EE 430 Analysis and Design of Electronic Circuits

Professor Hakan Töreyin

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EE 430 SPICE ASSIGNMENT #1

DIFFERENTIAL AMPLIFIER DESIGN

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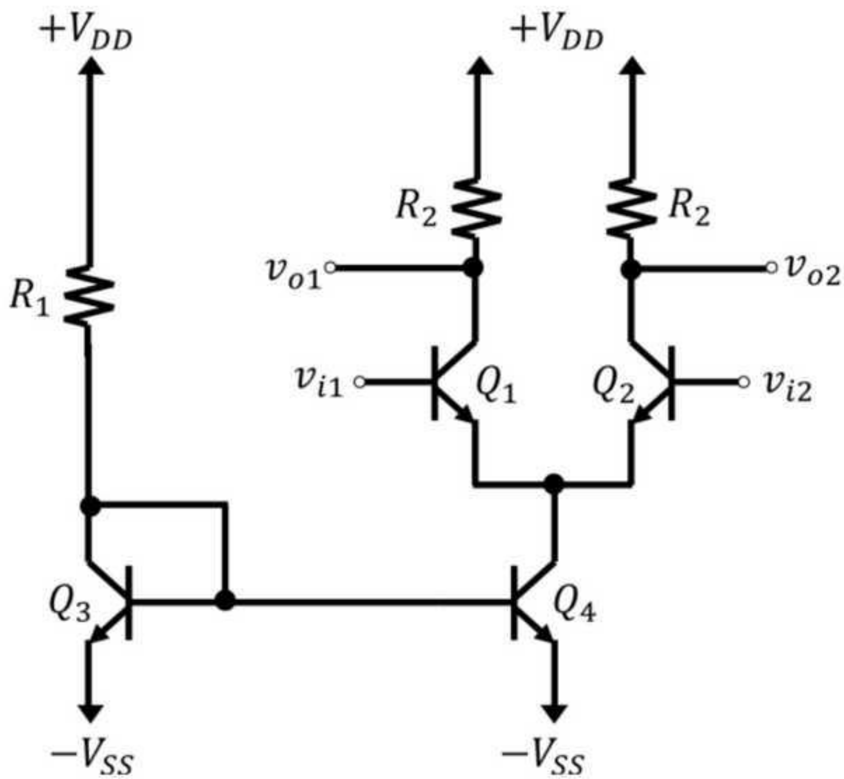


A. Hand design: Design the bipolar differential amplifier and the current source and bias network ($R1, Q3, and\ Q4$) above such that: (i) Differential gain: $Ad \geq 200 VV$, (ii) Input differential resistance: $Rid \geq 50\ k\Omega$, and (iii) $\boldsymbol{Acm < 0.1}$ where Acm is the single-ended common-mode gain (the gain to a common-mode input signal when the output is measured not differentially but from one of the outputs with respect to ground). Design the circuit with BJTs having $\beta = 200, VA = 100\ V, and\ VBE = \sim 0.7\ V\ in\ Forward\ Active$. Use $+VDD = 9\ V$ and $-VSS = -9\ V$. Clearly show your steps.

Design Suggestion for Part A.

1. Derive $Ad, Rid, and\ Acm$ expressions. (When deriving Acm and Rid you can ignore ro of Q1 and Q2. Needless to say, you cannot ignore ro of Q4 when deriving Acm. Do not ignore ro of Q1 or Q2 when deriving Ad).
2. Plug the "dc currents", "resistors", "Vth", "β", "VA", etc. into $Ad, Rid, and\ Acm$ expressions and simplify the expressions to the extent possible (e.g., manipulate the expressions and then replace $VA = 100\ V$, $\beta = 200$, etc.)
3. Consider the three design constraints. You basically have each constraint represented in terms of the dc currents, and resistors.
4. Start with dc current selection satisfying your constraint(s) => Find R1, and other parameters associated with the dc current selected.
5. Then based on the constraint(s) => Find R2.

