THE 741 OPERATIONAL AMPLIFIER

ELEC 3509A – L6

Lab 3 Report

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PRELAB CALCULATIONS

DC Analysis:

- Transistors Q14, Q20

$$V_{BE20} + R_7(I_{E20}) + R_6(I_{R10} + I_{R10}) + V_{BE14} = -1.4$$

$$ln\left(\frac{I_C}{I_{S14}}\right)V_T + R_7(I_{E20}) + R_6(I_{E20} + I_{R10}) + ln\left(\frac{I_C}{I_{S20}}\right)V_T = 1.4$$

$$ln\left(\frac{(100/101)I_{E20}}{I_{S14}}\right)(25mV) + (30)(I_{E20}) + ln\left(\frac{(100/101)I_{E20}}{I_{S20}}\right) = 1.4$$

$$\therefore\ I_{E20} = I_{E14} = 1.14\ mA$$

$$I_{C20} = I_{C14} = I_E\frac{\beta}{\beta + 1} = (1.14 * 10^{-3}) * \frac{100}{100 + 1} = 1.13\ mA$$

$$g_{m20} = g_{m14} = \frac{I_C}{V_T} = \frac{1.13 * 10^{-3}}{25 * 10^{-3}} = 45.2mA/V$$

$$r_{o20} = \frac{V_A}{I_{C20}} = \frac{20}{1.13 * 10^{-3}} = 17.7\ k\Omega$$

$$r_{o14} = \frac{80}{1.13 * 10^{-3}} = 70.8\ k\Omega$$

- Transistor Q23

$$I_{E23} = \frac{I_C}{\beta} + \left[180\ \mu A + \left(\frac{5 - 3.22}{R_{13}} - \frac{I_{C14}}{\beta}\right)\right] = \frac{1.13\ mA}{100} + \left[180\ \mu A + \left(\frac{5 - 3.22}{90\ k\Omega} - \frac{1.13\ mA}{100}\right)\right]$$
$$= 200\ \mu A$$

$$I_{C23} = I_{E23}\frac{\beta}{\beta + 1} = 200\ \mu A\frac{100}{100 + 1} = 198\ \mu A$$

$$g_{m23} = \frac{I_{C23}}{V_T} = \frac{198\ \mu A}{25\ mV} = 7.92\ mA/V$$

$$r_{o23} = \frac{V_A}{I_{C23}} = \frac{20}{198\ \mu A} = 101\ k\Omega$$

- Transistor Q17

$$I_{C17} = \frac{I_{C23}}{\beta} + 550\ \mu A + \frac{5 - 1.22}{30\ k\Omega} = \frac{198\ \mu A}{100} + 500\ \mu A + \frac{5 - 1.22}{30\ k\Omega} = 678\ \mu A$$

$$g_{m17} = \frac{I_{C17}}{V_T} = \frac{678\ \mu A}{25\ mV} = 27.1\ mA/V$$

$$r_{o17} = \frac{V_A}{I_{C17}} = \frac{80}{678\ \mu A} = 118\ k\Omega$$

- Transistor Q16

$$I_{E16} = \frac{I_{C17}}{\beta} + \frac{669\ mV}{R_9} = \frac{678\ \mu A}{100} + \frac{669\ mV}{50\ k\Omega} = 20.2\ \mu A$$

$$I_{C16} = \frac{\beta}{\beta + 1} I_{E16} = \frac{100}{100 + 1} * 20.2\ \mu A = 19.96\ \mu A$$

$$g_{m16} = \frac{I_{C16}}{V_T} = \frac{19.96\ \mu A}{25\ mV} = 798\ \mu A/V$$

$$r_{o16} = \frac{V_A}{I_{C16}} = \frac{80}{19.96\ \mu A} = 4\ M\Omega$$

- Transistor Q1

$$V_{in} = 2.5\ V \ \therefore V_{E1} = 2.5\ V$$

$$V_{E1} = V_{E2} = 2.5\ V + 0.6\ V = 3.1\ V$$

$$\therefore\ I_{E1} = I_{E2} = 10.45\ \mu A$$

$$I_{C1} = \frac{\beta}{\beta + 1} I_{E1} = \frac{100}{100 + 1} (10.45\ \mu A) = 10.35\ \mu A$$

$$g_{m1} = \frac{I_{C1}}{V_T} = \frac{10.35\ \mu A}{25\ mV} = 414\ \mu A/V$$

$$r_{o1} = \frac{V_A}{I_{C1}} = \frac{80}{10.35\ \mu A} = 1.93\ M\Omega$$

- <u>Transistor Q2</u>

$$I_{C2} = I_{C1} = 10.35\ \mu A$$

$$g_{m2} = g_{m1} = 414\ \mu A/V$$

$$r_{o2} = r_{o1} = 1.93\ M\Omega$$

- <u>Transistor Q6</u>

$$I_{C6} = I_{C2} - \frac{I_{C16}}{\beta} = 10.35\ \mu A - \frac{19.96\ \mu A}{25\ mV} = 10.15\ \mu A$$

$$g_{m6} = \frac{I_{C6}}{V_T} = \frac{10.15\ \mu A}{25\ mV} = 406\ \mu A/V$$

$$r_{o6} = \frac{V_A}{I_{C16}} = \frac{80\ V}{10.15\ \mu A} = 7.9\ M\Omega$$

- <u>Transistor Q5</u>

$$I_{E5} = \frac{10.25\ mV}{R_1} = \frac{10.25\ mV}{1\ k\Omega} = 10.25\ \mu A$$

$$I_{C5} = \frac{\beta}{\beta + 1} I_{E5} = \frac{100}{100 + 1}(10.25\ \mu A) = 10.15\ \mu A$$

$$g_{m5} = \frac{I_{C5}}{V_T} = \frac{80\ V}{25\ mV} = 406\ \mu A/V$$

$$r_{o5} = \frac{V_A}{I_{C5}} = \frac{80}{10.15\ \mu A} = 7.9\ M\Omega$$

- <u>Transistor Q7</u>

$$I_{E7} = \frac{I_{C5}}{\beta} + \frac{0.61}{R_3} + \frac{I_{C6}}{\beta} = \frac{10.15\ \mu A}{100} + \frac{0.61\ V}{50\ k\Omega} + \frac{10.15\ \mu A}{100} = 12.4\ \mu A$$

