THE PENNSYLVANIA STATE UNIVERSITY

EE 310 : ELECTRONIC CIRCUIT DESIGN I

Amplifier Design Using an Active Load

William David Stranburg

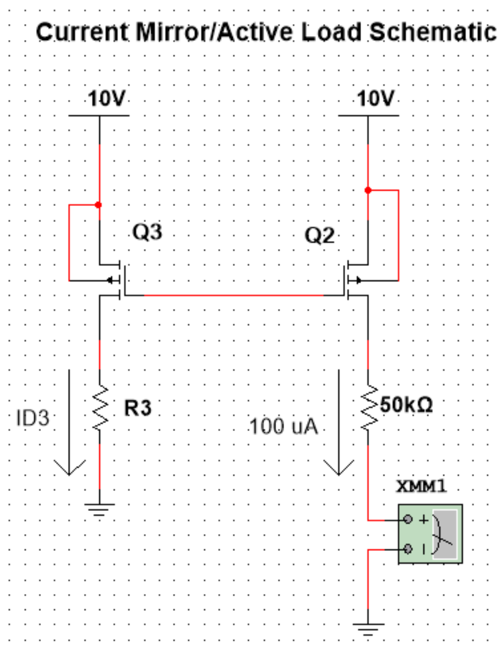
Introduction:

In Part 1 of this lab, we used an NMOS amplifying transistor with a complementary PMOS transistor configured as a current mirror/active load. The goal of this circuit is to amplify small time-varying input signals. An active load consists of purely transistors, opposed to a resistive load which can include resistors. An active load is advantageous because it presents a high small-signal impedance but without requiring a high DC voltage drop. We had to establish a Quiescent Point (Q-point) near the center of the saturation region of the transistors in order to create the best amplifying device. We then superimposed the AC source and calculated the theoretical gain and compared it to the experimental gain.

The second part of this lab required us to investigate how the Body Effect changed the small-signal gain, particularly in the Common-Drain and Common-Gate transistor configurations. The Body Effect, in short, is due a reverse bias voltage across a source terminal's substrate which changes the threshold voltage. The Body Effect is a semi-conductor parameter and is a function of the semiconductor doping. We were to design a circuit that directly measured the body transconductance and the body effect parameter. **We were required to use transistor parameter values that were found in previous Labs and have been conveniently organized into the following table in the lab notes. For this reason, the table is omitted from this written report.**

Task 1: Current Mirror/Active Load

Two PMOS devices on the CD-4007 chip were used, with previously determined parameters, to create a DC drain current of 100 µA in Q3. Since the drain-to-gate voltage is 0 Volts, we know the device is operating in saturation. With the transistors having "matched" parameters due to production methods, the current should be mirrored to Q2 and be read by the ammeter.



Data/Calculations:

$I_{D3} = K_P (V_{SG} + V_{TP})^2$

$V_{SG} = (I_{D3}/K_p)^{1/2} + V_{TP}$

$= (100\ \mu A/0.394\ mA/V^2)^{1/2} + (1.60\ V)$

$\mathbf{V_{SG2} = 2.10\ V}$

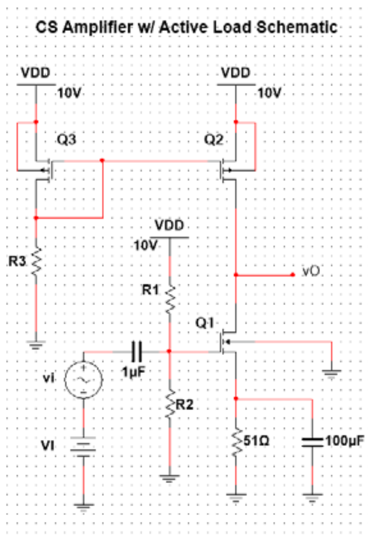
$R_3 = (V_{DD} - V_{SG2})/ I_{D3}$

$= (10\ V - 2.10\ V)/ 100\ \mu A$

R_3 = 79 kΩ and **R_3 (measured) = 80.7kΩ**

Task 2: Common-Source (CS) Amplifier Circuit

Now, we had to add another transistor, Q1, which was an NMOS common source amplifier that used the current mirror from Task 1 as an active load. Resistors R1 and R2 had to be properly chosen to keep all transistors functioning in the saturation region. The 1 uF capacitor was necessary at the gate of Q1 to couple the AC input signal to the gate without disturbing the DC value of V_{GS}.



