932k) + (436.8 \times 10^{-6})I_{D_1}^2 - (2080 \times 10^9)I_{D_1}^3]$

$(83.2 \times 10^{-6})I_{D_1}^3 - 94.272kI_{D_1}^2 + 18.04528I_D - (8.467 \times 10^{-4}) = 0$

$\therefore I_{D_1} = 0.906106$ mA or 0.154076 mA or 0.0728939 mA

For $I_{D_1} = 0.906106$ mA, $V_{GS_1} = -31.2464$ V

For $I_{D_1} = 0.154076$ mA, $V_{GS_1} = -1.16304$ V

For $I_{D_1} = 0.0728939$ mA, $V_{GS_1} = 2.084244$ V

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

$\therefore V_{GS_1} = 2.084244$ V

$\therefore I_{D_1} = 0.0728939$ mA $= I_{D_2}$

$V_{DS_1} = V_{DS_2} = 10 - 0.0728939 \times 10^{-3} \times 65 \times 10^3 = 5.261955$ V

$V_{D_1} = V_{DD} - I_{D_1} R_{D_1} = V_{D_2} = 3.177675$ V

$I_S = I_{D_1} = 0.0728939$ mA

AC analysis:

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

$g_m = g_{m_1} = g_{m_2} = 2 \times 40 \times 10^{-6}(2.0842 - 0.8)(1 + 0.1052)$

$\therefore g_m = g_{m_1} = g_{m_2} = 0.113547$ mA/V

$$r_{d_2} = r_{d_1} = \frac{1}{\lambda I_{D_1}} = \frac{1}{0.02 \times 72.893 \times 10^{-6}} = 685.936 \text{ k}\Omega$$

$$|A_d| = \frac{g_m(r_d||R_D)}{2} = \frac{0.113547 \times 10^{-3} 685.936k||25k}{2} = 1.369422$$

$$|A_{cm}| = \frac{g_m(r_d||R_D)}{1 + 2g_m R_S} = 0.4942$$

$$\text{CMRR} = \left|\frac{A_d}{A_{cm}}\right| = \left|\frac{1.369}{0.4942}\right| = 2.770133$$

CMRR in dB $= 20\ log_{10}(2.770133) = 8.85$ dB

SIMULATED RESULTS:
Above circuit is simulated using LTspice and the results are presented below:

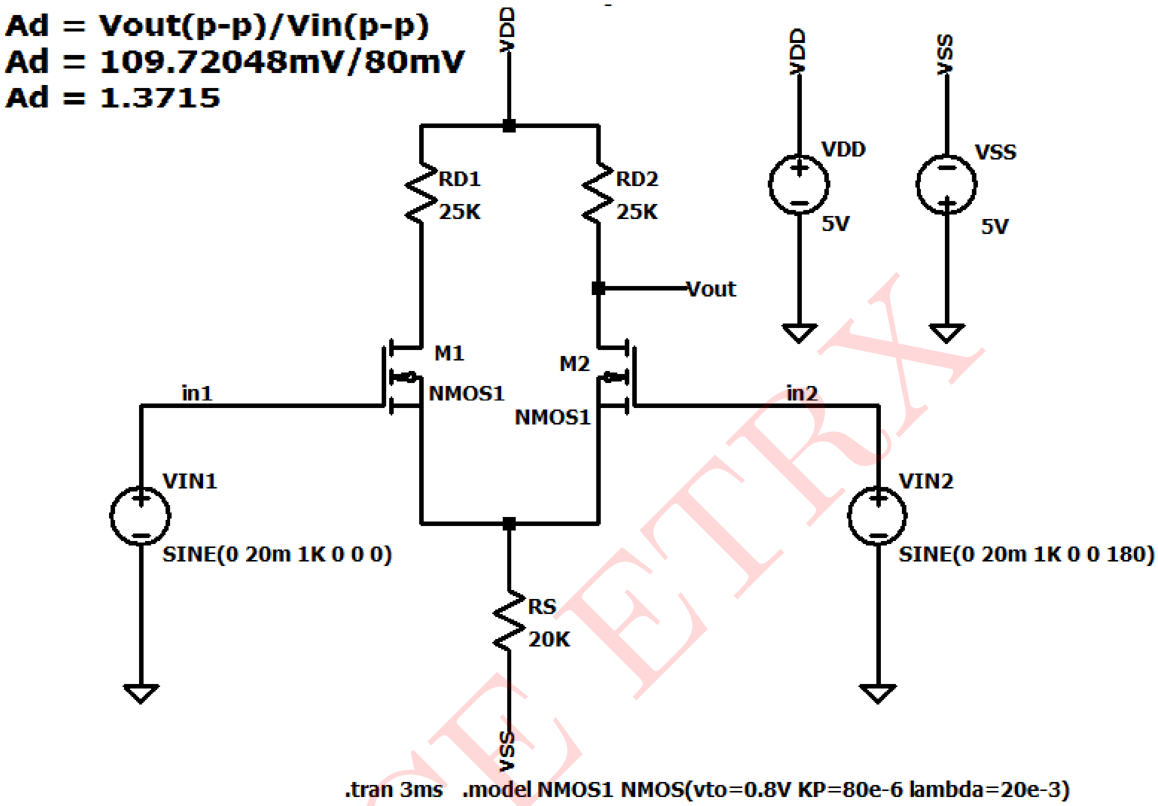

Figure 7: Circuit schematic

The waveforms for input and output voltage are shown in Figure 8

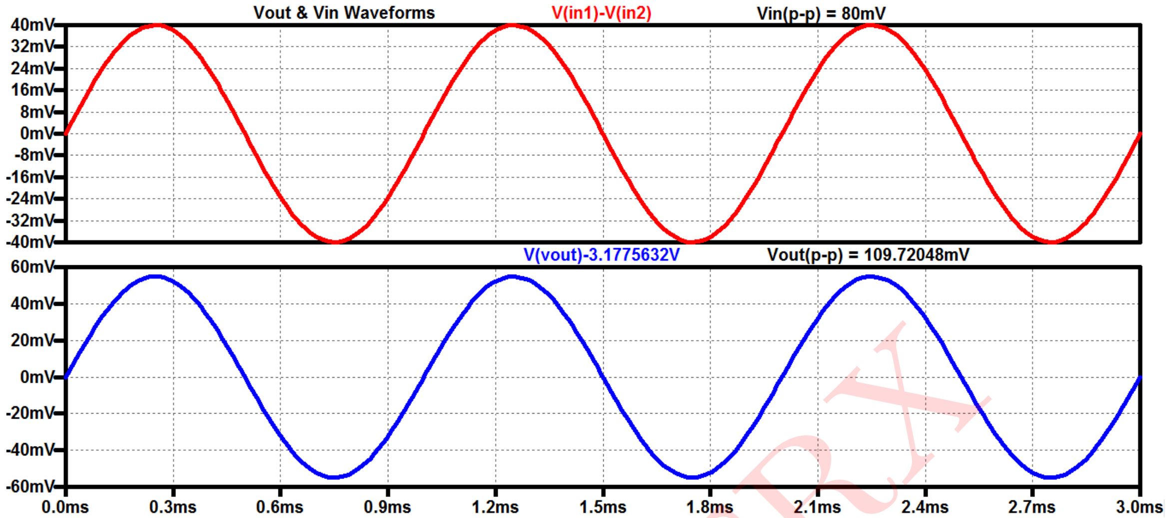

Figure 8: Input and output voltage waveforms

Comparison of theoretical and simulated values:

Parameters	**Theoretical**	**Simulated**
I_S	72.893 μA	72.8975 μA
I_{D_1}	72.893 μA	72.8975 μA
I_{D_2}	72.893 μA	72.8975 μA
V_{D_1}	3.177675 V	3.17756 V
V_{D_2}	3.177675 V	3.17756 V
V_{DS_1}	5.261955 V	5.26166 V
V_{DS_2}	5.261955 V	5.26166 V
Differential voltage gain $\|A_d\|$	1.369422	1.37
Common mode voltage gain A_{cm}	0.4942	–
CMRR in dB	8.85 dB	–

Table 2: Numerical 2

3. For the circuit shown in Figure 9, consider
$R_{C_1} = R_{C_2} = 5\ \text{k}\Omega$, current source $= 2.5$ mA and $R_{in} = 50\ \Omega$
Calculate
a) I_{C_1}, I_{C_2}
b) V_{C_1}, V_{C_2}
c) Differential voltage gain A_d