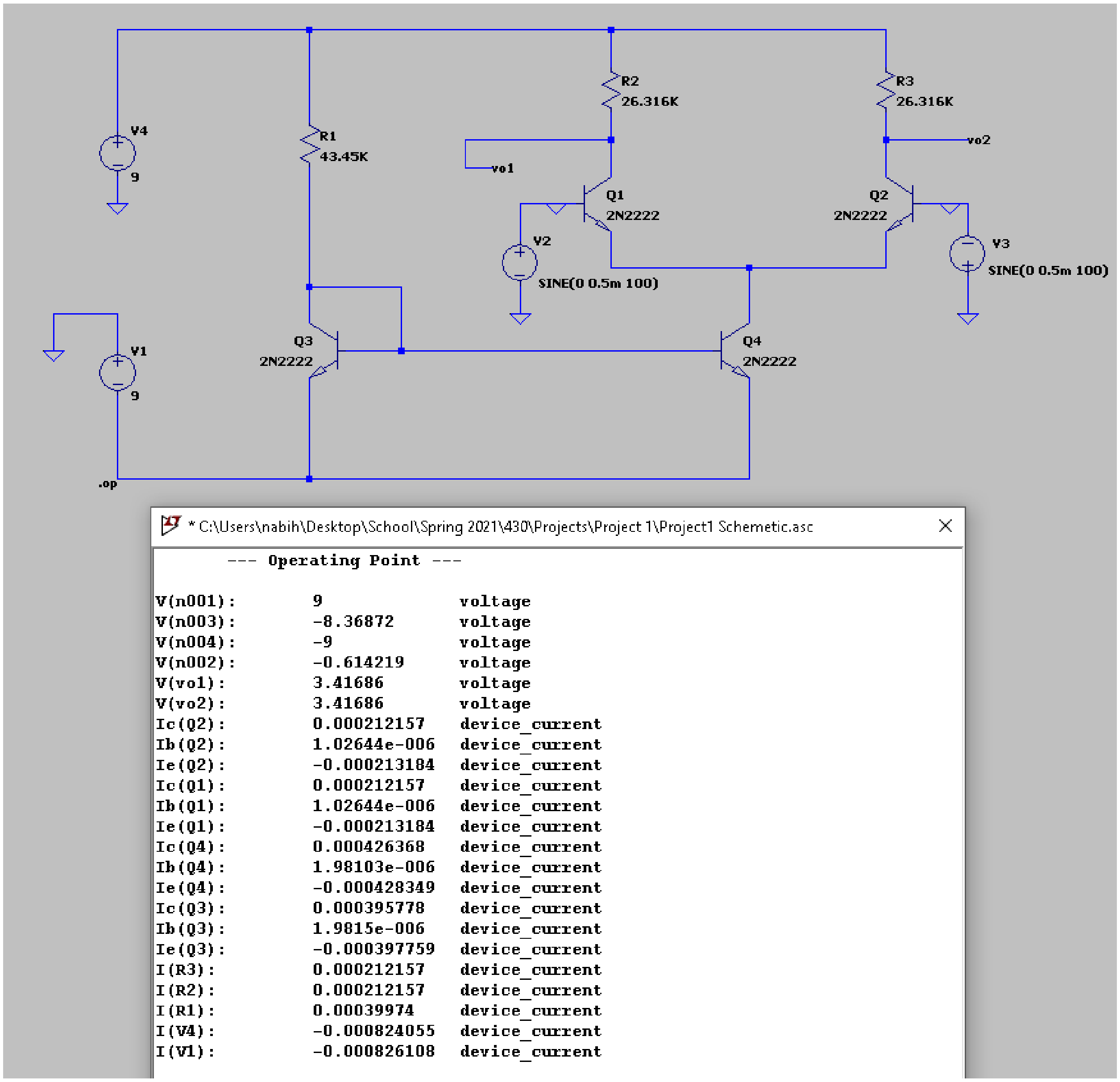
In your simulations on the next page, use the BJT model 2N2222 of NXP, which has a SPICE model as below with VA and β highlighted:

SPICE Model

```
.model 2N2222 NPN(IS=1E-14 VAF=100 BF=200 IKF=0.3 XTB=1.5 BR=3 CJC=8E-12 CJE=25E-12 TR=100E-9 TF=400E-12 ITF=1 VTF=2 XTF=3 RB=10 RC=.3 RE=.2 Vceo=30 Icrating=800m mfg=NXP)
```

B. DC Analysis: In LTSpice do a DC operating point simulation (.op) with both inputs connected to ground. Find the simulated DC values for $IR1, IC3, IC4, IC1, IC2, VB3, VE1,2, VO1, VO2$. Compare them with your hand calculations. Additionally, comment on the matching between $IR1\ and\ IC4$ and comment on the theoretical vs. simulated match between $IR1\ and\ IC4$.

- When looking at IR1 and IC4, I noticed that these currents are not identical. Just because they are mirrored does not mean they are the same. The difference might be because of how the BJTs interact with each other.



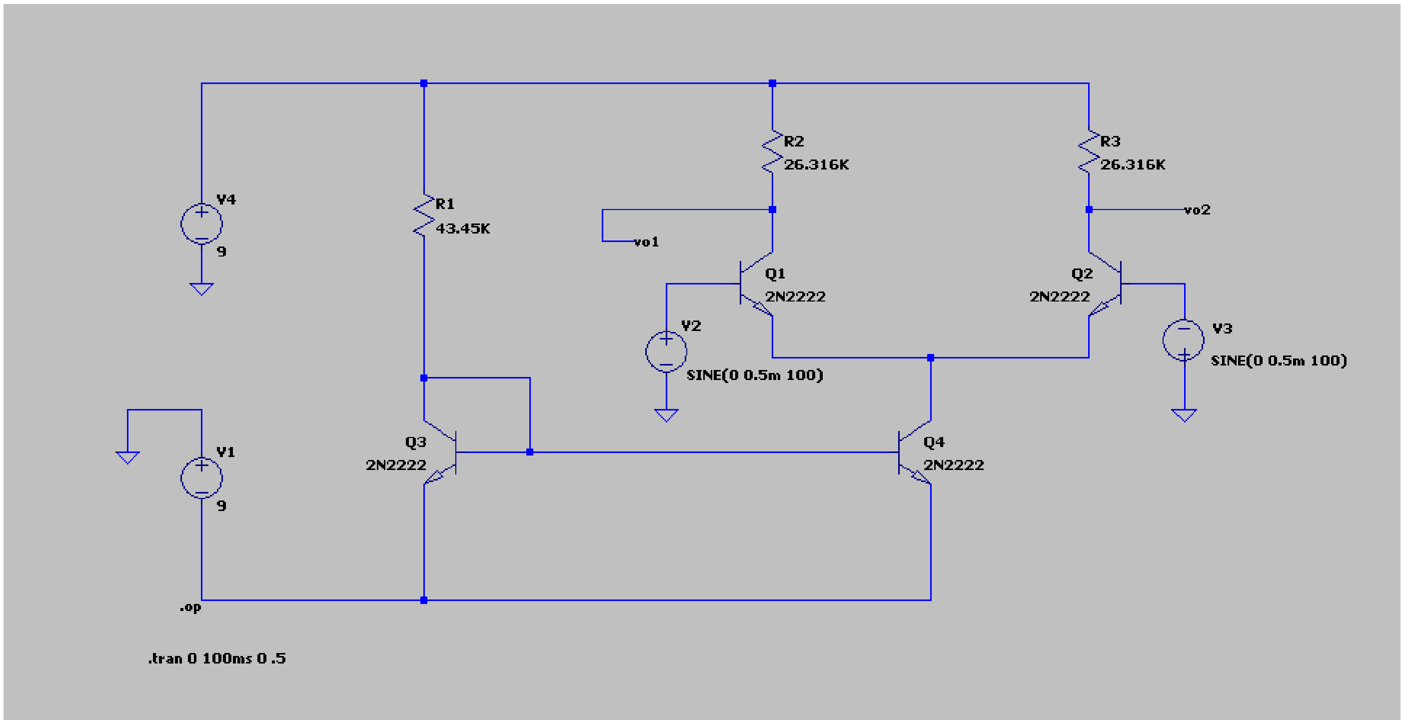
C. Transient Analysis: In LTSpice do a transient simulation (.tran) for 100 ms.