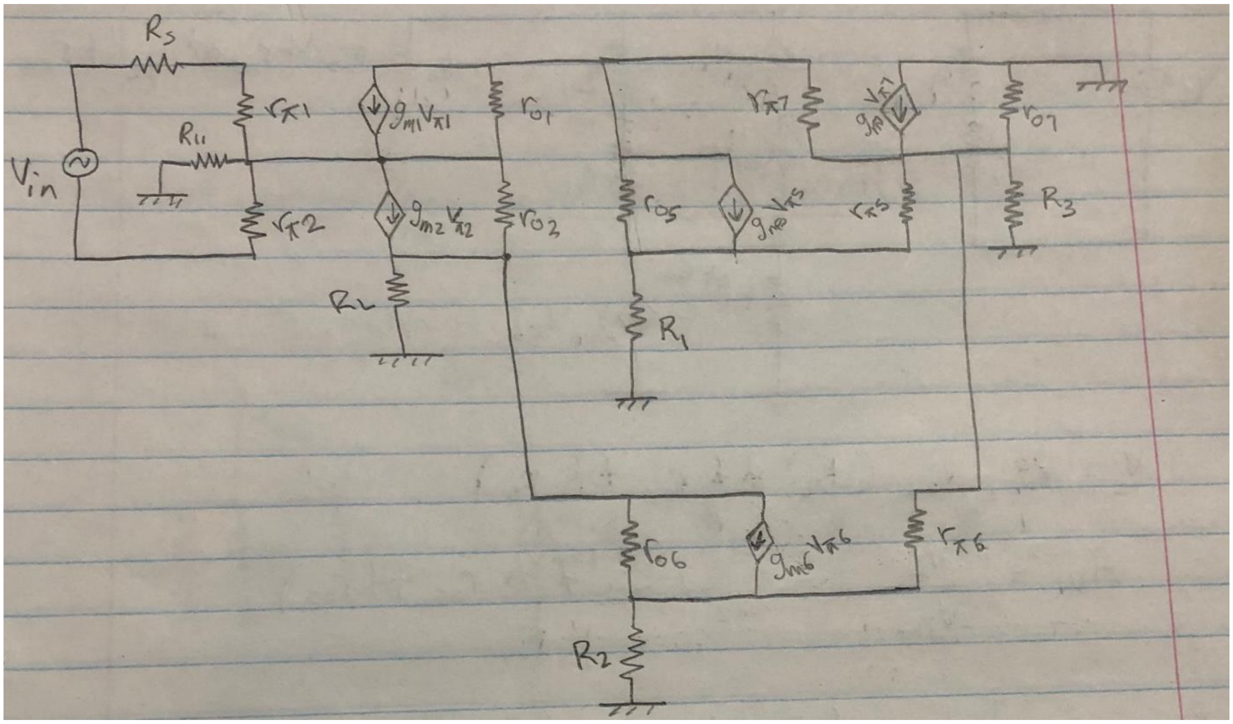
$$I_{C7} = \frac{\beta}{\beta + 1} I_{E7} = \frac{100}{100 + 1} * 12.4\ \mu A = 12.28\ \mu A$$

$$g_{m7} = \frac{I_{C7}}{V_T} = \frac{12.28\ \mu A}{25\ mV} = 491.2\ \mu A/V$$

$$r_{o7} = \frac{V_A}{I_{C7}} = \frac{80}{12.28\ \mu A} = 6.5\ M\Omega$$

AC Analysis

- First Stage Gain A_{V1}



$$I_5 = \frac{V_{\pi 5}}{r_{o5}} + \frac{V_{\pi 5}}{r_{\pi 5}} + g_{m5}V_{\pi 5}$$

$$I_5 = \frac{V_{\pi 5}}{r_{o5}//r_{\pi 5}//\frac{1}{g_{m5}}}\ parallel\ with\ r_{\pi 6}$$

$$V_L = 2g_{m2}V_{\pi 2}(R_{L1}//r_{o6}//r_{o2})$$

$$A_{V1} = \frac{V_L}{V_{in}} = g_{m2}(R_{L1}//r_{o6}//r_{o2})$$

$$R_{out1} = r_{o6}[1 + g_{m6}(R_2//r_{\pi 6})] + (R_2//r_{\pi 6})$$

$$R_{out1} = (7.9\ M\Omega)[1 + 406\ \mu A/V * (1\ k\Omega//249\ \text{k}\Omega)] + (1\ k\Omega//249\ k\Omega)$$

$$R_{out1} = 11.095\ M\Omega$$

$$R_{in2} = (\beta_{16} + 1)[(r_{e16} + r_{o16})//R_9//\left(r_{\pi 17} + R_8 + (R_8 * g_{m17} * r_{\pi 17})\right)]$$

