K. J. SOMAIYA COLLEGE OF ENGINEERING
DEPARTMENT OF ELECTRONICS ENGINEERING
ELECTRONIC CIRCUITS
MULTI TRANSISTOR CIRCUITS

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

1. Calculate the voltage gain of each stage and the overall AC voltage gain for the BJT cascade amplifier shown in Figure 1. Also calculate Z_i and Z_o for the given circuit Given: $\beta = 140$, $V_T = 26$ mV

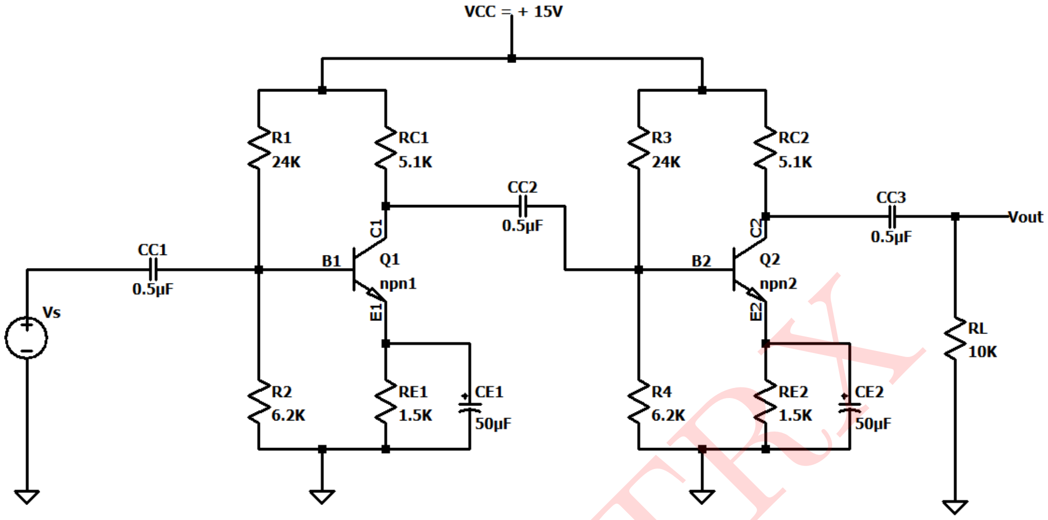

Figure 1: Circuit 1

Solution: The given circuit is a 2-stage RC-coupled CE-CE amplifier.

DC Analysis:
Assumption: $V_{BE_1} = V_{BE_2} = 0.7$ V

Due to R-C coupling, the Q-points of both the stages are isolated.

Since, both stages are symmetric in parameters and resistor values, DC analysis of one stage is sufficient.

The capacitors act as open circuit. $f = 0, \therefore X_C = \dfrac{1}{2\pi f C} = \infty$

Applying Thevenin's equivalent at base,

$$V_{th} = \frac{R_2}{R_1 + R_2} \times V_{CC} = \frac{6.2k}{24k + 6.2k} \times 15$$

$\therefore V_{th} = 3.07947$ V

$R_{th} = R_1 || R_2 = 6.2k || 24k$

$\therefore R_{th} = 4.92715\ k\Omega$

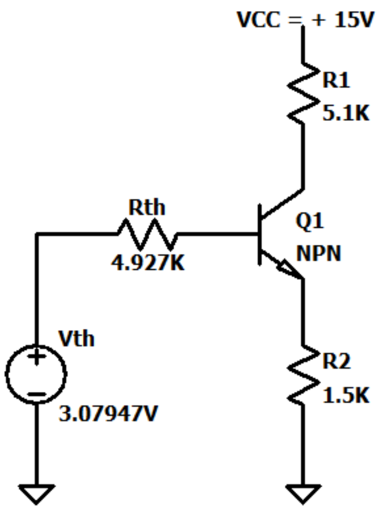

Figure 2: Thevenin's equivalent circuit

Applying KVL to input base-emitter loop

$$I_{B_1Q} = \frac{V_{th} - V_{BE}}{R_{th} + (1+\beta)R_{E_1}} = \frac{3.079 - 0.7}{4.927k + (141 \times 1.5k)}$$

$\therefore I_{B_1Q} = 10.9943\ \mu$A

Since both stages have same parameters, $I_{B_1Q} = I_{B_2Q} = 10.9943\ \mu$A

$$I_{C_1Q} = \beta I_{B_1Q} = 140 \times 10.9943 \times 10^{-6}$$

$\therefore I_{C_1Q} = I_{C_2Q} = 1.539205$ mA

$$V_{CEQ} = V_{CC} - I_C R_C - (I_B + I_C)R_E$$

$\therefore V_{CE_1Q} = V_{CE_2Q} = 4.8261$ V

Small-signal parameters: Assuming $r_{d1} = r_{d2} = \infty\Omega$

$$r_{\pi_1} = \frac{\beta_1 V_T}{I_{C_1Q}} = \frac{140 \times 26mV}{1.539205mA} = 2.364857\ k\Omega$$

$$g_{m_1} = \frac{I_{C_1Q}}{V_T} = \frac{1.539205mA}{26mV} = 59.20019\frac{mA}{V}$$