For differential small-signal input simulations:

Apply vid=1 mVp $sinusoidal$ $signal$ at 100 Hz. [i.e., $vid1=+vid2=0.5\ mV$ sin $(2*\pi*100Hz*t)$ and $vid2=-vid2=0.5\ mV$ sin $((2*\pi*100Hz*t)+\pi)$ with DC offset = 0V.]

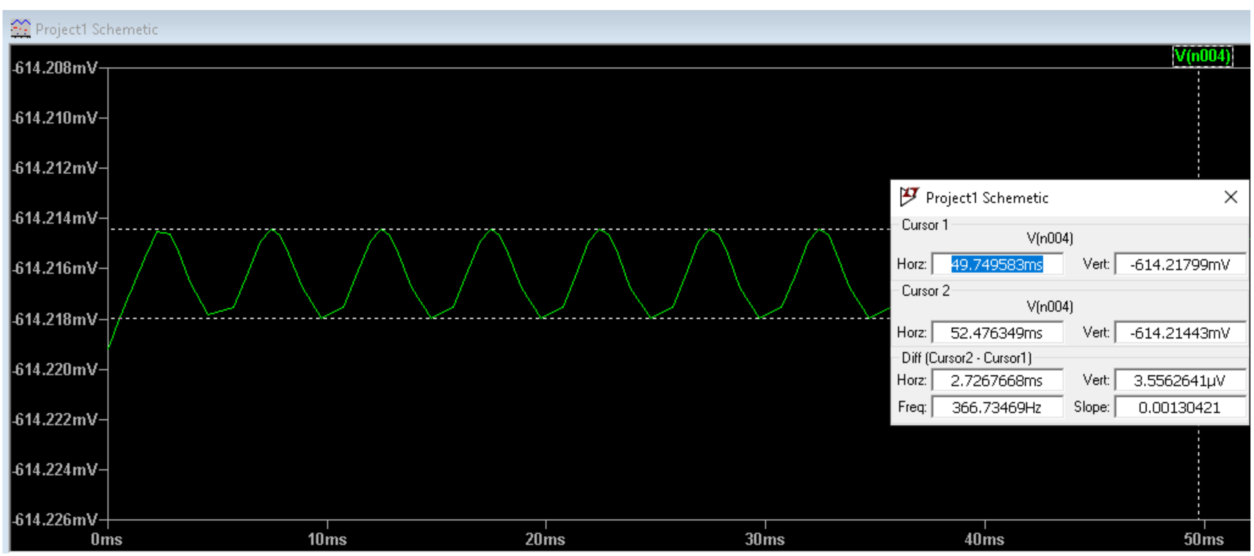
For common-mode small-signal input simulations:

Apply vcm=1 mVp $sinusoidal$ $signal$ at 100 Hz. [i.e., $vicm1=vicm2=vcm=1\ mV$ sin $(2*\pi*100Hz*t)$ with DC offset = 0V.]



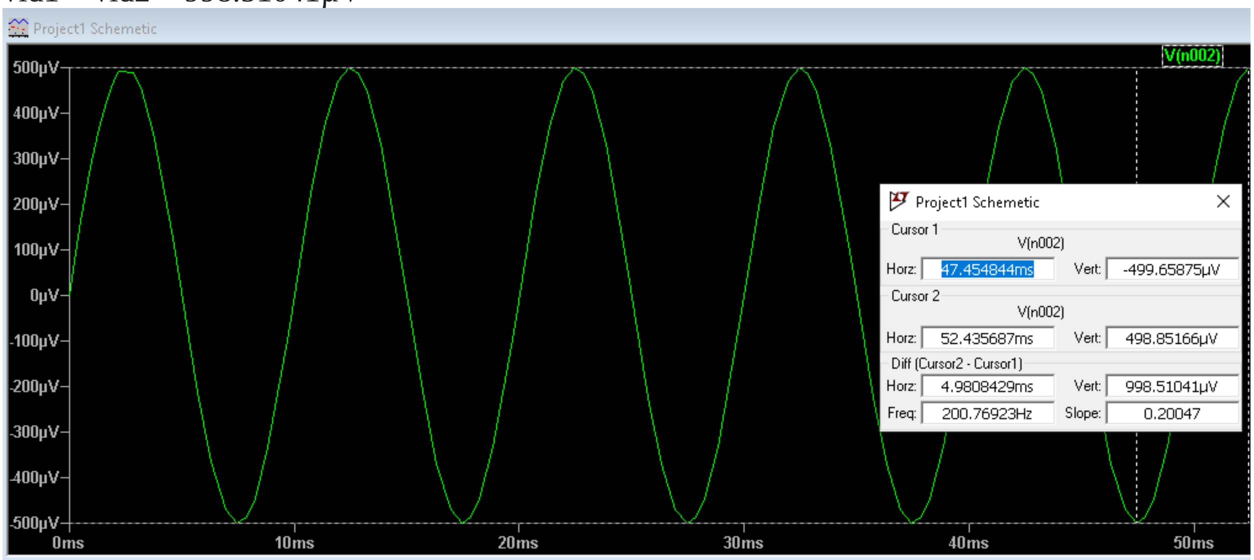
1. For the differential small-signal input, what is the expected emitter voltage of Q1 and Q2, $ve1(=ve2)$? Plot the simulated waveform. What is the simulated value of $ve1(=ve2)$?