$$R_{in2} = 1.218\ M\Omega$$

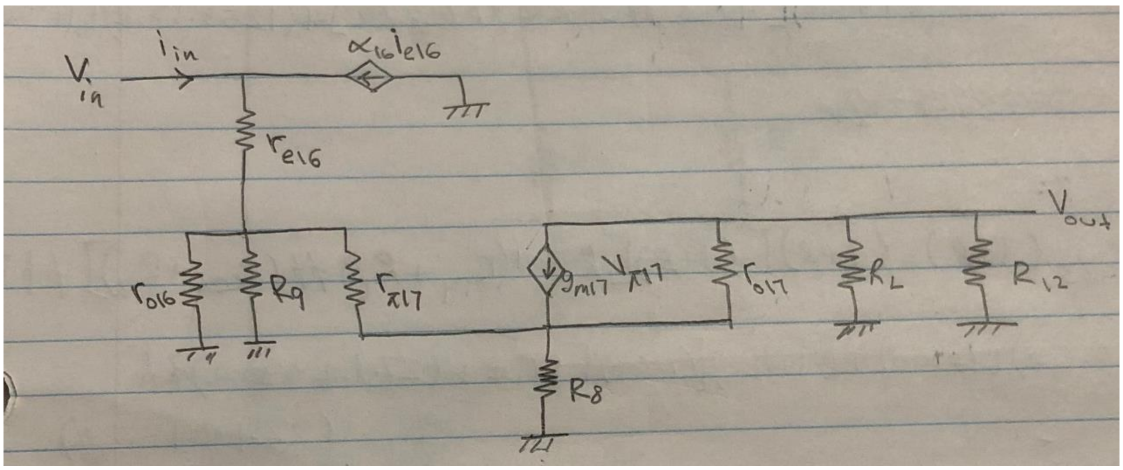
$$R_{L1} = R_{in2}//R_{out1} = 1.218\ M\Omega//11.095\ M\Omega$$

$$R_{L1} = 1.098\ M\Omega$$

$$A_{V1} = g_{m2}(R_{L1}//r_{o6}//r_{o2}) = 414\ \mu A/V(1.098\ M\Omega//7.9\ \mathrm{M\Omega}//1.93\ \mathrm{M\Omega})$$

$$A_{V1} = 266.16\ V/V$$

- Second Stage Gain A_{V2}



$$A_{V2} = \frac{V_{out}}{V_{in}} = \frac{V_{out}}{V_{\pi 17}} * \frac{V_{\pi 17}}{V_{b17}} * \frac{V_{b17}}{V_{in}}$$

$$\frac{V_{\pi 17}}{V_{b17}} = \frac{r_{\pi 17}}{r_{\pi 17} + R_8(1+\beta)} = \frac{3.7\ k\Omega}{3.7\ k\Omega + 100(100+1)} = 0.2681\ V/V$$

$$r'_{\pi 17} = r_{\pi 17} + R_8(\beta + 1) = 3.7\ k\Omega + (100+1) * 100 = 13.8\ k\Omega$$

$$\frac{V_{b17}}{V_{in}} = \frac{(r'_{\pi 17}//R_9//r_{o16})(\beta+1)}{(r'_{\pi 17}//R_9//r_{o16})(\beta+1) + r_{e16}(\beta+1)}$$

$$\frac{V_{b17}}{V_{in}} = \frac{(13.8\ k\Omega//50\ k\Omega//4\ M\Omega)(100+1)}{(13.8\ k\Omega//50\ k\Omega//4\ M\Omega)(100+1) + 1253.13\ \Omega(100+1)} = 0.8959\ V/V$$

$$\frac{V_{out}}{V_{\pi 17}} = -(R_{12}//R_{L2})g_{m17} = -(30\ k\Omega//R_{L2})27.1\ mA/V$$

$$R_{L2} = R_{in3}$$

$$R_{in3} = \Big((\beta+1)\big(R_{10} + (R_6 + r_{e14})//(r_{e20} + R_7)\big)//R_{13}\Big)(\beta+1) + r_{e23}(\beta+1)$$

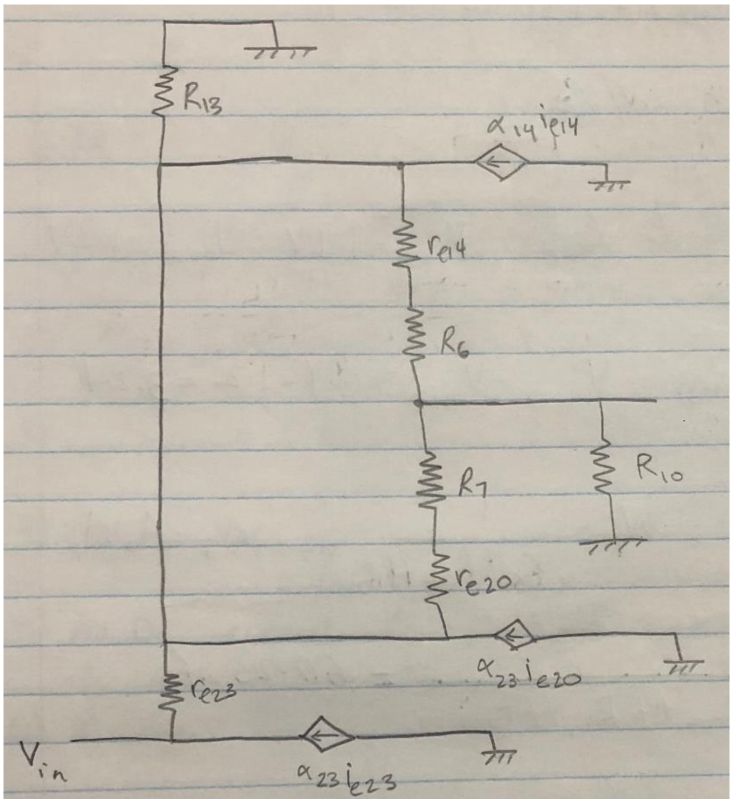
$$R_{in3} = \left((100+1)(1\ M\Omega + (30\ \Omega + 22.1\ \Omega)//(22.1\ \Omega + 30\ \Omega)//90\ k\Omega)\right)(100+1) + 126.6\ \Omega(100+1) = 9.095\ M\Omega$$

$$\therefore\ R_{L2} = 9.095\ M\Omega$$

$$\frac{V_{out}}{V_{\pi17}} = -(R_{12}//R_{L2})g_{m17} = -(30\ k\Omega//9.095\ \mathrm{M\Omega})27.1\ mA/V = -810.33\ V/V$$

$$A_{V2} = \frac{V_{out}}{V_{in}} = \frac{V_{out}}{V_{\pi17}} * \frac{V_{\pi17}}{V_{b17}} * \frac{V_{b17}}{V_{in}} = -810.33\ V/V * 0.2681\ V/V * 0.8959\ V/V = -194.63$$