Since both stages are identical, we have,

$$r_{\pi_1} = r_{\pi_2} = 2.364857\ k\Omega$$

$$g_{m1} = g_{m2} = 59.20019\frac{mA}{V}$$

The mid-band AC equivalent circuit is shown in Figure 3

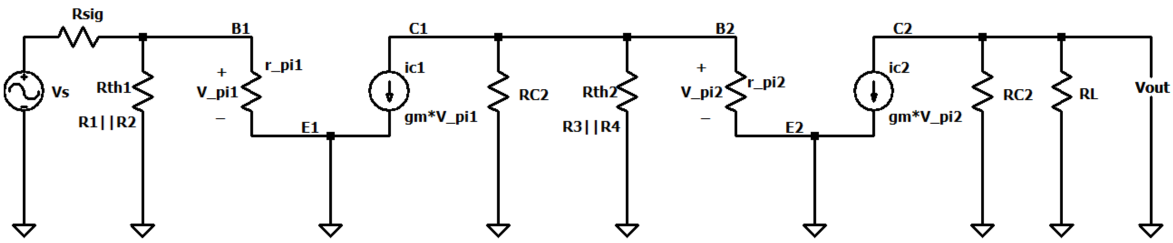

Figure 3: Mid frequency equivalent circuit

$A_{V_1} = \frac{V_1}{V_{in}}$, $A_{V_2} = \frac{V_o}{V_1}$, $A_{V_T} = A_{V_1} \times A_{V_2}$

Input impedence $Z_i = R_1||R_2||r_{\pi_2} = 4.927k||2.3648k$

$\therefore Z_i = \mathbf{1.5979\ k\Omega}$

Output impedence $Z_o = R_{C_2}||R_L = 5.1k||10k$

$\therefore \mathbf{Z_o = 3.37748\ k\Omega}$

$$A_{V_2} = \frac{V_o}{V_1} = \frac{-g_{m_2}V_{\pi_2}(R_{C_2}||R_L)}{V_{\pi_2}} = -g_m(R_{C_2}||R_L)$$

$\therefore A_{V_2} = -199.947$

$$A_{V_1} = \frac{V_1}{V_{in}} = \frac{-g_{m_1}V_{\pi_1}(R_{C_1}||R_3||R_4||r_{\pi_2})}{V_{\pi_1}} = -g_{m_1}(R_{C_1}||R_{th_2}||r_{\pi_2})$$

$\therefore A_{V_1} = -59.20019 \times 10^{-3} \times (5.1k||3.37k) = -72.08977$

$A_{V_T} = A_{V_1} \times A_{V_2} = -72.08977 \times -199.947$

$\therefore A_{V_T} = 14402.019$

$|A_{V_T}|$ (in dB) $= 20log_{10}(14402.019) = \mathbf{83.1684\ dB}$

SIMULATED RESULTS:

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

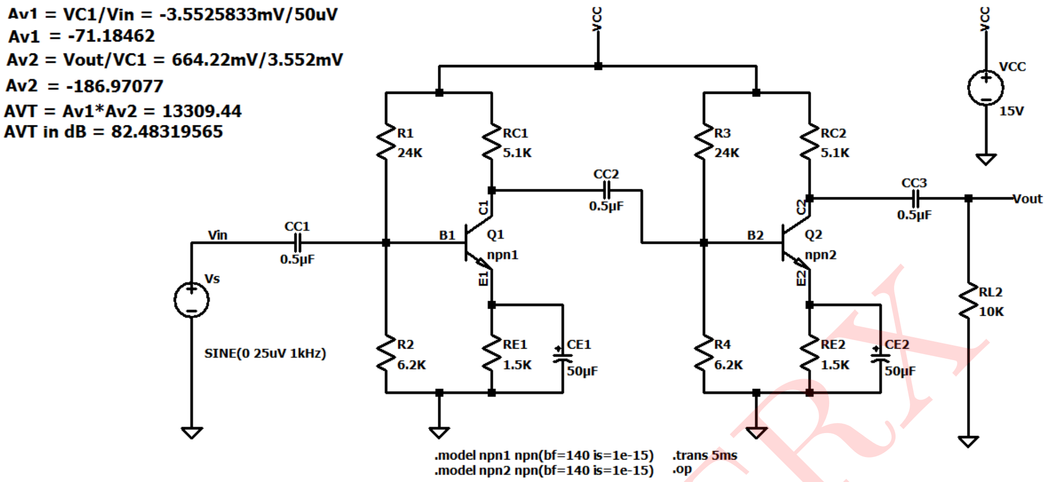

Figure 4: Circuit schematic

The input and output waveforms for voltage gain A_{V_1} are shown in Figure 5

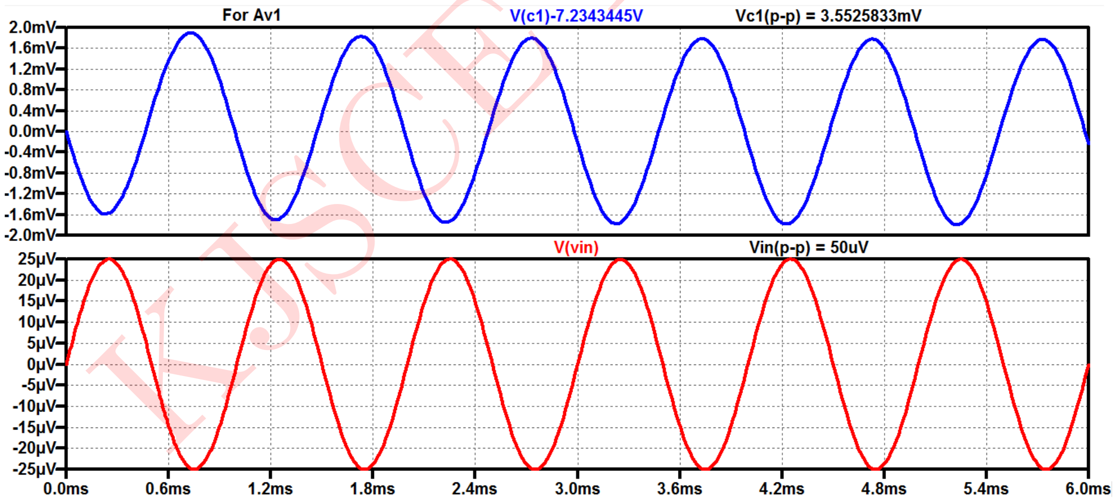

Figure 5: Input and output waveforms for voltage gain A_{V_1}

The input and output waveforms for voltage gain A_{V_2} are shown in Figure 6

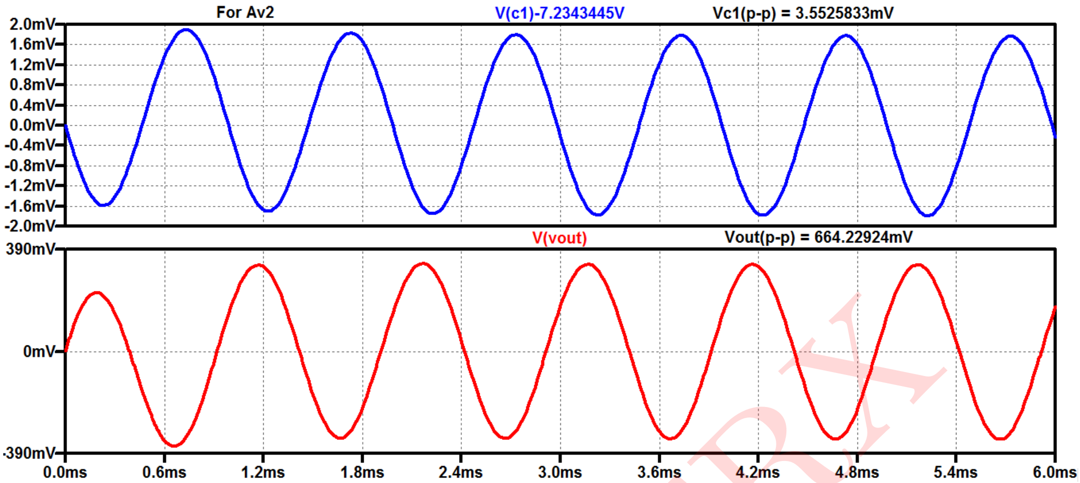

Figure 6: Input and output waveforms for voltage gain A_{V_2}

Comparison of theoretical and simulated values:

Parameters	Theoretical	Simulated
Stage 1: Q-point (I_{C_1Q}, V_{CE_1Q})	(1.539205 mA, 4.826 V)	(1.52268 mA, 4.93401 V)
Stage 2: Q-point (I_{C_2Q}, V_{CE_2Q})	(1.539205 mA, 4.826 V)	(1.52268 mA, 4.934014 V)
Voltage gain of 1^{st} stage A_{V_1}	-72.08977	-71.18462
Voltage gain of 2^{nd} stage A_{V_2}	-199.947	-186.97077
Overall voltage gain (A_{V_T})	83.1684 dB	82.48319 dB
Input impedence(Z_i) of 1^{st} stage	1.5979 kΩ	–
Output impedence (Z_o) of 2^{nd} stage	3.37748 kΩ	–

Table 1: Numerical 1

2. For the JFET cascade amplifier shown in Figure 7, using identical JFETs with $I_{DSS} = 8$ mA and $V_P = -4.5$ V, calculate the voltage gain of each stage, the overall gain of the amplifier and the output voltage V_o

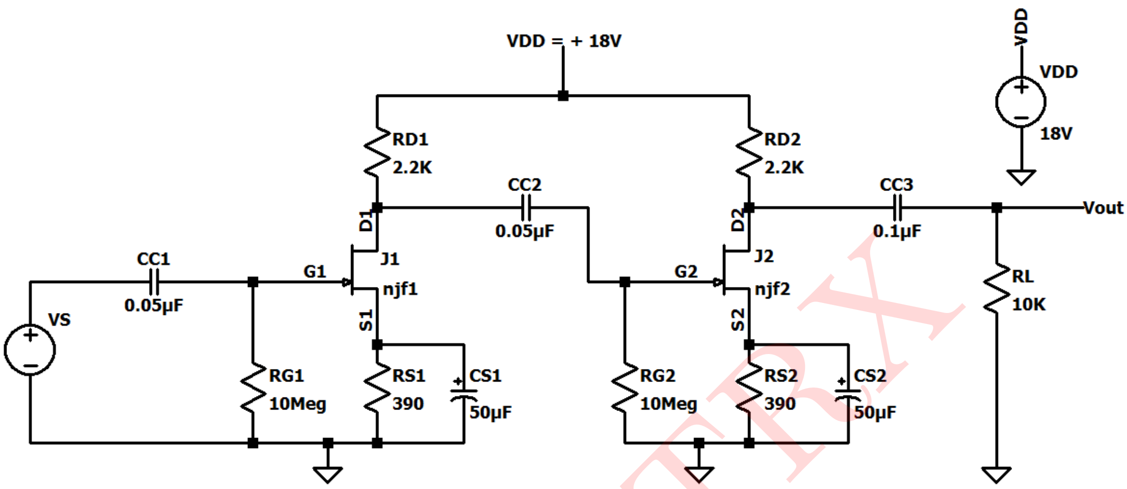

Figure 7: Circuit 2

Solution: The above circuit is a CS-CS cascade amplifier and both the stages are symmetric, hence, DC analysis of single stage is sufficient.