   ve1 = ve2 = 3.5562641µV

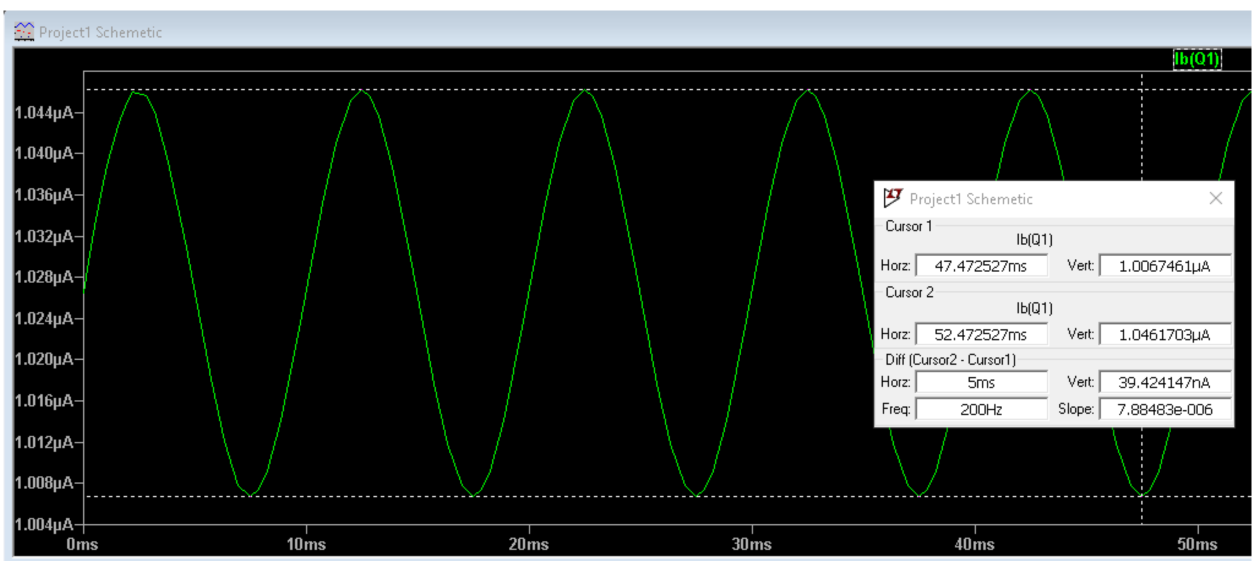


2. Plot $vid, vod (vod = vo2 - vo1), and\ iid$. Note that iid is the base current of Q1 ($iid = ib1$). Calculate the simulated $Ad = vod/vid$ and $Rid = vid/iid$. Compare the values with your design targets.