- <u>Third Stage Gain A_{V3}</u>



$$A_{V3} = \frac{(\beta+1)\left(R_{10} + \left(R_{13}//(r_{e16}+R_6)//(R_7+r_{e20})\right)\right)}{r_{e23} + (\beta+1)\left(R_{10} + \left(R_{13}//(r_{e16}+R_6)//(R_7+r_{e20})\right)\right)} * \frac{R_{10}}{R_{10} + (r_{e20}+R_7)//(r_{e14}+R_6)}$$

$$\therefore\ A_{V3} = 0.99\ V/V$$

- Total Gain

$$A_V = A_{V1} * A_{V2} * A_{V3} = 266.16\ V/V * -194.63\ V/V * 0.99\ V/V = -51.3\ kV/V$$

- Input Common Mode Range (CMR)

$$V_{max} = 5 - 0.6 = 4.4\ V$$
$$V_{min} = 5 - (V_{BE5} + V_{BE6} + V_{BE7} + V_{BE14} + V_{BE16} + V_{BE17}) = 1.2\ V$$

- Output Swing

$$V_{max} - V_{min} = 4.4\ V - 1.2\ V = 3.2\ V$$

- Value of C_1 for $f_u = 1\ MHz$

$$C_A = C_1(1 + A_{V2});\ W_P = \frac{1}{C_A(R_{out}//R_{in})};\ W_T = A_O W_P$$

$$C_1 = \frac{A_O}{2\pi f_u(A_{V2} + 1)(R_{in}//R_{out}//r_{o2})} = 60.23\ pF$$

- Slew Rate

$$Slew\ Rate = \frac{I_{C1}}{C_1} = \frac{19\ \mu A}{60.23\ pF} = 0.316\ V/\mu S$$

Transistor	I_C	r_o	g_m
Q_1**(PNP)**	$10.35\ \mu A$	$1.93\ M\Omega$	$414\ \mu A/V$
Q_2**(PNP)**	$10.35\ \mu A$	$1.93\ M\Omega$	$414\ \mu A/V$
Q_5**(NPN)**	$10.15\ \mu A$	$7.9\ M\Omega$	$406\ \mu A/V$
Q_6**(NPN)**	$10.15\ \mu A$	$7.9\ M\Omega$	$406\ \mu A/V$
Q_7**(NPN)**	$12.28\ \mu A$	$6.5\ M\Omega$	$491.2\ \mu A/V$
Q_{14}**(NPN)**	$1.13\ mA$	$70.8\ k\Omega$	$45.2\ mA/V$
Q_{16}**(NPN)**	$19.96\ \mu A$	$4\ M\Omega$	$798\ \mu A/V$
Q_{17}**(NPN)**	$678\ \mu A$	$118\ k\Omega$	$27.1\ mA/V$
Q_{20}**(PNP)**	$1.13\ mA$	$17.7\ k\Omega$	$45.2\ mA/V$
Q_{23}**(PNP)**	$198\ \mu A$	$101\ k\Omega$	$7.92\ mA/V$

REPORT QUESTIONS

1. Explain the difference in role of V10 and V5. Why are both needed?

V10 is the input DC offset voltage applied to the op-amp terminals. V5 is the common node voltage that is connected to both op-amp's terminals. V10 is used to offset the difference between biasing voltages of Q1 and Q2. V5 is used to observe the common mode input voltage supplied to the Q1 and Q2 positive terminals.

2. What is the purpose of Q7 and R3 in this circuit? What difference would there be if instead of both, the collector and base of Q5 were shorted as in the current mirror in Lab 1? You may want to consider the impact of Q16.

The purpose of Q7 and R3 in this circuit is to stabilize the signal by acting as a load for the op-amp input. If the collector and base of Q5 were shorted as in the current mirror in Lab 1, this would make the base current of Q16 to be similar to that of Q7.

3. What is the role of C1 and what would happen if it were absent?

The role of C1 is to short the high frequency signals and maintain a unit gain frequency of 1 MHz. This prevents the distortion of signal.

4. The circuit uses ideal current sources. How would these be implemented in a real circuit? What differences in performance might be seen as a result? The answer is not finite output impedance since the output impedances are already modeled by R11, R12 and R13.

This can be implemented in a real circuit by switching the current sources with current mirrors which will cause the gain, also the input and output impedance will change, impacting the amplifiers frequency response.

5. What is the purpose of V2? How would V2 be implemented in a real circuit?

The purpose of V2 is biasing voltage of Q14 and Q20 to drive them into active mode. V2 can be applied in a real circuit by using a circuit breaker.

6. Why are 3 stages used in this op-amp design? Why bother with the third stage if it provides such a low gain?

The first stage is used to produce the differential gain, the second stage is used as a high gain amplifier, the third stage is used to achieve a low output impedance which is essential to achieve a high voltage gain and hence making it a wise choice for it to be added to the circuit.