DC Analysis:

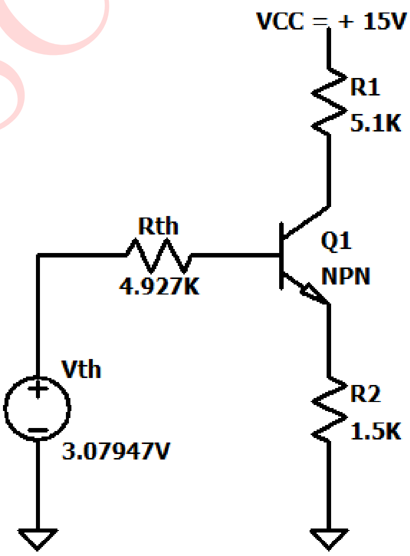

Figure 8: DC equivalent circuit

$V_{G_1} = V_{GS_1} - V_{S_1}$

$V_{G_1} = 0 - I_{D_1}R_{S_1} = 0 - 390I_{D_1}$

$\therefore V_{G_1} = -390I_{D_1}$ ....(1)

$$I_{D_1} = I_{DSS}\left(1 - \frac{V_{GS_1}}{V_P}\right)^2$$

$$I_{D_1} = 8 \times 10^{-3}\left(1 + \frac{V_{GS_1}}{4.5}\right)^2 \qquad ....(2)$$

Substituting the value of I_{D_1} from equation (2) in equation (1), we get

$$V_{GS_1} = -390 \times 8 \times 10^{-3} \times \left(1 + \frac{V_{GS_1}}{4.5}\right)^2$$

$$V_{GS_1} = -3.12 \times \left(1 + \frac{V_{GS_1}}{4.5}\right)^2$$

$V_{GS_1} = -3.12 \times (1 + 0.44V_{GS_1} + 0.0491V_{GS_1}^2)^2$

$\therefore 0.015406V_{GS_1}^2 + 2.3728V_{GS_1} + 3.12 = 0$

$\therefore V_{GS_1} = -1.4517$ V or $V_{GS_1} = -13.9505$ V

Since $V_{GSQ} > V_P$, $\therefore V_{GS_1} = -1.4517$ V

$\therefore V_{GS_1Q} = V_{GS_2Q} = -1.4517$ V

From equation (2), $I_{DQ} = 8 \times 10^{-3}\left(1 + \frac{-1.4517}{4.5}\right)^2$

$\therefore I_{D_1Q} = I_{D_2Q} = 3.722$ mA

Small-signal parameters:

$$g_{m_1} = \frac{2I_{DSS}}{|V_P|}\left(1 - \frac{V_{GSQ}}{V_P}\right)$$

$$g_{m_1} = \frac{2 \times 8 \times 10^{-3}}{4.5} \times \left(1 - \frac{(-1.4517)}{(-4.5)}\right)$$

$$\therefore g_{m_1} = g_{m_2} = 2.408533\frac{mA}{V}$$

$r_d = 0\ \Omega$

The mid-band AC equivalent circuit is shown in Figure 9

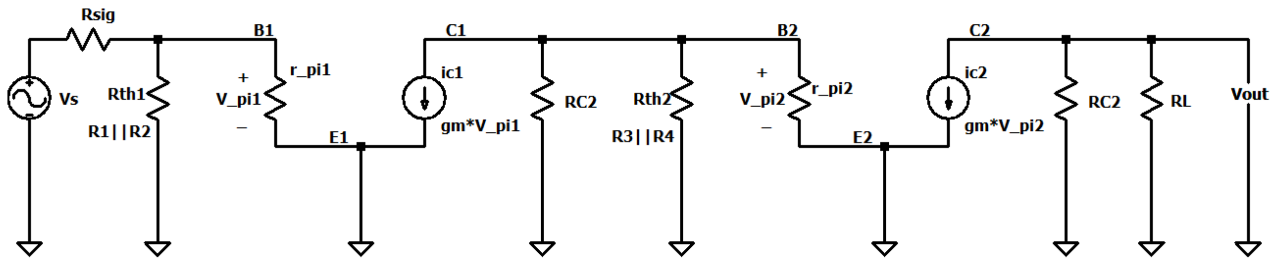

Figure 9: Mid frequency equivalent circuit

$Z_i = R_G = 10\ \text{M}\Omega$

$Z_o = R_{D_2}||R_L = 2.2k||10k$

$\therefore Z_o = 1.803\ \text{k}\Omega$

$$A_{V_T} = A_{V_1} \times A_{V_2} = \frac{V_1}{V_S} \times \frac{V_{out}}{V_1}$$

$$A_{V_1} = \frac{V_1}{V_S} = \frac{-g_{m1} V_{gs1}(R_{D_1}||R_{G_2})}{V_{gs_1}}$$

$$A_{V_1} = -g_{m_1}(R_{D_1}||R_{G_2}) = -2.408533 \times 10^{-3} \times (2.2k||10M)$$

$\therefore A_{V_1} = \mathbf{-4.6366}$

$$A_{V_2} = \frac{V_{out}}{V_S} = \frac{-g_{m_2} V_{gs_2}(R_{D_2}||R_L)}{V_{gs_2}}$$