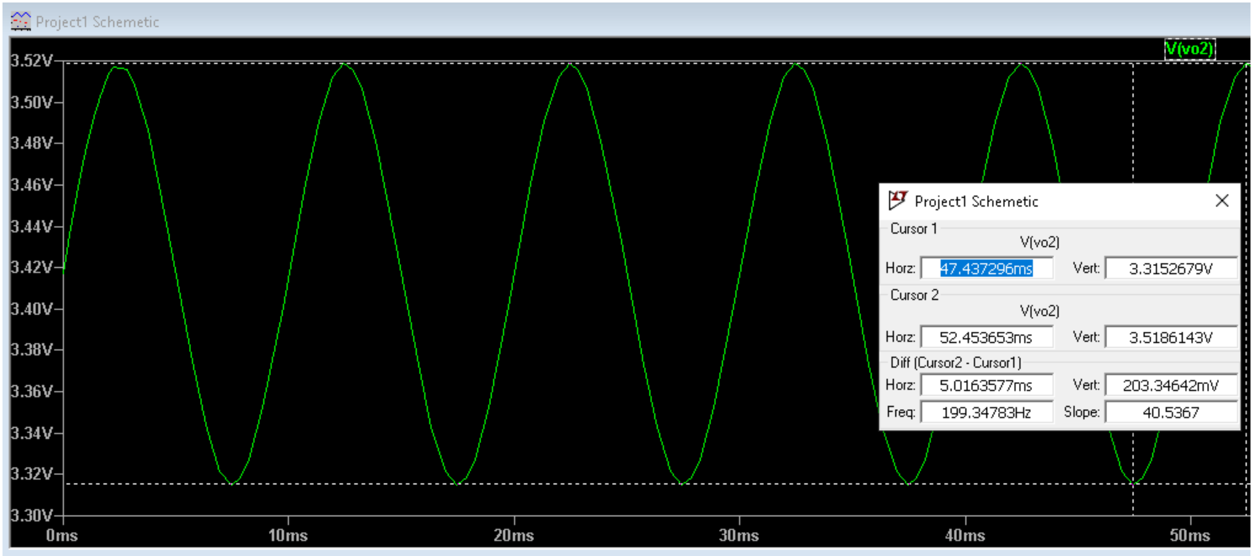
vid1 = vid2 = 998.51041μV



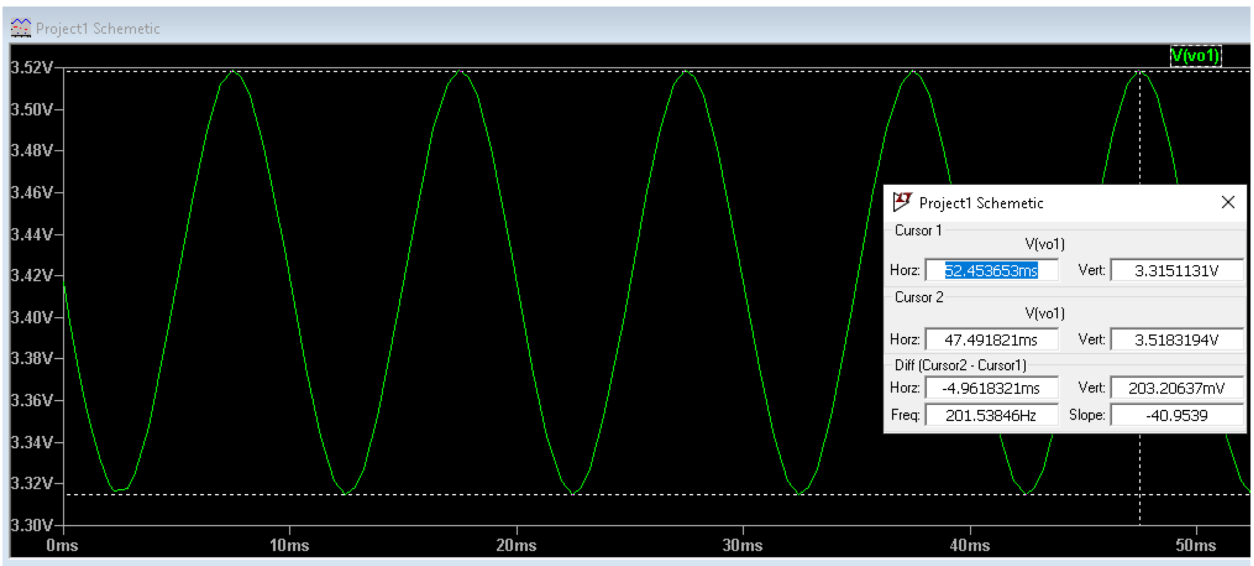
iid = 39.265618nA



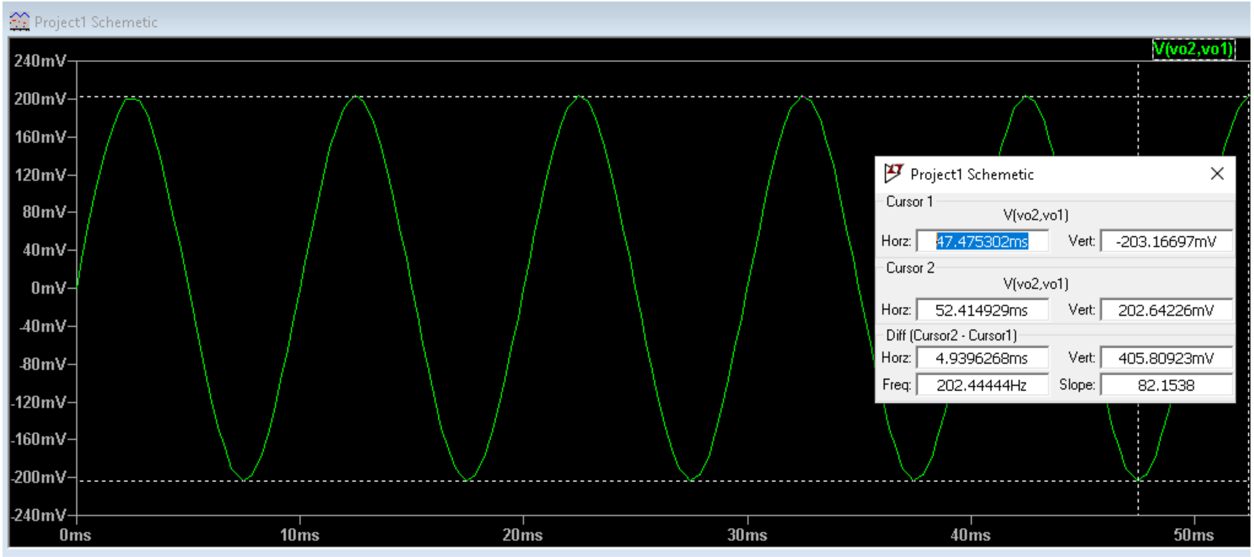
vo2 = 203.34642mV



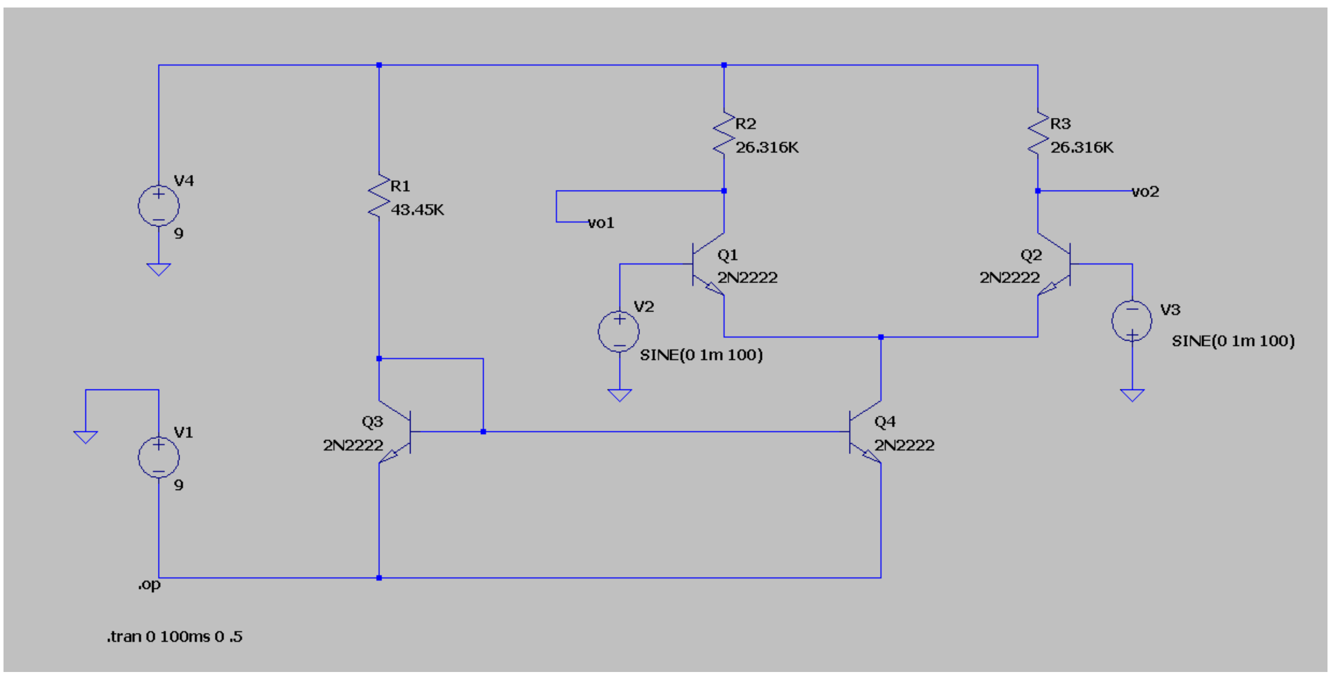
vo1 = 203.20637mV



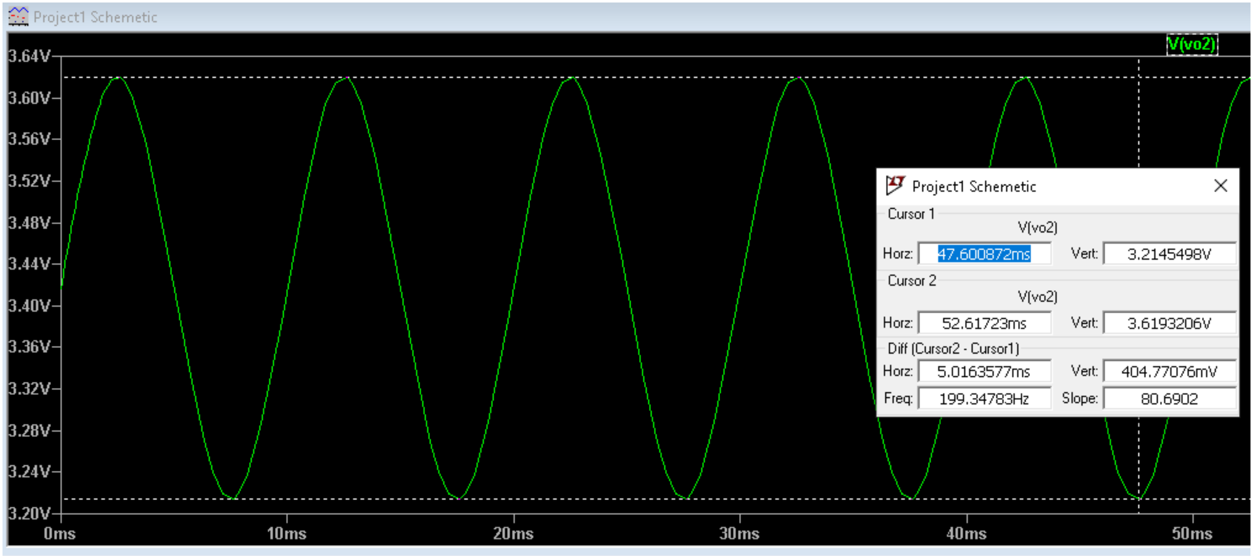
vod = vo2 – vo1 = 405.80923mV



3. If the simulation results do not match the design constraints, tune your circuit to achieve the goals.
4. For the common-mode small-signal input, plot vcm and $vocm$. ($vocm$=$vocm2$=$vocm1$ $when\ the\ input\ is\ a\ common–mode\ signal$)