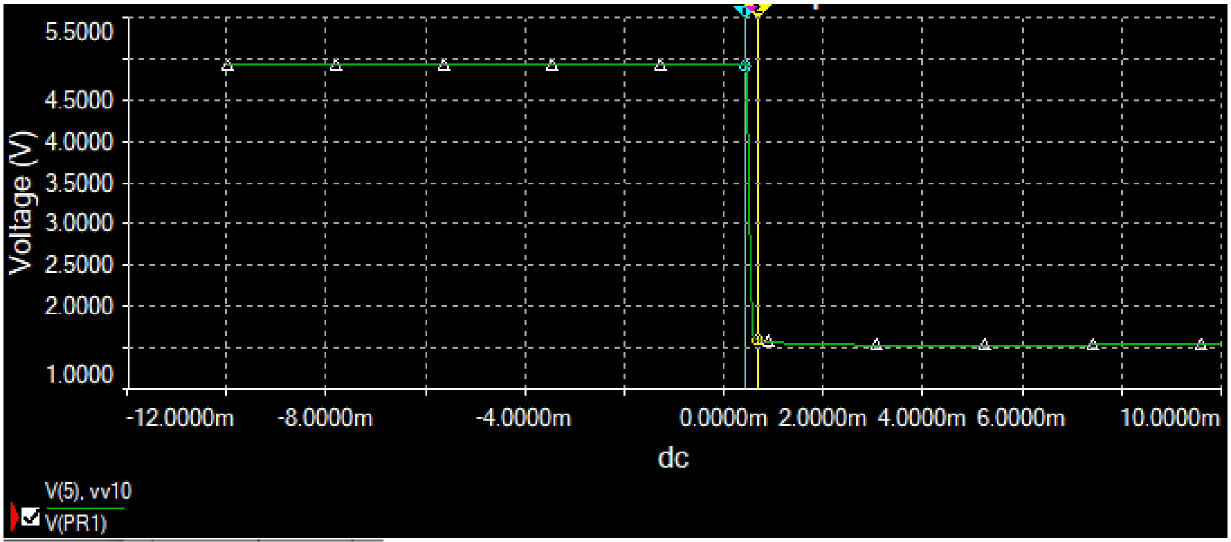
7. What is the DC power consumption of the entire circuit (assume no input signal).

$$P = (I_1 + I_2 + I_3 + I_{C14} + I_{C16} + I_{R11} + I_{R12} + I_{R13})V_{CC} + V_o I_o$$

$$P = 10.25\ mW$$

SIMULATION RESULTS AND DISCUSSION

Part 1



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	V(5), vv10 / V(PR1)
x1	469.8884µ
y1	4.8715
x2	530.3987µ
y2	1.7548
dx	60.5104µ
dy	-3.1167
dy/dx	-51.5065k
1/dx	16.5261k

As seen from the plot, the range of linear regression is from 1.7548 V to 4.8715 V

$$Output\ Voltage\ Swing = 4.8715\text{ V} - 1.7548\text{ V} = 3.1167\ V$$

The simulated output voltage swing is 3.1167 V which is very close to the prelab 3.2 V.

$$Differential\ Gain = \frac{y_2 - y_1}{x_2 - x_1} = \frac{(1.7548) - (4.8715)}{(530.3987 * 10^{-6}) - (469.8884 * 10^{-6})} = -51.5\ kV/V$$

The simulated differential gain is -51.5 kV/V which is very close to the prelab -51.3 kV/V.

The input offset voltage at Vo equal 2.5 V is approximately 515 μV which was found by exporting the graph into an excel file and searching for the value of Vd at Vo equal 2.5 V.

Transistor	**Prelab**				**Simulated**			
	$\boldsymbol{I_C}(\mu A)$	$\boldsymbol{r_o}(M\Omega)$	$\boldsymbol{g_m}(\mu A/V)$	$\boldsymbol{\beta}$	$\boldsymbol{I_C}(\mu A)$	$\boldsymbol{r_o}(M\Omega)$	$\boldsymbol{g_m}(\mu A/V)$	$\boldsymbol{\beta}$
$\boldsymbol{Q_1}$**(PNP)**	10.35	1.93	414	100	10.30	1.94	399	194
$\boldsymbol{Q_2}$**(PNP)**	10.35	1.93	414	100	10.50	1.90	404	192
$\boldsymbol{Q_5}$**(NPN)**	10.15	7.9	406	100	10.20	7.32	394	79.4
$\boldsymbol{Q_6}$**(NPN)**	10.15	7.9	406	100	10.20	7.33	394	79.5
$\boldsymbol{Q_7}$**(NPN)**	12.28	6.5	491.2	100	11.30	6.91	436	83.7
$\boldsymbol{Q_{14}}$**(NPN)**	1130	0.0708	45200	100	757	0.01	28900	151
$\boldsymbol{Q_{16}}$**(NPN)**	19.96	4	798	100	19.60	3.97	757	91.5
$\boldsymbol{Q_{17}}$**(NPN)**	678	0.118	27100	100	680	0.109	26000	147
$\boldsymbol{Q_{20}}$**(PNP)**	1130	0.0177	45200	100	757	0.0271	29000	194
$\boldsymbol{Q_{23}}$**(PNP)**	198	0.101	7920	100	197	0.1	7600	190

As seen in the table above, most of the simulated values were very close to the prelab values with some exceptions that had values a bit different. This difference in values can be attributed to the beta value being used in prelab is same for all transistors, while in reality beta value depends on the collector and base currents which is different for each transistor.

- First Stage Gain A_{V1}

$$V_L = 2g_{m2}V_{\pi 2}(R_{L1}//r_{o6}//r_{o2})$$

$$A_{V1} = \frac{V_L}{V_{in}} = g_{m2}(R_{L1}//r_{o6}//r_{o2})$$

$$R_{out1} = r_{o6}[1 + g_{m6}(R_2//r_{\pi 6})] + (R_2//r_{\pi 6}) = 10.1\ M\Omega$$

$$R_{in2} = (\beta_{16} + 1)[(r_{e16} + r_{o16})//R_9//\big(r_{\pi 17} + R_8 + (R_8 * g_{m17} * r_{\pi 17})\big)] = 1.5\ M\Omega$$

$$R_{L1} = R_{in2}//R_{out1} = 1.31\ M\Omega$$

$$A_{V1} = g_{m2}(R_{L1}//r_{o6}//r_{o2}) = 283.29\ V/V$$

- <u>Second Stage Gain A_{V2}</u>

$$A_{V2} = \frac{V_{out}}{V_{in}} = \frac{V_{out}}{V_{\pi 17}} * \frac{V_{\pi 17}}{V_{b17}} * \frac{V_{b17}}{V_{in}}$$

