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ELECTRONIC CIRCUITS
Differential Amplifier Circuits

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Numerical 1:
For the differential amplifier shown in figure 1, $\beta = 100$, find:
a. Name of the circuit
b. Differential voltage gain
c. Common mode gain
d. CMRR

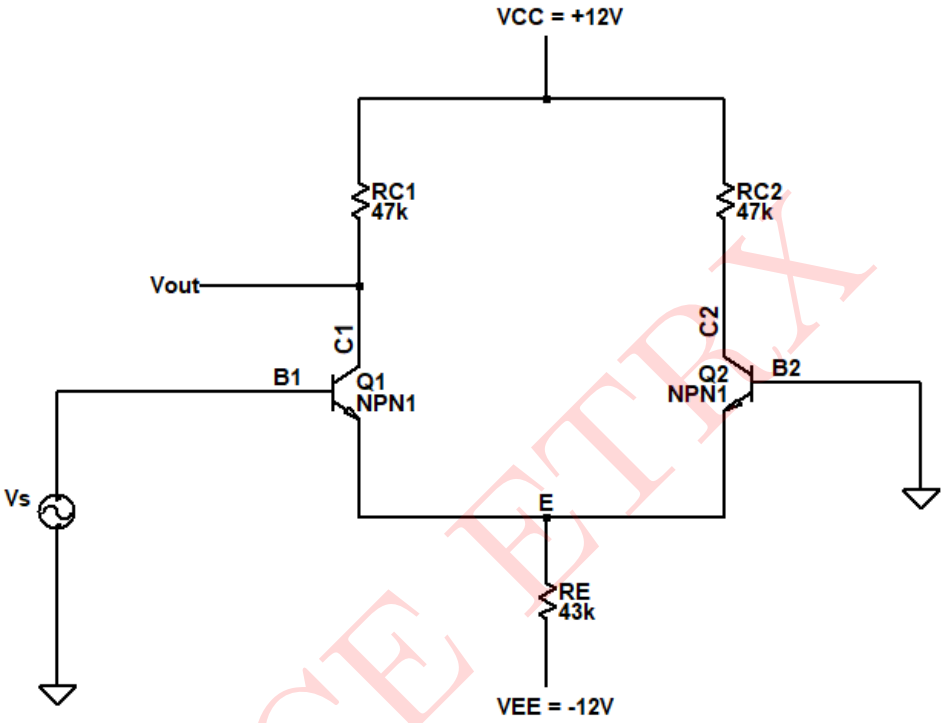

Figure 1: Circuit diagram

Solution: Circuit shown in figure 1 is a single input unbalanced output (SIUO) differential amplifier.

DC Analysis: Considering all the internal and external parameters same,
$V_{CE1} = V_{CE2} = V_{CEQ}$

Also, $I_{CQ1} = I_{CQ2} = I_{CQ}$
and $I_{EQ} = I_{EQ1} + I_{EQ2} = 2I_{EQ1}$

Applying KVL to B-E loop of Q1:
$V_{EE} - 2I_E R_E - V_{BE} = 0 \quad ...(\because I_{EQ} = (\beta + 1)I_{BQ})$

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

$$\therefore I_{BQ} = \frac{V_{EE} - V_{BE}}{2(\beta + 1)R_E} = \frac{12 - 0.7}{12 \times 101 \times 43k\Omega}$$

$\therefore I_{BQ} = 1.301\mu A$

$\therefore I_{CQ} = \beta I_{BQ} = 100(1.301\mu A)$

$\therefore I_{CQ} = 0.1301mA$

$\therefore I_{CQ1} = I_{CQ2} = I_{CQ} = 0.1301mA$

Applying KVL to C-E loop of Q1:
$V_{CC} - I_{CQ}(R_{C1}) - V_{CE1} - 2I_{EQ1}R_E - V_{EE} = 0$

$V_{CC} - I_{CQ}(R_{C1}) - V_{CE1} - 2I_{CQ}R_E - V_{EE} = 0 \qquad ...(\because I_{CQ} \approx I_{EQ})$

$\therefore V_{CE1} = (V_{CC} - V_{EE}) + I_{CQ}(R_{C1} + 2R_E)$

$\therefore V_{CE1} = (12 + 12) + (0.1301mA)(47k\Omega + 2 \times 4.3k\Omega)$

$\therefore V_{CE1} = 6.6967V$

$\therefore V_{CE1} = V_{CE2} = V_{CE} = 6.6967V$

Small signal parameters:

$r_\pi = \dfrac{\beta V_T}{I_{CQ}} = \dfrac{100 \times 26mV}{0.1301mA}$

$\therefore r_\pi = 19.984k\Omega$

$\therefore$ Q-point $\equiv (V_{CE1}, I_{CQ1}) \equiv$ (6.6967V, 0.1301mA)