$$A_{V_2} = -g_{m_2}(R_{D_2}||R_L) = -2.408533 \times 10^{-3} \times 1.803k$$

$\therefore A_{V_2} = \mathbf{-4.34258}$

$A_{V_T} = A_{V_1} \times A_{V_2} = -4.6366 \times -4.34258$

$\therefore A_{V_T} = 20.135$

$|A_{V_T}|$ (in dB) $= 20log_{10}(20.135) =$ **26.079 dB**

$$A_{V_T} = \frac{V_o}{V_S}$$

$\therefore V_o = A_{V_T} \times V_S = 20.135 \times 20 \times 10^{-3}$

$\therefore V_o =$ **402.7 mV**

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

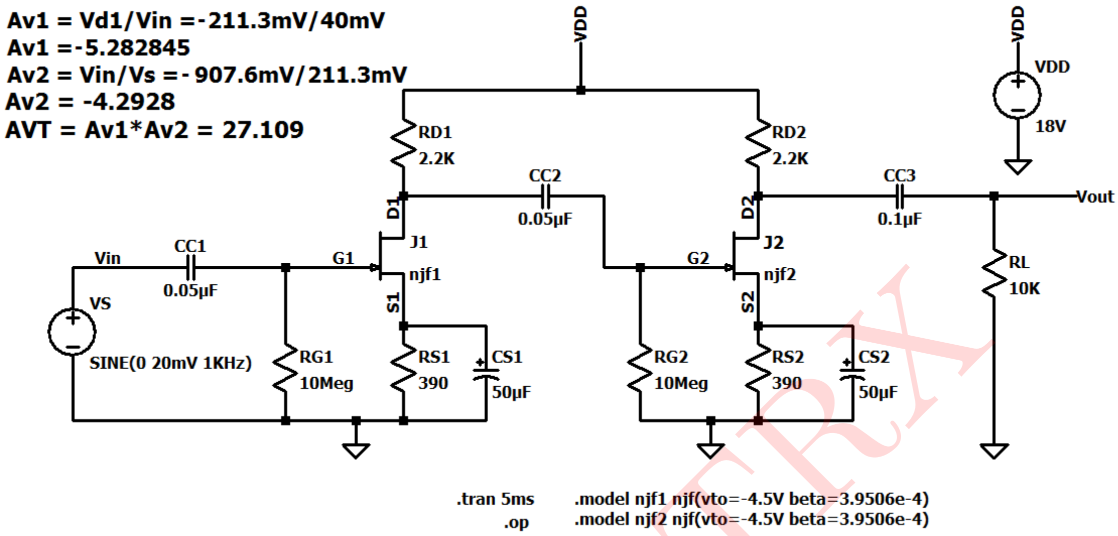

Figure 10: Circuit schematic

The input and output waveforms for voltage gain A_{V_1} are shown in Figure 11

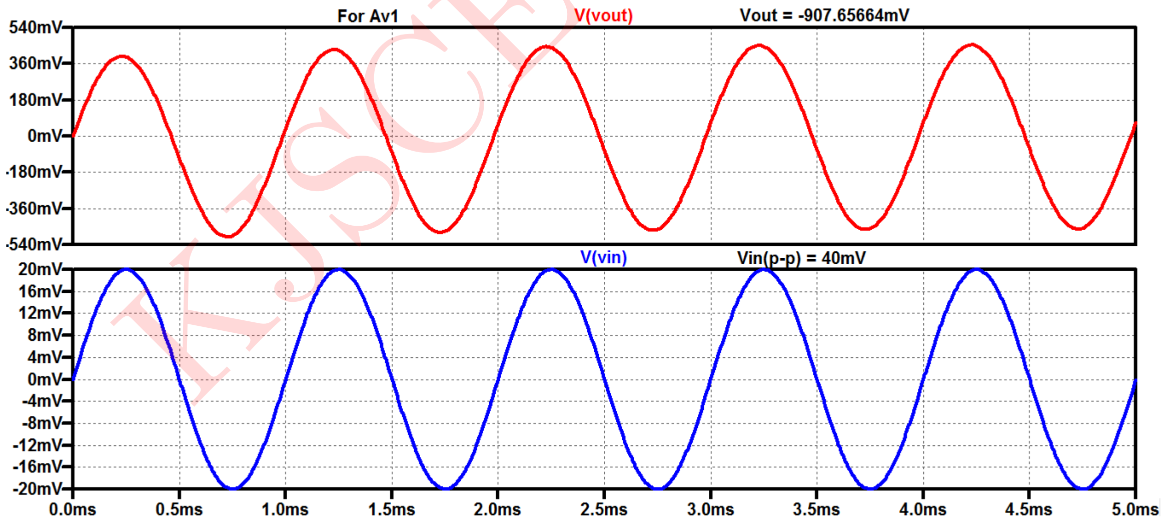

Figure 11: Input and output waveforms for voltage gain A_{V_1}

The input and output waveforms for voltage gain A_{V_2} are shown in Figure 12

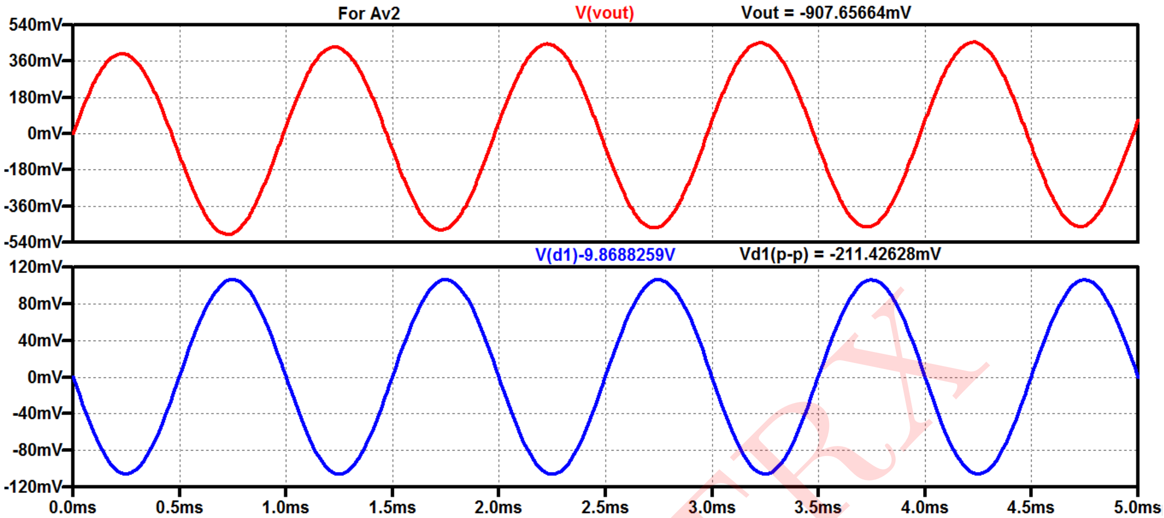

Figure 12: Input and output waveforms for voltage gain A_{V_2}

Comparison of theoretical and simulated values:

Parameters	**Theoretical**	**Simulated**
Stage 1: Q-point (I_{D_1Q}, V_{GS_1Q})	(3.722 mA, −1.4517 V)	(3.69599 mA, −1.4413267 V)
Stage 2: Q-point (I_{D_2Q}, V_{GS_2Q})	(3.722 mA, −1.4517 V)	(3.69599 mA, −1.4413267 V)
Voltage gain of 1^{st} stage A_{V_1}	−4.6366	−5.282845
Voltage gain of 2^{nd} stage A_{V_2}	−4.34258	−4.2928
Overall voltage gain (A_{V_T})	26.079 dB	27.109 dB
Input impedence(Z_i) of 1^{st} stage	10 MΩ	–
Output impedence (Z_o) of 2^{nd} stage	1.803 kΩ	–
Output voltage	402.7 mV	453.5 mV

Table 2: Numerical 2

3. For each transistor in the circuit shown in Figure 13, the parameters are:
   $\beta = 125$, $V_{BE}(on) = 0.7$ V and $r_o = \infty\ \Omega$
   a) Determine the Q-points of each transistor
   b) Determine the input resistance R_i and output resistance R_o
   c) Find the overall voltage gain A_V

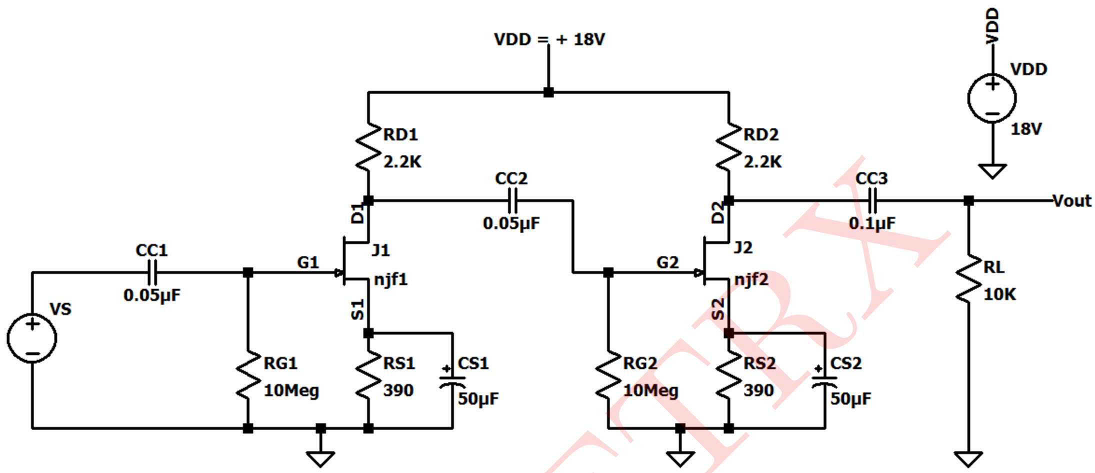

Figure 13: Circuit 3

Solution:

DC Analysis:

The capacitors act as open circuit. $f = 0, \therefore X_C = \dfrac{1}{2\pi f C} = \infty$

$$V_{th} = \left[\frac{R_2}{R_1 + R_2} \times (V_{CC} + V_{EE})\right] - 5 = \left[\frac{6k}{70k + 6k} \times 10\right] - 5$$

$\therefore V_{th} = -4.21015$ V

$R_{th} = R_1 || R_2 = 70k || 6k$

$\therefore R_{th} = 5.526\ k\Omega$

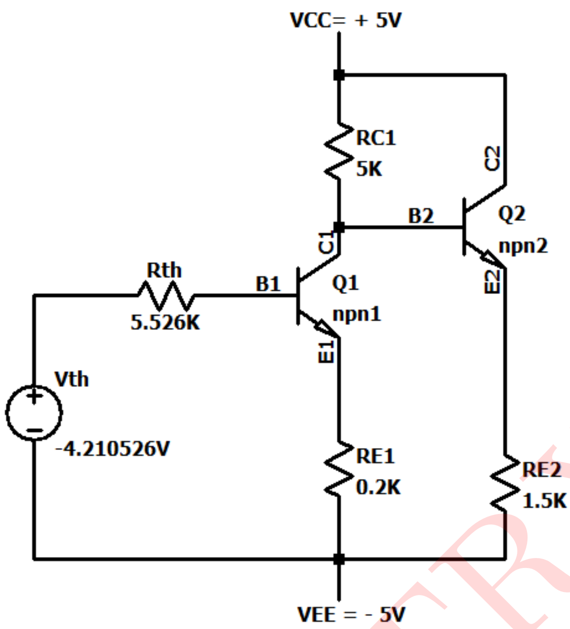

Figure 14: DC equivalent circuit

Applying KVL to input base-emitter loop

$I_{B_1} = \dfrac{V_{th} - V_{BE} + V_{EE}}{R_{th} + (1+\beta)R_{E_1}} = \dfrac{-4.21015 - 0.7 + 5}{5.526k + (126 \times 0.2k)}$

$\therefore I_{B_1Q} = 10.9943\ \mu\text{A}$

Since both stages have same parameters, $I_{B_1Q} = I_{B_2Q} = 2.924\ \mu\text{A}$

$I_{C_1Q} = \beta I_{B_1Q} = 125 \times 2.924 \times 10^{-6}$

$\therefore I_{C_1Q} = 0.365\ \text{mA}$

$I_{E_1Q} = I_{B_1Q} + I_{C_1Q}$

$\therefore I_{E_1Q} = 0.3684\ \text{mA}$

$V_{C_1} = V_{CC} - I_C R_{C_1} = 5 - (0.3655 \times 10^{-3} \times 5k)$

$\therefore V_{C_1} = 3.1725\ \text{V}$

$V_{E_1} = I_E R_{E_1} - V_{EE}$

$\therefore V_{E_1} = -4.926\ \text{V}$

For stage 2, $V_{B_2} = V_{C_1}$

$V_{B_2} = V_{E_2} + V_{BE} + V_{EE}$

$\therefore V_{E_2} = V_{B_2} - 0.7 + V_{EE} = 3.1725 - 0.7 + 5$

$\therefore V_{E_2} = 2.5275$ V

$$I_{E_2} = \frac{V_{E_2} + V_{EE}}{R_{E_2}} = 1.648 \text{ mA}$$

$$I_{C_2} = \alpha I_{E_2} = \left(\frac{\beta}{1+\beta}\right) \times I_E = \frac{125}{126} \times 1.648 \times 10^{-3}$$