$$\frac{V_{\pi 17}}{V_{b17}} = \frac{r_{\pi 17}}{r_{\pi 17} + R_8(1+\beta_{17})} = 0.28\ V/V$$

$$r'_{\pi 17} = r_{\pi 17} + R_8(\beta + 1) = 20.4\ k\Omega$$

$$\frac{V_{b17}}{V_{in}} = \frac{(r'_{\pi 17}//R_9//r_{o16})(\beta_{16}+1)}{(r'_{\pi 17}//R_9//r_{o16})(\beta+1) + r_{e16}(\beta+1)} = 0.92\ V/V$$

$$R_{L2} = R_{in3}$$

$$R_{in3} = \Big((\beta+1)\big(R_{10} + (R_6 + r_{e14})//(r_{e20} + R_7)\big)//R_{13}\Big)(\beta+1) + r_{e23}(\beta+1) = 17.2\ M\Omega$$

$$\therefore\ R_{L2} = 17.2\ M\Omega$$

$$\frac{V_{out}}{V_{\pi 17}} = -(R_{12}//R_{L2})g_{m17} = -778.6\ V/V$$

$$A_{V2} = \frac{V_{out}}{V_{in}} = \frac{V_{out}}{V_{\pi 17}} * \frac{V_{\pi 17}}{V_{b17}} * \frac{V_{b17}}{V_{in}} = -778.6\ V/V * 0.28\ V/V * 0.92\ V/V = -200.57\ V/V$$

- <u>Third Stage Gain A_{V3}</u>

$$A_{V3} = \frac{(\beta+1)\Big(R_{10} + \big(R_{13}//(r_{e16}+R_6)//(R_7 + r_{e20})\big)\Big)}{r_{e23} + (\beta+1)\Big(R_{10} + \big(R_{13}//(r_{e16}+R_6)//(R_7+r_{e20})\big)\Big)} * \frac{R_{10}}{R_{10} + (r_{e20}+R_7)//(r_{e14}+R_6)}$$

$$A_{V3} = 0.99\ V/V$$

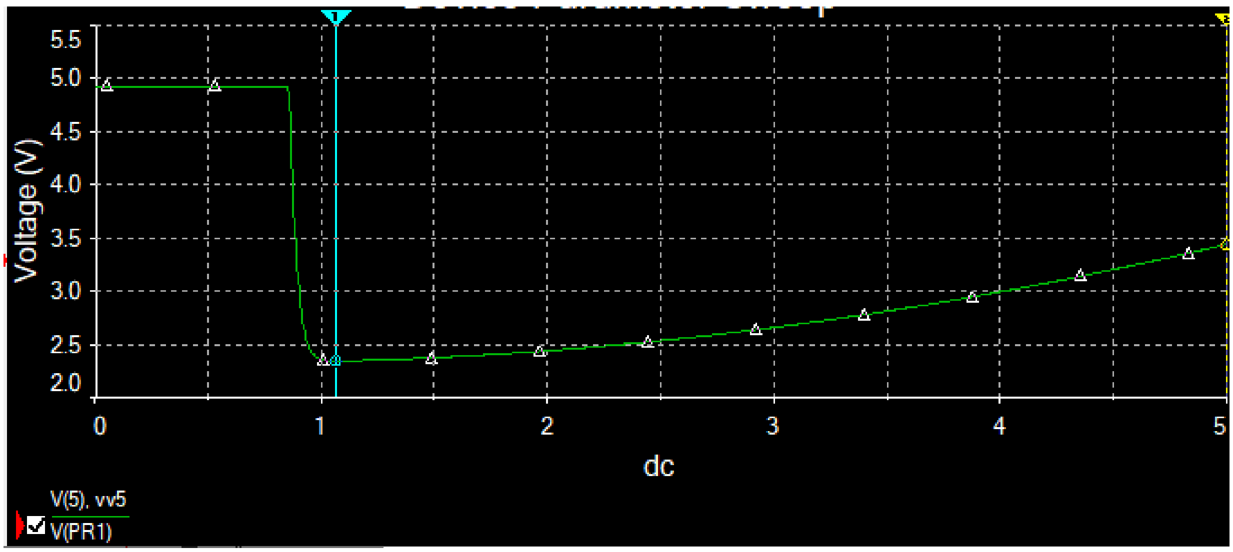
- <u>Total Gain (A_V)</u>

$$A_V = A_{V1} * A_{V2} * A_{V3} = 283.29\ V/V * -200.57\ V/V * 0.99\ V/V = -56.25\ kV/V$$

	Prelab	Simulated
First Stage (A_{V1})	$266.16\ V/V$	$283.29\ V/V$
Second Stage (A_{V2})	$-194.63\ V/V$	$-200.57\ V/V$
Third Stage (A_{V3})	$0.99\ V/V$	$0.99\ V/V$
Total Gain (A_V)	$-51.3\ kV/V$	$-56.25\ kV/V$

The simulated first stage gain, second stage gain, and total gain is very close to each other which shows that the equations used to find the gain is accurate, specially the third stage gain being the most accurate with the least error.

A plot for Vo versus Vcm is shown below.