Now, $V_{E1} = V_{E2} = R_E(2I_{EQ}) + V_{EE}$

$\therefore V_{E1} = V_{E2} = (43k\Omega)(2 \times 0.1301mA) - 12 = -0.8114V$

$\therefore V_{C1} = V_{CE1} + V_{E1} = 6.6967 + (-0.8114)$

$\therefore V_{C1} = 5.8853V$

$\therefore$ Q-point $\equiv (V_{CEQ1}, I_{CQ1}) \equiv (V_{CEQ2}, I_{CQ2})$

$\therefore$ Q-point $\equiv (V_{CEQ}, I_{CQ}) \equiv$ (6.6967V, 0.1301mA)

Differential mode gain:

$$| A_d | = \frac{1}{2} \times \frac{\beta R_C}{r_\pi + R_B}$$

here, $R_B = 0\Omega$

$$\therefore | A_d | = \frac{1}{2} \times \frac{100 \times 47k\Omega}{19.984k\Omega + 0}$$

$$\therefore | A_d | = 117.5941$$

Common mode gain:

$$A_{CM} = \left| \frac{R_C}{2R_E} \right| = \left| \frac{47k\Omega}{2(43k\Omega)} \right|$$

$$\therefore A_{CM} = 0.5465$$

$CMRR$ (Common Mode Rejection Ratio):

$$CMRR = \left| \frac{A_d}{A_{CM}} \right| = \frac{117.5941}{0.5465}$$

$$CMRR = 215.1768$$

$$CMRR \text{ (in dB)} = 20 \log_{10} \left(\frac{A_d}{A_{CM}} \right) = 20 \log_{10}(215.78)$$

$$\therefore CMRR = 46.5591dB$$

SIMULATED RESULTS:
Above circuit was simulated in LTspice and results obtained are as follows:

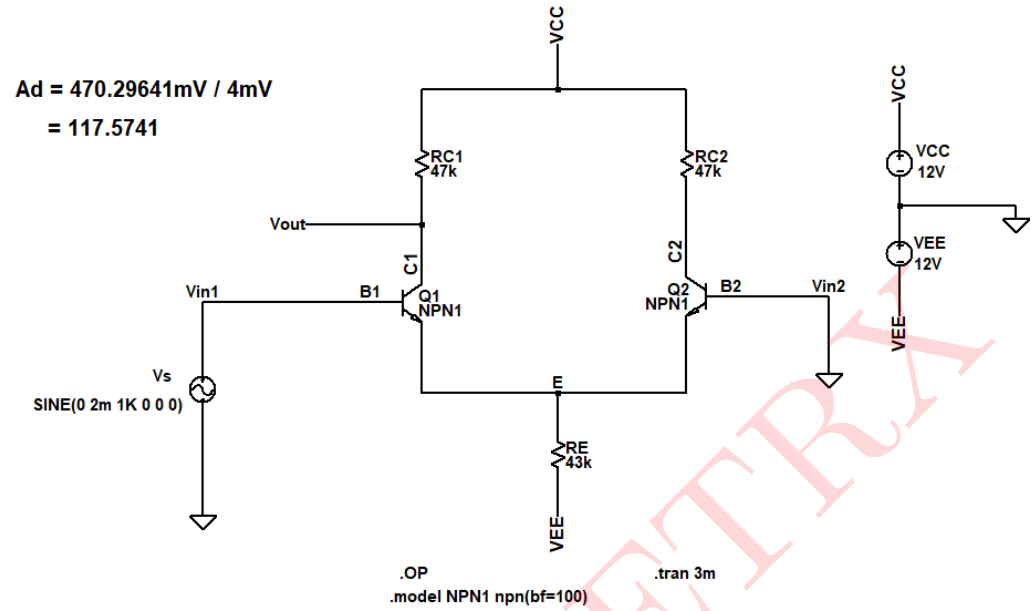

Figure 2: Circuit Schematic: Results for differential mode

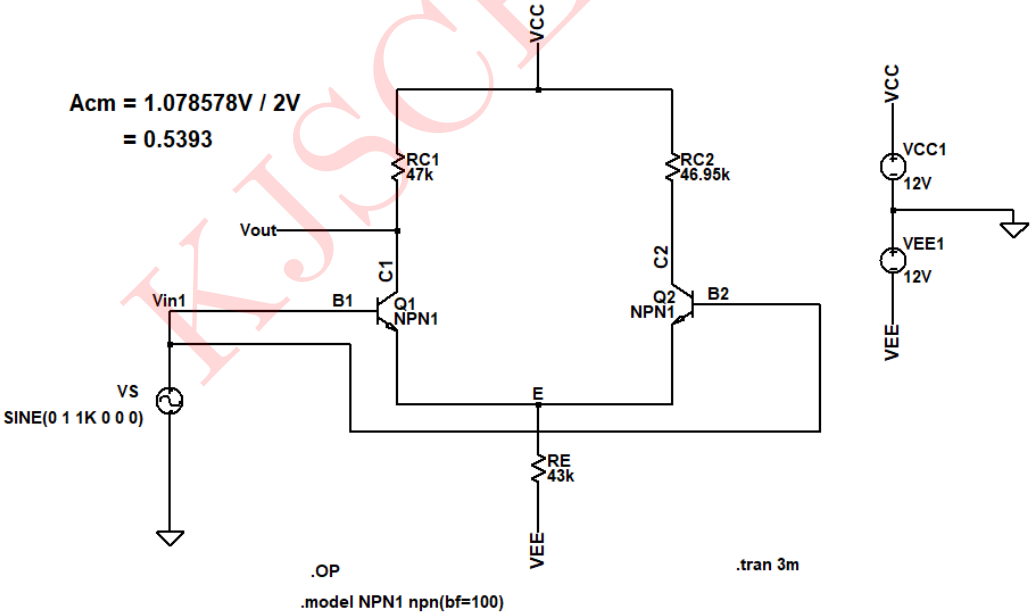

Figure 3: Circuit Schematic: Results for common mode

Input and output waveforms for differential and common mode are shown below:

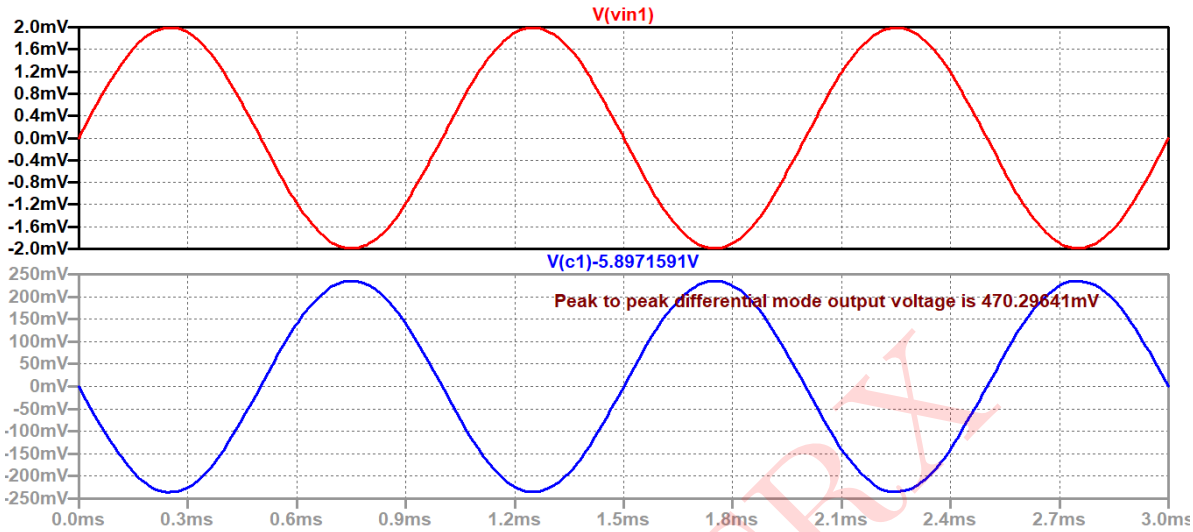

Figure 4: For differential mode

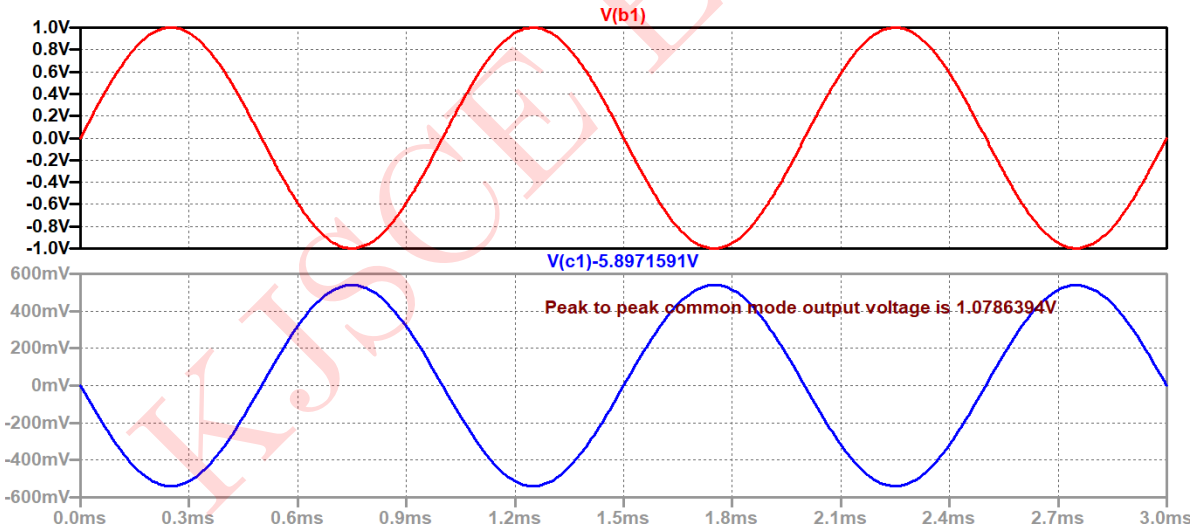

Figure 5: For common mode

Comparison between theoretical and simulated values:

Parameter	Theoretical value	Simulated value
I_{C1}, I_{C2}	0.1301mA	0.1298mA
V_{C1}, V_{C2}	5.8853V	5.8972
V_{CE1}, V_{CE2}	6.6967V	6.6186V
Differential voltage gain $\mid A_d \mid$	117.5941	117.5814
Common mode voltage gain $\mid A_{CM} \mid$	0.5465	0.5390
CMRR (in dB)	46.6559	46.7750

Table 1: Numerical 1

Numerical 2:
For circuit shown in figure 6, determine the following:
a. Name the circuit
b. Current flowing through resistor R_{D1}, R_{D2}, R_{S1} and R_{S2}
c. V_{D1}, V_{D2}, V_{GS1}, V_{GS2}
d. Differential voltage gain
e. Common mode gain
f. CMRR in dB
Assume: $V_{TN1} = V_{TN2} = 1V$, $k_{N1} = k_{N2} = 50\mu A/V^2$

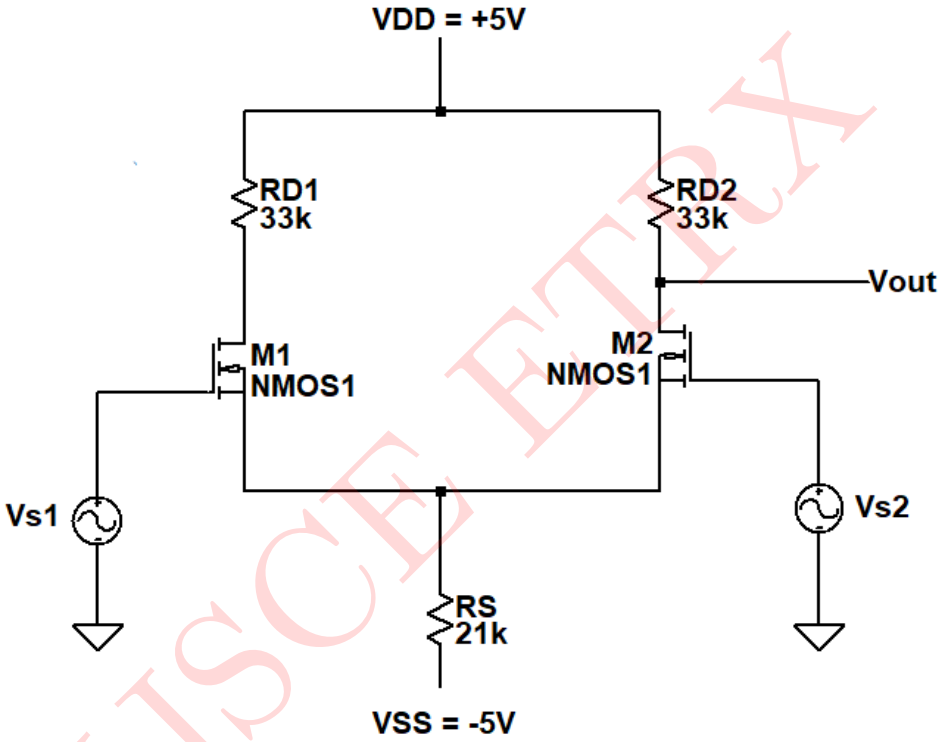

Figure 6: Circuit diagram

Solution: Circuit shown in figure 6 is a Dual Input Balanced Output differential amplifier circuit.