$\therefore I_{C_2} = 1.635$ mA

$$I_{B_2} = \frac{I_{E_2}}{1+\beta} = 1.3185 \times 10^{-5} = 13.184 \ \mu\text{A}$$

$$V_{C_1 new} = V_{CC} - I_C R_{C_1} = 5 - 5k(I_{C_1} + I_{B_2})$$

$$\therefore V_{C_1 new} = 5 - 5k(0.378 \times 10^{-3}) = 3.11 \text{ V}$$

$$V_{E_2 new} = V_{C_1 new} - 0.7 = 2.41 \text{ V}$$

$$I_{E_2 new} = \frac{V_{E_2 new}}{R_{E_2}} = \frac{2.41 + 5}{1.5k}$$

$\therefore I_{E_2 new} = 4.94$ mA

$$I_{B_2 new} = \frac{I_{E_2}}{1+\beta} = 39.206 \ \mu\text{A}$$

$$I_{C_2 new} = \beta I_{B_2 new} = 4.9 \text{ mA}$$

$$V_{C_2} = 5 \text{ V}$$

Small-signal parameters:

$$r_{\pi_1} = \frac{\beta V_T}{I_{C_1 Q}} = 8.8919 \text{ k}\Omega$$

$$r_{\pi_2} = \frac{\beta V_T}{I_{C_2 Q}} = 663.26 \text{ k}\Omega$$

$$g_{m_1} = \frac{I_{C_1 Q}}{V_T} = 14.038 \frac{mA}{V}$$

$$g_{m_2} = \frac{I_{C_2 Q}}{V_T} = 188.46 \frac{mA}{V}$$

The mid-band AC equivalent circuit is shown in Figure 15

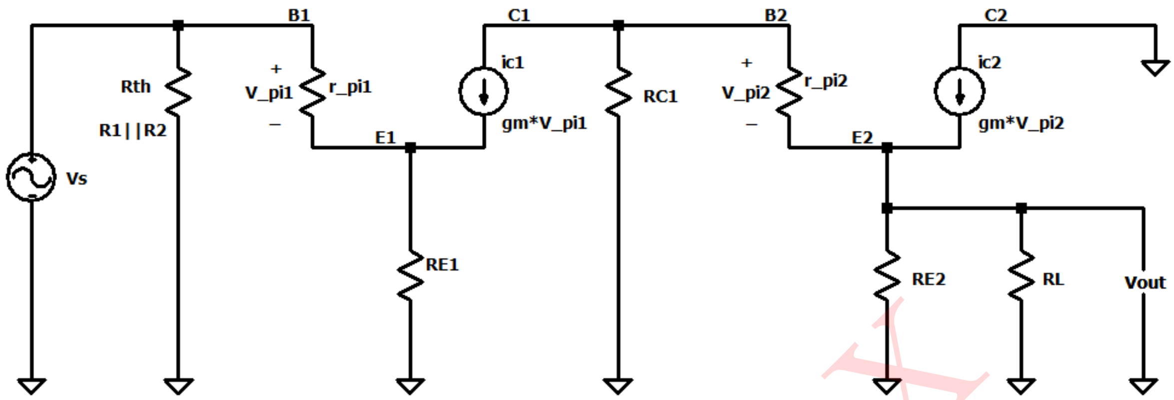

Figure 15: Mid frequency equivalent circuit

$$A_{V_T} = \frac{V_o}{V_S} = \frac{V_o}{V_1} \times \frac{V_1}{V_S}$$

$$A_{V_2} = \frac{V_o}{V_1} = \frac{(R_{E_2}||R_L)}{\dfrac{1}{g_{m_2}} + (R_{E_2}||R_L)}$$

$$\therefore A_{V_2} = \frac{1.304k}{\dfrac{1}{188.46 \times 10^{-3}} + 1.304k} = 0.9959$$

$$A_{V_1} = \frac{V_1}{V_S} = \frac{-g_{m_1} V_{\pi_1} R_{C_1}}{r_\pi + (1+\beta_1) R_{E_1}}$$

$$\therefore A_{V_1} = \frac{-\beta R_{C_1}}{r_{\pi_1} + (1+\beta) R_{E_1}} = -18.33$$

$$A_{V_T} = A_{V_1} \times A_{V_2} = -18.33 \times 0.9959$$

$$\therefore A_{V_T} = -18.257$$

Input impedence $Z_i = R_1||R_2||[r_{\pi_1} + (1+\beta)R_E] = 5.526k||[8.8919k + (126 \times 0.2k)]$

$\therefore Z_i = \mathbf{4.7552\ k\Omega}$

Output impedence $Z_o = [R_{E_2}||R_L]||\dfrac{1}{g_{m_2}} = [1.5k||10k]||\dfrac{1}{188.46 \times 10^{-3}} = 1.304k||5.3061$