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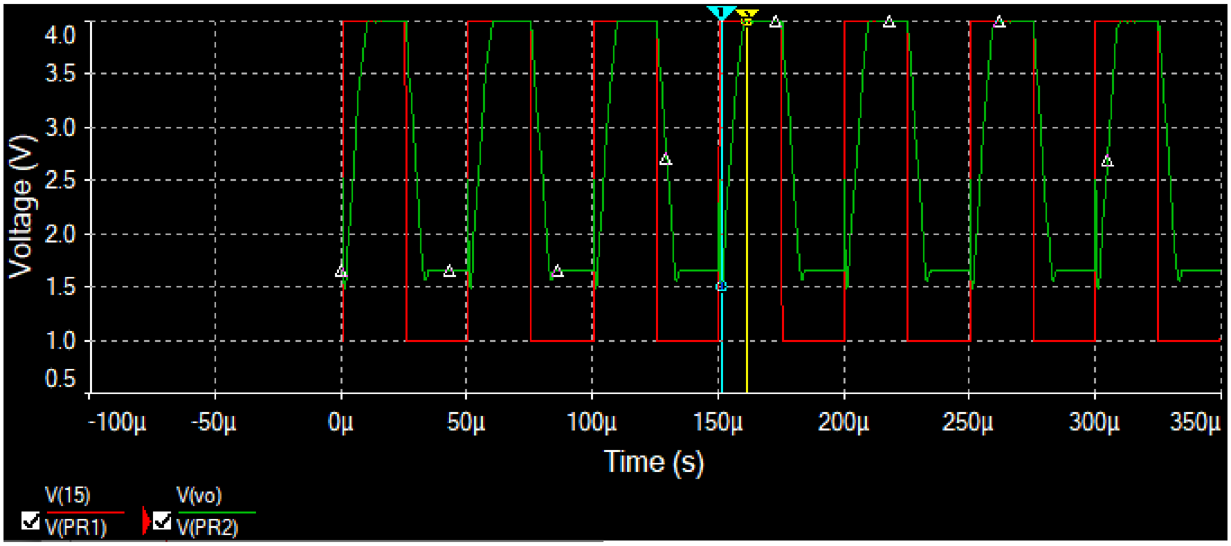
	V(5), vv5 V(PR1)
x1	1.0606
y1	2.3430
x2	5.0000
y2	3.4403
dx	3.9394
dy	1.0973
dy/dx	278.5457m
1/dx	253.8462m

The plot above shows that the common mode range is from 1.0606 V to 5 V which is close to the prelab value 1.2 V to 4.4 V. The plot shows that the input can reach to 5 V which is due to the upper limit of the AC sweep being 5 V.

Part 2

A plot for the input and output transient voltage waveforms is shown below.



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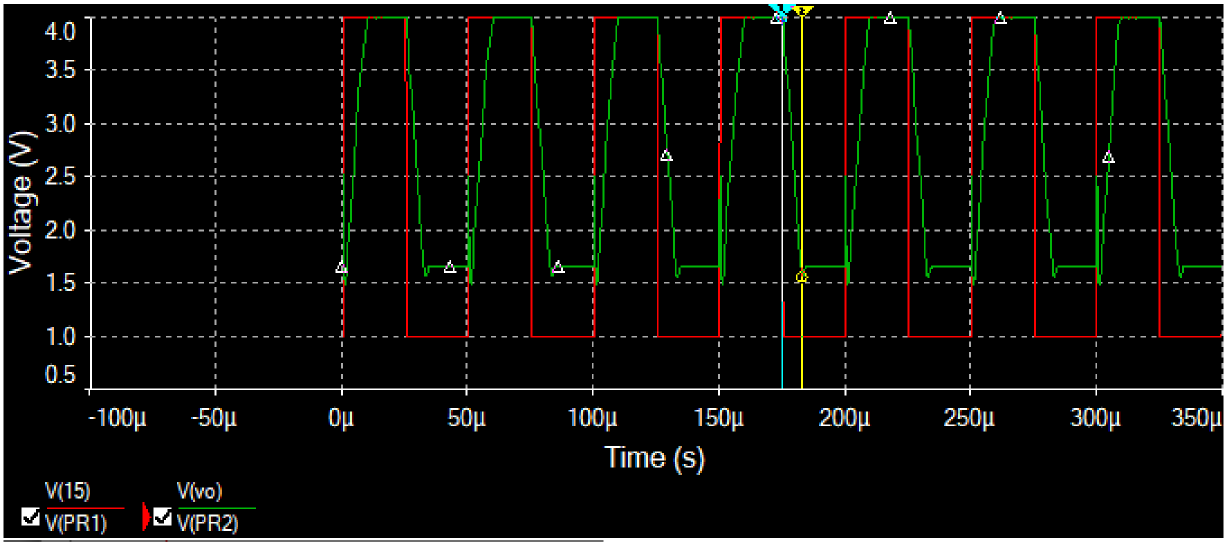
	V(15) V(PR1)	V(vo) V(PR2)
x1	151.1962µ	151.1962µ
y1	4.0000	1.5071
x2	161.2440µ	161.2440µ
y2	4.0000	4.0090
dx	10.0478µ	10.0478µ
dy	0.0000	2.5019
dy/dx	0.0000	248.9952k
1/dx	99.5238k	99.5238k

$$+ve\ Slew\ Rate = \frac{y_2 - y_1}{x_1 - x_2} = \frac{4.0090 - 1.5071}{(161.2440 * 10^{-6}) - (151.1962 * 10^{-6})} = 0.249\ V/\mu s$$

The positive slew rate is 0.249 V/μs.



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	V(15) V(PR1)	V(vo) V(PR2)
x1	174.8804µ	174.8804µ
y1	4.0000	4.0017
x2	182.7751µ	182.7751µ
y2	1.0000	1.5686
dx	7.8947µ	7.8947µ
dy	-3.0000	-2.4331
dy/dx	-380.0000k	-308.1948k
1/dx	126.6667k	126.6667k