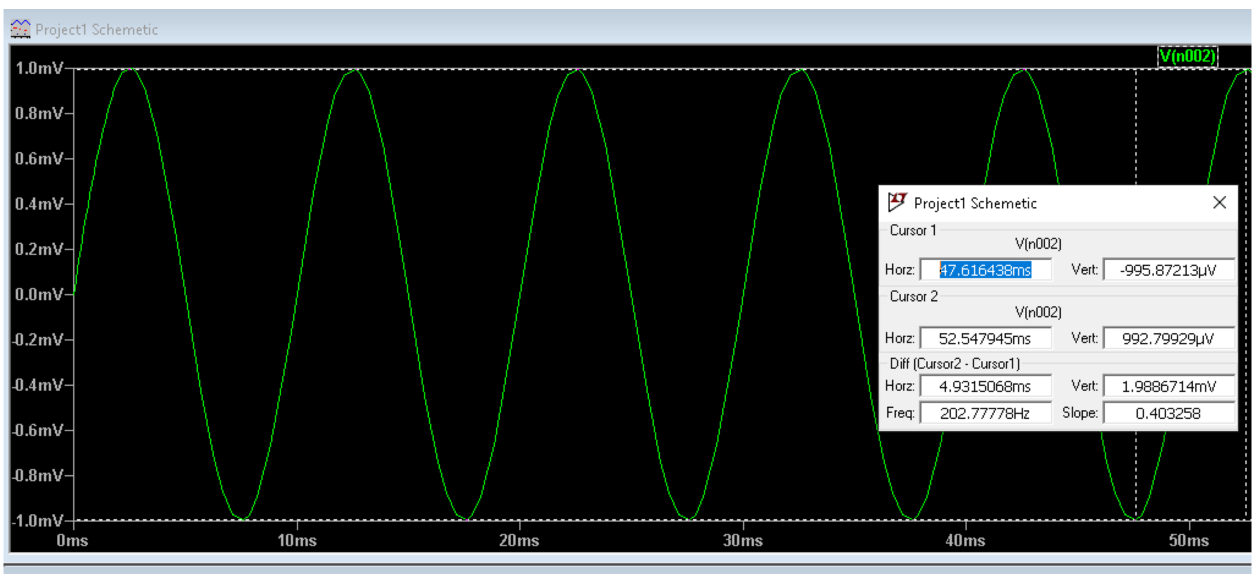


vocm1 = vocm2 = 404.77076mV



vocm = vocm1 -vocm2 = 0

vicm = 1.9886714mV



Report Requirements

A. In part A, your hand calculations must follow a flow, you must show every step for derivations, and clearly present how/why you select the parameters with any approximations you might have made.

B and C. For parts B and C, in addition to answering the questions and plotting the simulation results requested, fill the table below, and explain the reasons for any discrepancy exceeding 10%.

	$IR1$	$IC3$	$IC4$	$IC1$	$IC2$
Hand calculations	**0.398mA**	**0.398mA**	**0.398mA**	**0.2mA**	**0.2mA**
Simulated	**399.74044μA**	**395.7779μA**	**426.36786 μA**	**212.15749 μA**	**212.15749 μA**
Percent discrepancy	**0.438%**	**0.558%**	**7.13%**	**6.08%**	**6.08%**

	$VB3$	$VE1,2$	$VO1$	$VO2$	Ad	Rin	Acm
Hand calculations	**-8.3V**	**-0.7V**	**3.74V**	**3.74V**	**200.00 V/V**	**25KΩ**	**0.052 V/V**
Simulated	**-8.368722 V**	**-614.21883 mV**	**3.4168634V**	**3.4168634V**	**203.21 V/V**	**25.4296 KΩ**	**0 V/V**
Percent discrepancy	**0.83%**	**12.25%**	**8.64%**	**8.64%**	**1.605 %**	**1.7184 %**	**100%**

- For VE1/2, the reason the discrepancy is exceeding 10% is because we assume that VBE is close to 0.7 V. VBE could have been rounded up from a lower number. If VBE is lower, my discrepancy would be lower too. Possibly below the 10% margin.
- For Acm, the discrepancy is 100%. no matter how small I calculated Acm. By giving my calculated Acm a bird's eye view, I realize how small it is. If my calculated Acm was very high, then there would be a cause for concern. Since the calculated Acm is not high, we don't need to worry about the 100% discrepancy.

Handwritten Work:

Part A

Derive A_d, R_{iD}, A_{cm}. can't ignore r_o of Q_4

$A_d \geq 200 \frac{V}{V}$ $R_{id} \geq 50k\Omega$ $A_{cm} < 0.1$

$\beta = 200$ $V_A = 100V$ $V_{BE} = \sim 0.7V$

$V_{DD} = 9_V$ $-V_{SS} = -9V$

1) $A_d = \frac{V_{o2} + V_{o1}}{V_{id}} = \left(\frac{g_{m_2} R_2 // r_{o2}}{2} + \frac{g_{m_2} R_2 // r_{o2}}{2}\right) = \boxed{g_{m_2} R_2 // r_{o2}}$

$V_{o2} = \frac{g_m R_2}{2} \cdot V_{id}$ $V_{o1} = \frac{g_m R_2}{2} \cdot V_{id}$

$\cancel{R_2 = R_1 \quad r_{o1} = r_{o2}}$

$\frac{V_{id}}{2} = i_b \cdot r_\pi$ $\frac{V_{id}}{i_b} = 2r_\pi = \boxed{R_{id} = 2r_\pi}$

$A_{cm1} = \frac{V_{o1}}{V_{icm}} = \frac{-\alpha R_2}{r_e + 2R_{EE}}$

$\boxed{A_{cm} = \frac{\alpha \Delta R_2}{r_e + 2r_{o4}}}$

$A_{cm_2} = \frac{V_{o2}}{V_{icm}} = \frac{-\alpha R_2}{r_e + 2R_{EE}}$

$\boxed{R_{EE} = r_{o4}}$

2) $A_d = g_m R_2 // r_{o2}$

$$A_d = \frac{I_c}{V_T} \cdot \frac{R_2 \cdot \frac{V_A}{I_C}}{R_2 + \frac{V_A}{I_C}} = \boxed{\frac{R_2 \cdot 100V}{25mV\left(R_2 + \frac{100V}{I_C}\right)}}$$

$$R_{id} = 2r_\pi = 2 \cdot \frac{\beta \cdot V_T}{I_C} = \frac{2 \cdot 200 \cdot 25mV}{I_C}$$

$$\boxed{R_{id} = \frac{10}{I_C}}$$

$$A_{cm} = \frac{\alpha R_2}{r_e + 2r_{o4}} = \frac{\frac{200}{200+1} \cdot R_2}{\alpha \frac{V_T}{I_{E_1}} + 2\frac{V_A}{I_{C4}}} = \boxed{\frac{0.995 \cdot R_2}{\frac{0.995 \cdot 25mV}{I_{E_1}} + \frac{200}{I_{C4}}}}$$