DC Analysis:
Applying KVL to G-S loop of M1:

$$-V_{GSQ1} - 2I_{DQ1}R_S + V_{SS} = 0$$

$$\therefore V_{GSQ1} = V_{SS} - 2I_{DQ1}R_S \quad ...(1)$$

Also, for MOSFET in saturation,

$$I_{DQ1} = k_N[V_{GSQ1} - V_{TN}]^2$$

From (1):

$$I_{DQ1} = \frac{5 - V_{GSQ1}}{2R_S}$$

$$\therefore \frac{5 - V_{GSQ1}}{2R_S} = k_N[V_{GSQ1} - V_{TN}]^2$$

Substituting values:

$$\frac{5 - V_{GSQ1}}{2(21k\Omega)} = (50 \times 10^{-6})[V_{GSQ1} - 1]^2$$

$$\therefore 5 - V_{GSQ1} = 2.1[V_{GSQ1}^2 + 1 - 2V_{GSQ1}]$$

$$\therefore 2.1V_{GSQ1}^2 - 3.2V_{GSQ1} - 2.9 = 0$$

$$\therefore V_{GSQ1} = 2.1624V,\ -0.63861V$$

$$\because V_{SQ1} > V_{TN1}$$

$$\therefore V_{GSQ1} = 2.1624V$$

$$\therefore I_{DQ1} = \frac{5 - 2.1624}{42k\Omega} = 67.5619\mu A$$

Applying KVL to D-S loop of M1:

$$V_{DD} - I_{DQ}(R_{D1}) - V_{DSQ1} - 2I_{DQ}R_S + V_{SS} = 0$$

$$\therefore V_{DSQ1} = (V_{DD} + V_{SS}) + I_{DQ}[R_{D1} + 2R_S]$$

$$\therefore V_{DSQ} = (5 + 5) + (67.5619\mu A)[33k\Omega + 42k\Omega]$$

$$\therefore V_{DSQ1} = 4.9329V$$

Now, $V_{D1} = V_{D2} = V_D = V_{DD} - I_{DQ}R_D$

$$\therefore V_D = 5 - (67.5619\mu A)(33k\Omega)$$

$$\therefore V_D = 2.7705V$$

Also, $I_S = \frac{V_S - V_{SS}}{21k\Omega}$ ...(2)

We know, $V_D = 2.7705$

$$\therefore V_{DS} = V_D - V_S$$

$$\therefore V_S = V_D - V_{DS} = 2.7705 - 4.9329$$

$$V_S = -2.1624$$

From (2),

$$I_S = \frac{-2.1624 + 5}{21k\Omega} = 0.1351mA$$

Due to symmetry of the circuitry,
$I_{DQ1} = I_{DQ2} = I_{DQ}$, $V_{GSQ1} = V_{GSQ2} = V_{GSQ}$

and $V_{DSQ1} = V_{DSQ2} = V_{DSQ}$

Small signal parameters:
$g_m = 2k_N[V_{GSQ} - V_{TN}]$

$\therefore g_m = 2(50 \times 10^{-6})[V_{GSQ} - 1]$

$\therefore g_m = 100 \times 10^{-6}(1.1624)$

$\therefore g_m = 0.11624mA/V$

Differential gain:
$A_d = 0.5 \times g_m \times R_D = 0.5(0.11624 \times 10^{-3})(33k\Omega)$

$\therefore A_d = 1.9180$

Common mode gain:

$$A_{CM} = \left|\frac{g_m R_D}{1 + 2g_m R_S}\right| = \left|\frac{(0.11624 \times 10^{-3})(33k\Omega)}{1 + 2(0.11624 \times 10^{-3})(21k\Omega)}\right|$$

$$\therefore A_{CM} = \frac{3.83592}{5.8821} = 0.6521$$

$$CMRR = \left|\frac{A_d}{A_{CM}}\right| = \frac{1.9180}{0.6521} = 3.0363$$

$$\therefore CMRR \text{ (in dB)} = 20\log_{10}\left(\frac{A_d}{A_{CM}}\right) = 20\log_{10}(3.0363)$$

$\therefore CMRR = 9.6470$dB

SIMULATED RESULTS:

Above circuit was simulated in LTspice and results obtained are as follows:

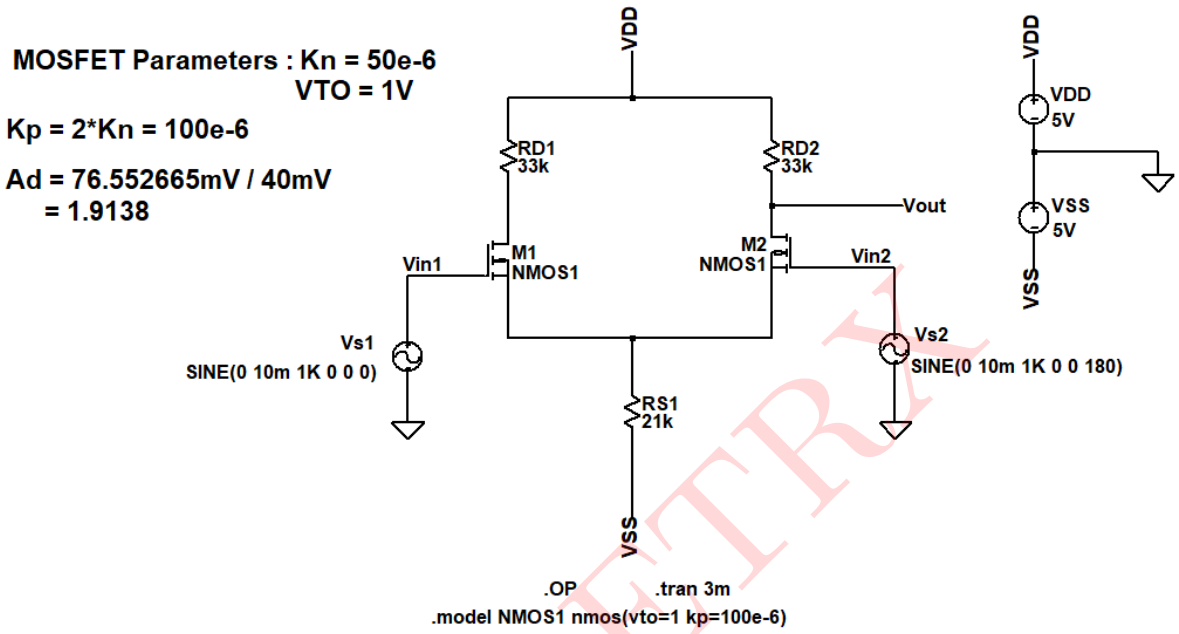

Figure 7: Circuit Schematic: Results

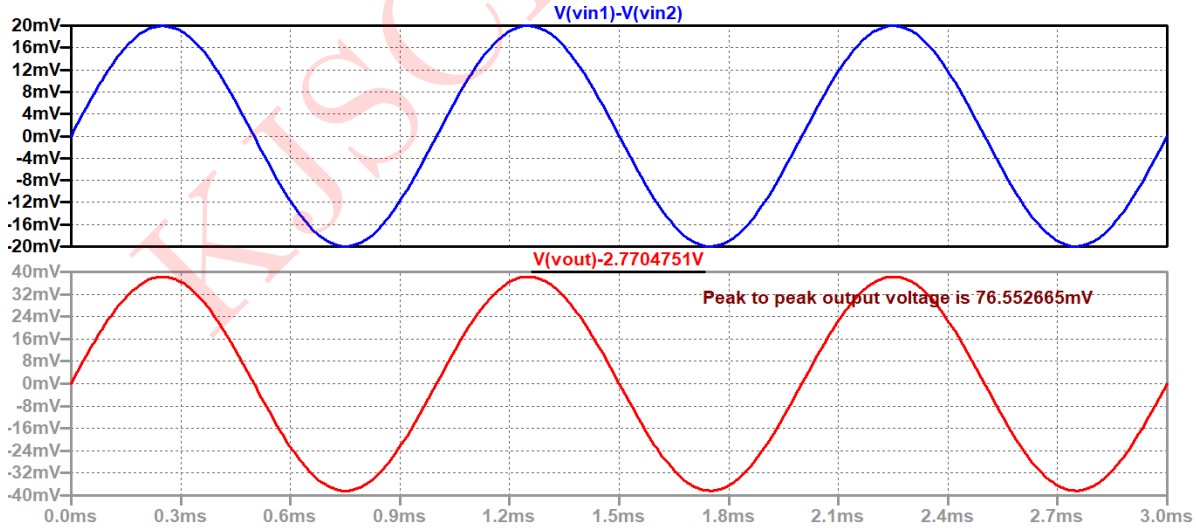

Figure 8: Input and output voltage waveform

Comparison between theoretical and simulated values:

Parameter	Theoretical value	Simulated value
I_S, I_{D1}, I_{D2}	0.1351mA, 67.5619μA, 67.5619μA	0.1351mA, 67.5614μA, 67.5614μA
V_{D1}, V_{D2}, V_{GS1}, V_{GS2}	2.7705V, 2.7705V, 2,1624V, 2.1624V	2.7705V, 2.7705V 2.1624V, 2.1624V
Differential gain: $\mid A_d \mid$	1.9180	1.9134
Common mode gain: $\mid A_{CM} \mid$	0.65821	–
CMRR (in dB)	9.6470dB	–