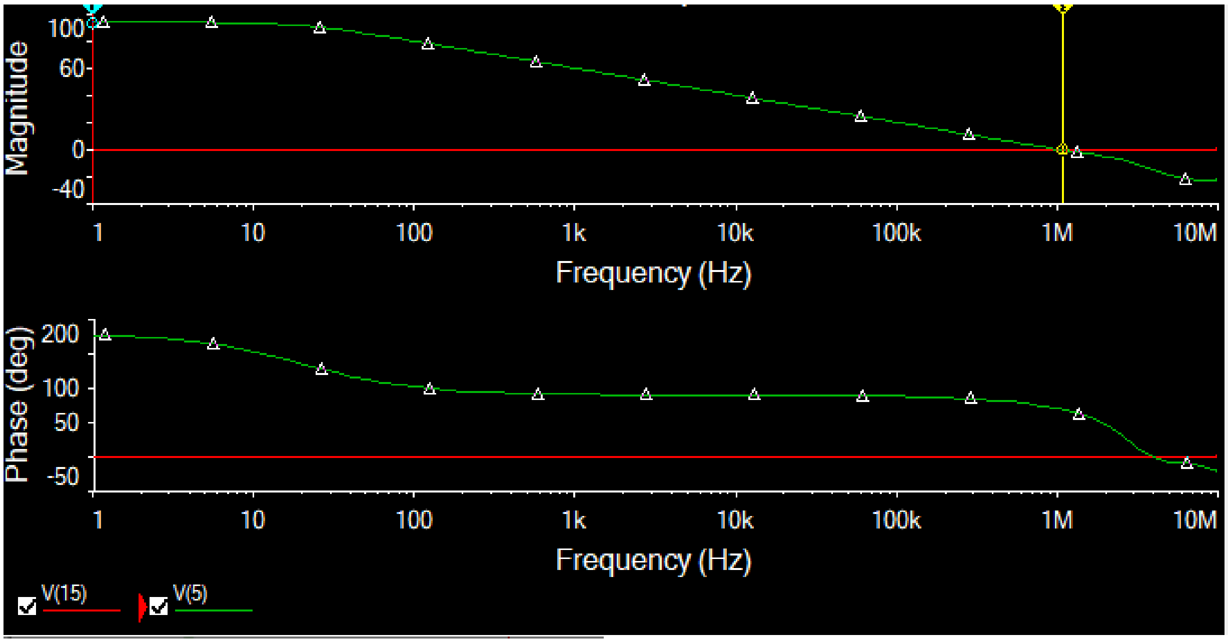
$$-ve\ Slew\ Rate = \frac{y_2 - y_1}{x_1 - x_2} = \frac{1.5686 - 4.0017}{(182.7751 * 10^{-6}) - (174.8804 * 10^{-6})} = -0.308\ V/\mu s$$

The negative slew rate is -0.308 V/μs.

There is a slight difference between the simulated slew rate and the prelab slew rate which is due to the difference in gains.

Part 3

A plot for differential magnitude and phase response of the circuit between 1 Hz to 10 MHz with the input voltage set to unity is shown below.



Cursor

	V(15)	V(5)
x1	1.0000	1.0000
y1	0.0000	94.3303
x2	1.0750M	1.0750M
y2	0.0000	1.6751m
dx	1.0750M	1.0750M
dy	0.0000	-94.3286
dy/dx	0.0000	-87.7500µ
1/dx	930.2584n	930.2584n

In order to find the unity gain frequency (f_u) using the frequency response above, I had to find the point at which the magnitude is equal to 0, which as at approximately frequency equal 1.075 MHz, hence the unity gain frequency (f_u) is equal to approximately 1.075 MHz which is very close to the prelab value which is 1 MHz.

CONCLUSION

In conclusion, this lab shows how to analyze an op-amp and determine its gain, voltage swing, common-mode range, and slew rate.

Overall, the equations used in the prelab were pretty accurate and for the most part, the simulated results were very close to the prelab results. There were little errors that was encountered that would have been because rounding the numbers during calculations or assuming the same beta value for all transistors during prelab.

APPENDIX

BJT: Bipolar Junction Transistor

Device	Q_Q14	Q_Q17	Q_Q16	Q_Q6	Q_Q5	Q_Q7
Model	2N3904	2N3904	2N3904	2N3904	2N3904	2N3904
ic	0.000757	0.000679	1.96e-05	1.02e-05	1.02e-05	1.13e-05
ib	5.79e-06	5.35e-06	2.58e-07	1.55e-07	1.55e-07	1.63e-07
ie	-0.000763	-0.000685	-1.98e-05	-1.04e-05	-1.03e-05	-1.14e-05
vbe	0.658	0.655	0.562	0.546	0.547	0.548
vbc	-1.78	-0.429	-3.71	-0.729	-0.548	-3.9
gm	0.029	0.026	0.000756	0.000394	0.000394	0.000436
gpi	0.000192	0.000177	8.27e-06	4.96e-06	4.96e-06	5.21e-06
gmu	1.36e-12	1.38e-12	1.36e-12	1.37e-12	1.37e-12	1.36e-12
gx	0.1	0.1	0.1	0.1	0.1	0.1
go	9.99e-06	9.12e-06	2.52e-07	1.36e-07	1.37e-07	1.45e-07
cpi	1.52e-11	1.43e-11	6.3e-12	6.13e-12	6.13e-12	6.15e-12
cmu	2.5e-12	3.16e-12	2.1e-12	2.95e-12	3.07e-12	2.07e-12
cbx	0	0	0	0	0	0
ccs	0	0	0	0	0	0

BJT: Bipolar Junction Transistor

Device	Q_Q20	Q_Q23	Q_Q1	Q_Q3
Model	2N3906	2N3906	2N3906	2N3906
ic	0.000757	0.000197	1.03e-05	1.05e-05
ib	3.85e-06	1.03e-06	5.33e-08	5.44e-08
ie	-0.000761	-0.000198	-1.04e-05	-1.05e-05
vbe	0.696	0.662	0.586	0.586
vbc	-1.81	-1.15	-1.4	-1.21
gm	0.029	0.00758	0.000399	0.000404
gpi	0.000149	3.98e-05	2.06e-06	2.1e-06
gmu	2.01e-13	2.01e-13	2.01e-13	2.01e-13
gx	0.1	0.1	0.1	0.1
go	3.69e-05	9.92e-06	5.15e-07	5.25e-07
cpi	1.89e-11	1.47e-11	1.26e-11	1.26e-11
cmu	4.78e-12	5.68e-12	5.3e-12	5.58e-12
cbx	0	0	0	0
ccs	0	0	0	0