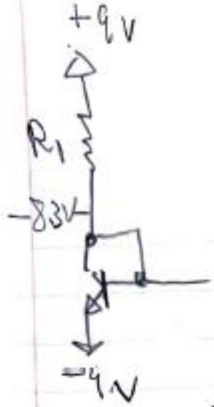
4) Find R_1. (Find I_C first)

$$R_{id} = \frac{10}{I_{C_1}} \Rightarrow I_{C_1} = \frac{10}{R_{id}} = \frac{10}{50k\Omega} = \boxed{0.2mA}$$

$$I_{E_1} = \frac{B}{B+1} I_{C_1} = 0.995 \cdot 0.2mA = 0.199mA$$

$$I_{E_1} = I_{E_2} \Rightarrow 2I_{E_1} = \boxed{I_{C4} = 0.398mA}$$

Q4 is mirrored to Q_3 so $I_{C4} = I_{C3}$



$V_B - V_E = 0.7V$ $V_{B_3} = V_{C_3}$

$V_B + 9V = 0.7V$

$V_B = 0.7V - 9V = -8.3V$

$R_1 \cdot I_{C3} = 9_V + 8.3V = 17.3V$

$\Rightarrow R_1 = \dfrac{17.3V}{0.348mA} = \boxed{43.45 K\Omega}$

5. Find R_2 have I_C ✓

$200\frac{V}{V} \cdot \dfrac{25mV}{100} = \dfrac{R_{o2}}{R_2 + \frac{100}{0.2mA}} \Rightarrow 0.05(R_2 + 500K) = R_2$

$0.05 R_2 + 500K \cdot 0.05 = R_2 \Rightarrow 0.95 R_2 = 25000$

$\boxed{R_2 = 26.316 K\Omega}$

$\boxed{V_{B_3} = -8.3V \quad V_{E_{1,2}} = -9V}$

$V_{o1} = 9_V - 26.316K\Omega \cdot 0.2mA = \boxed{3.737V}$

$A_d = \dfrac{26.316K\Omega \cdot 100}{25mV(26.316K\Omega + 100V/0.2mA)} = \boxed{200.60 V/V}$

$R_{in} = \dfrac{R_{id}}{2} = \boxed{25 K\Omega}$

$A_{cm} = \dfrac{0.995 \cdot (26.316 K\Omega)}{\frac{0.995 \cdot 25mV}{0.199mA} + \frac{200}{0.398mA}} = \boxed{0.052 \frac{V}{V}}$

c)

2) $V_{od} = 405.80923 mV$

Simurated

$V_{id_1} = 998.51041 \mu V$

$A_d = \frac{V_{od}}{2V_{id}} = \frac{405.80923 mV}{2 \cdot 998.51041 \mu V} = \boxed{203.21 \frac{V}{V}}$

$R_{id} = \frac{V_{id}}{i_{id}}$

$i_{id} = 39.265618 nA$

$R_{id} = \frac{998.51041 \mu A}{39.265618 nA} = \boxed{25.4296 k\Omega}$

$R_{id} = \boxed{R_{in} = 25.4296 k\Omega}$

4) $V_{ocm_1} = V_{ocm_2} = 404.77076 mV$
$V_{icm_1} = 1.9886714 mV$

$V_{ocm} = V_{ocm_2} - V_{ocm_1} = 0 V$

$A_{cm} = \frac{0}{V_{icm_1}} = \boxed{0 \frac{V}{V}}$

$$\frac{|Sim - Calc|}{Cal} \cdot 100$$

Percent Discrepancies

$$I_{R_1} \quad \frac{|399.74044\,\mu A - 0.398\,mA|}{0.398\,mA} \cdot 100 = 0.438\%$$

$$I_{C_3} \quad \frac{|0.3957779\,mA - 0.398\,mA|}{0.398\,mA} \cdot 100 = 0.558\%$$

$$I_{C_4} \quad \frac{|0.4263678\,mA - 0.398\,mA|}{0.398\,mA} \cdot 100 = 7.13\%$$

$$I_C \quad \frac{|0.21215749\,mA - 0.2\,mA|}{0.2\,mA} \cdot 100 = 6.08\%$$

$$I_{C_1} = I_{C_2} = 6.08\%$$

$$V_{B_3} = \frac{|-8.368722\,V + 8.3\,V|}{-8.3\,V} \cdot 100 = 0.83\%$$

$$V_{E_{1,2}} = \frac{|-614.21883\,mV - -0.7\,V|}{-0.7\,V} \cdot 100 = 12.25\%$$

· The reason this discrepancy is exceeding 10% because I assumed that $V_{BE} \simeq 0.7V$. V_{BE} could have been rounded up from a lower number. If V_{BE} could be lower, my discrepancy can be too, even below the 10% mark.

$V_{o1} = \frac{|3.4168634V - 3.74V|}{3.74V} \cdot 100 = 8.64\%$

$V_{o2} = V_{o1} = 8.64\%$

$A_d = \frac{203.21\frac{V}{V} - 200\frac{V}{V}}{200\frac{V}{V}} \cdot 100 = 1.605\%$

$A_{cm} = \frac{|0 - 0.052|}{0.052} \cdot 100 = 100\%$

- The Discrepancy is 100% no matter how small I calculated Acm. But by giving my calculated Acm another View, you realize how small it is. If my calculated Acm was Very high, then there would be cause for some concern over the Circuit.

$R_{in} = \frac{25.4296K\Omega - 25K\Omega}{25K\Omega} \cdot 100 = 1.7184\%$