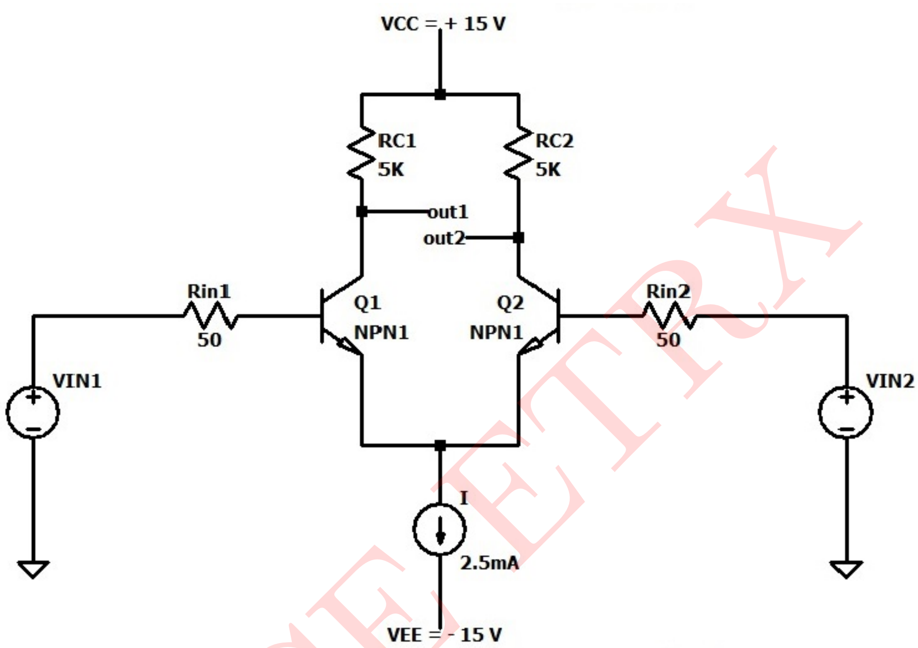

Figure 9: Circuit 3

Solution:

a) **DC Analysis:**

$$I_{E_1} = I_{E_2} = \frac{I}{2} = \frac{2.5 \times 10^{-3}}{2} = 1.25\ \text{mA}$$

$$I_E = I_C + I_B = I_C + \frac{I_C}{\beta} = I_C \left(1 + \frac{1}{\beta}\right)$$

$$\therefore I_{C_1} = \frac{I_{E_1}}{\left(1 + \dfrac{1}{\beta_1}\right)} = \frac{1.25 \times 10^{-3}}{1 + 0.01}$$

$$\therefore I_{C_1} = I_{C_2} = \mathbf{1.2376\ mA}$$

b) DC value of $V_{o_1} = V_{CC} - I_{C_1} R_C = V_{C_1} = 15 - (1.25 \times 10^{-3} \times 5k)$

$$\therefore V_{C_1} = \mathbf{8.75\ V}$$

$$V_{o_2} = V_{CC} - I_{C_2} R_{C_2} = V_{C_2} = 15 - (1.25 \times 10^{-3} \times 5k)$$

$$\therefore V_{C_2} = \mathbf{8.75\ V}$$

c) Output is being taken from collector of transistor Q_1

Assuming $V_{o_2} > V_{o_1}$,

$$A_d = \frac{V_{o_1}}{V_1 - V_2} = \frac{-\beta R_C}{2(r_\pi + R_{in})}$$

$$r_\pi = \frac{\beta V_T}{I_{CQ}} = \frac{100 \times 26 \times 10^{-3}}{1.2376 \times 10^{-3}} = 2.1008\ \text{k}\Omega$$

$$\therefore A_d = \frac{-100 \times 5k}{2(2.1008k + 50)} = -\mathbf{116.2358}$$

SIMULATED RESULTS:

Above circuit is simulated using LTspice and the results are presented below:

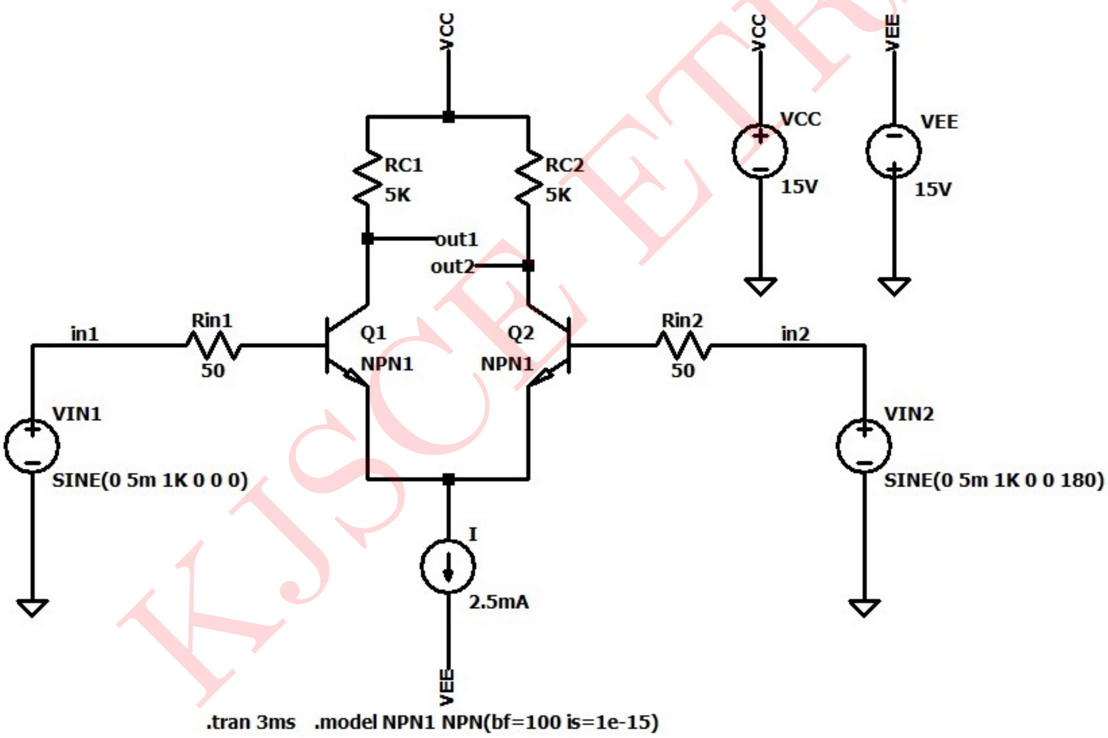

Figure 10: Circuit schematic

The waveforms for input and output voltage are shown in Figure 11

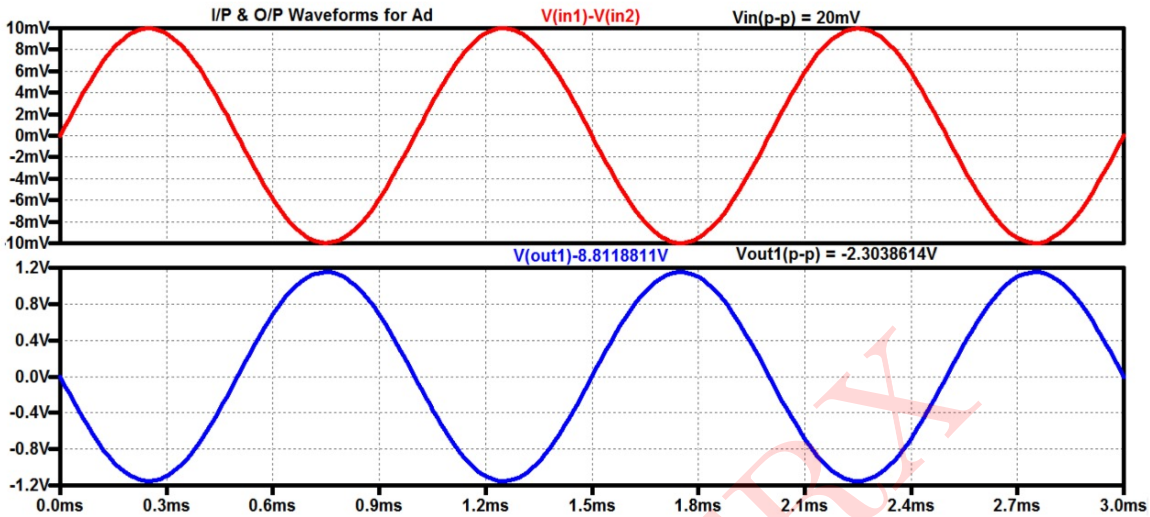

Figure 11: Input and output voltage waveforms

Comparison of theoretical and simulated values:

Parameters	Theoretical	Simulated
I_{C_1}, I_{C_2}	1.2376 mA	1.23762 mA
V_{C_1}, V_{C_2}	8.75 V	8.81188 V
Differential voltage gain A_d	-116.2358	-115.19307

Table 3: Numerical 3