$\therefore \mathbf{Z_o = 5.28459\ \Omega}$

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

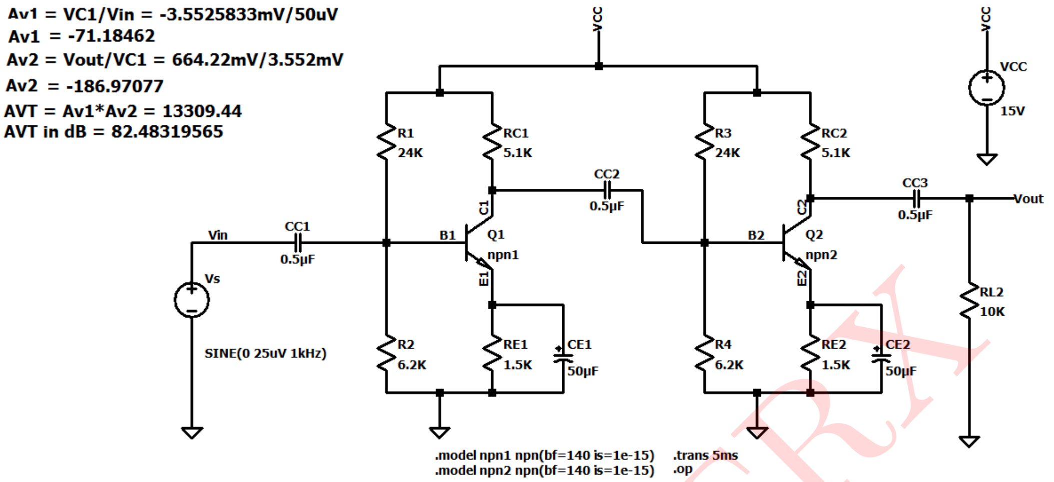

Figure 16: Circuit schematic

The input and output waveforms for voltage gain A_{V_1} are shown in Figure 17

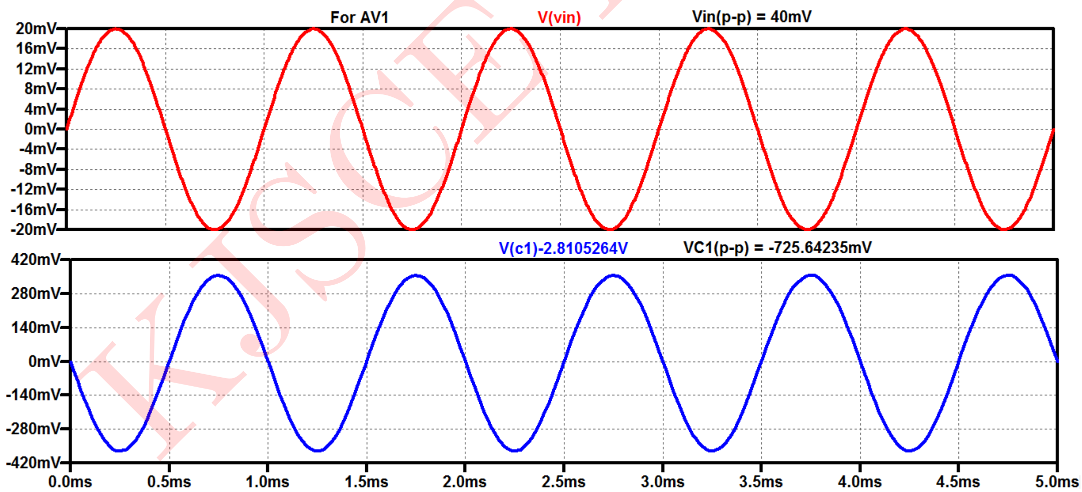

Figure 17: Input and output waveforms for voltage gain A_{V_1}

The input and output waveforms for voltage gain A_{V_2} are shown in Figure 18

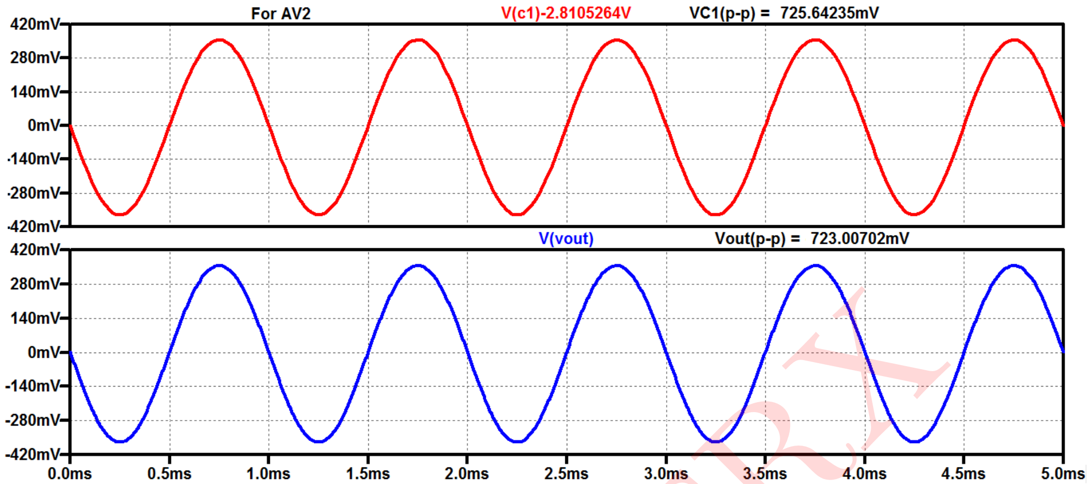

Figure 18: Input and output waveforms for voltage gain A_{V_2}

Comparison of theoretical and simulated values:

Parameters	Theoretical	Simulated
I_{B_1}	2.924 μA	3.20448 μA
I_{C_1}	0.3655 mA	0.400561 mA
I_{E_1}	0.3684 mA	0.403766 mA
I_{B_2}	39.206 μA	37.33 μA
I_{C_2}	4.9 mA	4.667 mA
I_{E_2}	4.94 mA	4.70401 mA
V_{C_1}	3.11 V	2.81053 V
V_{C_2}	5 V	5 V
V_{E_1}	-4.926 V	-4.91925 V
V_{E_2}	2.5275 V	2.05601 V
V_{B_1}	-4.21015 V	-4.22824 V
V_{B_2}	3.1725 V	2.81053 V
A_{V_T}	-18.257	-18.077

Table 3: Numerical 3