Table 2: Numerical 2

Numerical 3:
For differential amplifier circuit shown in figure 9, $k_{N1} = k_{N2} = 30\mu A/V^2$, $V_{TN1} = V_{TN2} = 0.7V$. Find:
a. I_{D1}, I_{D2}, V_{D1} and V_{D2}
b. A_d

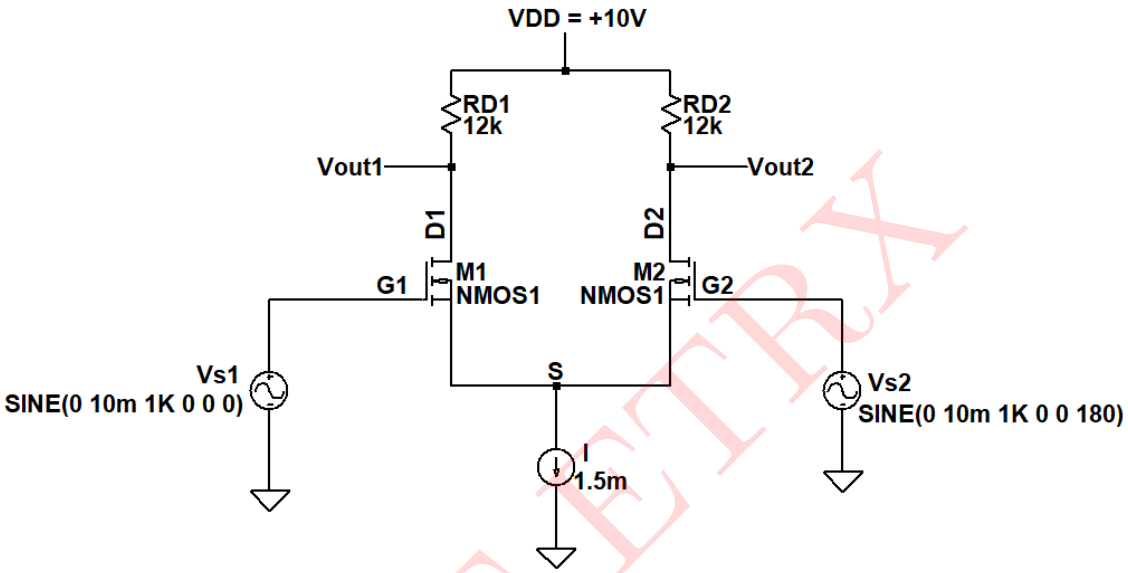

Figure 9: Circuit diagram

Solution: Circuit shown in figure 9 is Dual Input Balanced Output (DIBO) differential amplifier.

$$I_{D1} = I_{D2} = \frac{1.5mA}{2} = 0.75mA$$

Also, $V_{D1} = V_{DD} - I_{D1}R_D$

$\therefore V_{D1} = 10 - (0.75mA)(12k\Omega)$

$\therefore V_{D1} = 1V$

Due to symmetry of circuit,
$V_{D1} = V_{D2} = 1V$

For MOSFET in saturation,

$$I_D = k_N[V_{GS} - V_{TN}]^2 \quad ...(1)$$

$$g_m = 2k_N[V_{GS} - V_{TN}] \quad ...(2)$$

From (1) and (2):

$g_m = 2\sqrt{I_D k_N}$

$\therefore g_m = 2\sqrt{(0.75mA)(30\mu A/V^2)}$

$\therefore g_m = 0.3mA/V^2$

From (2):

$g_m = 2k_N[V_{GS} - V_{TN}]$

$\therefore 0.3 \times 10^{-3} = 2 \times 30 \times 10^{-6}[v_{GS} - 0.7]$

$\therefore V_{GS} = \dfrac{0.3 \times 10^{-3}}{2 \times 30 \times 10^{-6}} + 0.7$

$\therefore V_{GS} = 5.7V$

$\therefore V_{GSQ1} = V_{GSQ2} = 5.7V$

Differential gain:
$A_d = -g_m R_D = -(0.3 \times 10^{-3})(12k\Omega)$

$\therefore A_d = -3.6$

SIMULATED RESULTS:
Above circuit was simulated in LTspice and results obtained are as follows:

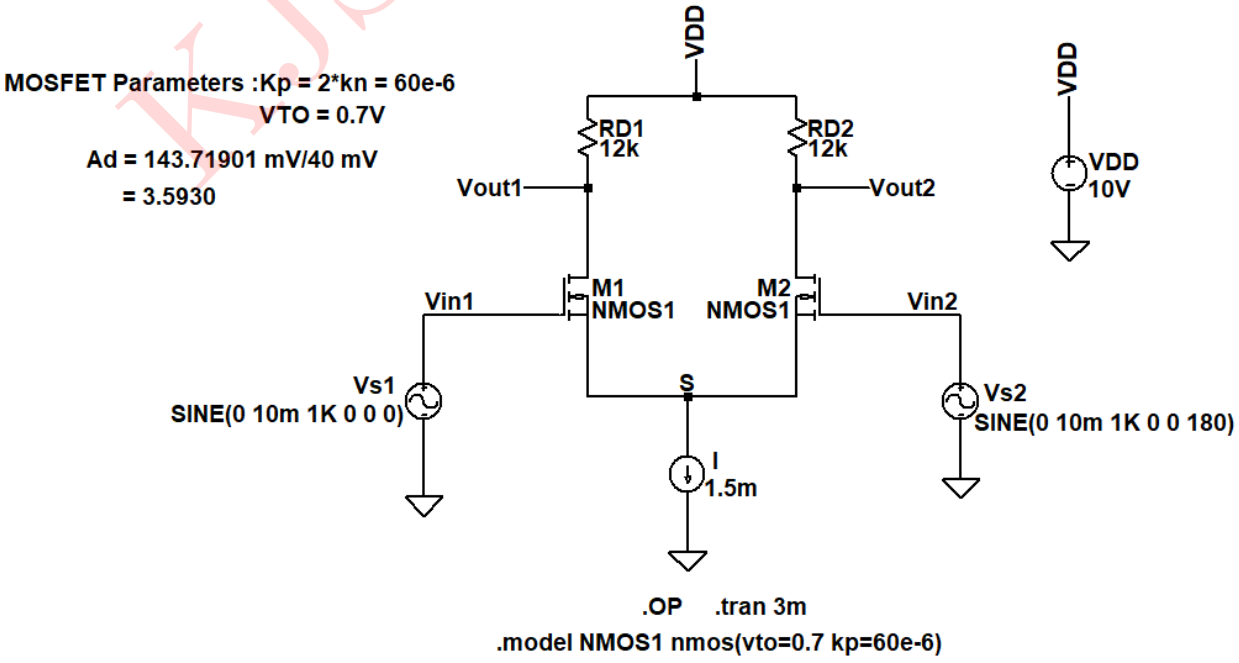

Figure 10: Circuit Schematic: Results

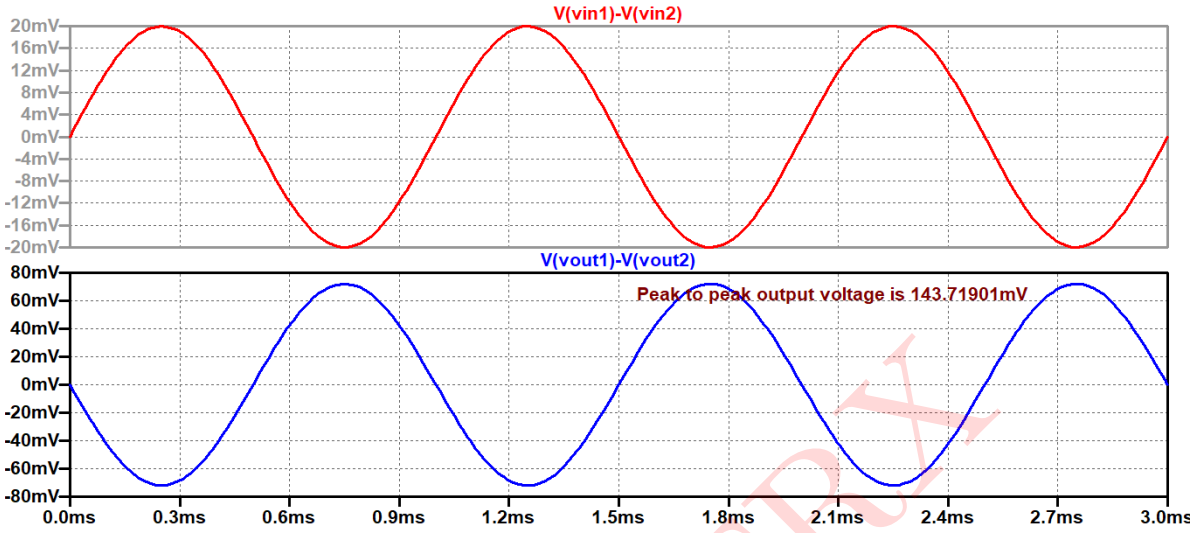

Figure 11: Input and output voltage waveform

Comparison between theoretical and simulated values:

Parameter	Theoretical value	Simulated value
I_{D1}, I_{D2}	0.75mA	0.75mA
V_{D1}, V_{D2}	1V	1V
Differential gain: $\mid A_d \mid$	3.6	3.5930

Table 3: Numerical 3