Data/Calculations:

$I_{D1} = K_N (V_{GS1} - V_{TN})^2$

$V_{GS1} = (I_{D1}/K_n)^{1/2} + V_{TN}$

$= (100\ \mu A)(0.329\ mA/V^2)^{1/2} + 1.20\ V$

$\mathbf{V_{GS1} = 1.75\ V}$

$R_1 = (V_{DD} - V_{GS2} - V_{SS})/10\ \mu A$

$= (10\ V - 2.10\ V)/10\ \mu A$

$\mathbf{R_1 = 790\ k\Omega}$

$R_2 = V_{SG2}/10\ \mu A$

$\mathbf{R_2 = 210\ k\Omega}$

Task 3: Adjusting the Q-Point

In order to achieve precise bias conditions, we had to use a potentiometer in series with R_2. We needed the output voltage to be half of the DC supply in order to establish the Q-Point in the center of the saturation region. We then used a high impedance probe on the oscilloscope to minimize loading effects.

Data/Calculations:

R_1 (measured) = 833 kΩ

R_2 (measured) = R_2 (actual) + potentiometer = **127.2 kΩ**

$v_o = V_{DD}/2 = 5v$ (ideal)

v_o (measured) = 5.17 V

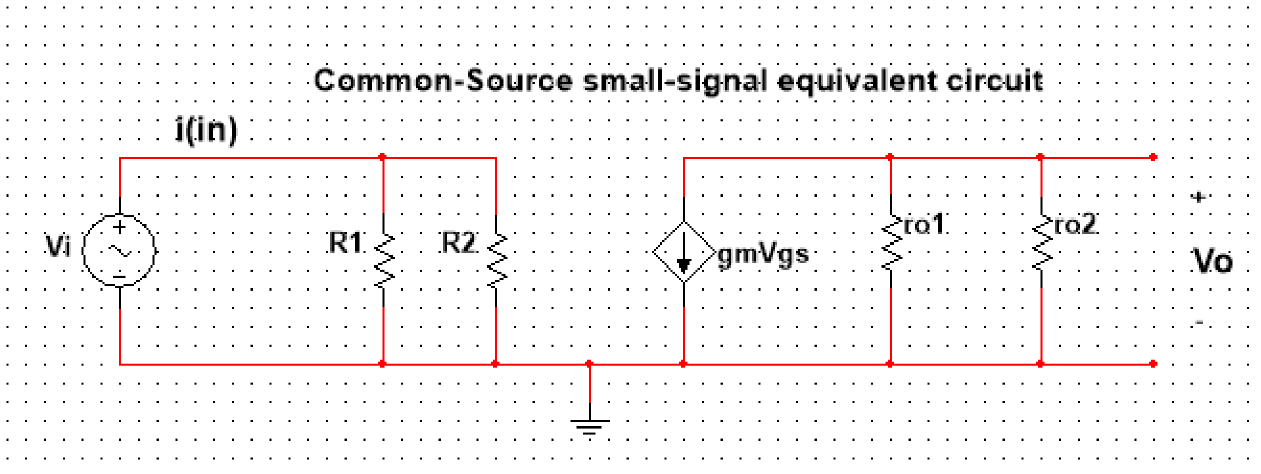
V_{GS1} (measured) = 1.56 V

V_{SG2} (measured) = 2.09 V

I_{D1} (measured) = 98.6 μA

Task 4: Measuring the Voltage Gain

We now had to develop a small-signal equivalent circuit model for the Common-Source Amplifier configuration. For extra precision, the channel-length modulation parameter (λ) in our calculations. From the small-signal circuit, we could calculate the small-signal voltage gain (A_v), as well as the input and output resistances, Ri and Ro, respectively.



Data/Calculations:

$g_{m1} = 2[K_n I_D(1+ \lambda V_{DS})]^{1/2}$

$= 2\{(0.329\ mA/V^2)(98.6\ \mu A)[(1+(.016\ V^{-1})(5.17\ V)]\}^{1/2}$

$g_{m1} = .375\ mA/V$

$R_{in} = R_1 // R_2$

$\mathbf{R_{in} = 110\ k\Omega}$

$r_{o1} = 1/(\lambda_1 I_D) = 634\ k\Omega$ and $r_{o2} = 1/(\lambda_2 I_D) = 5.1\ M\Omega$

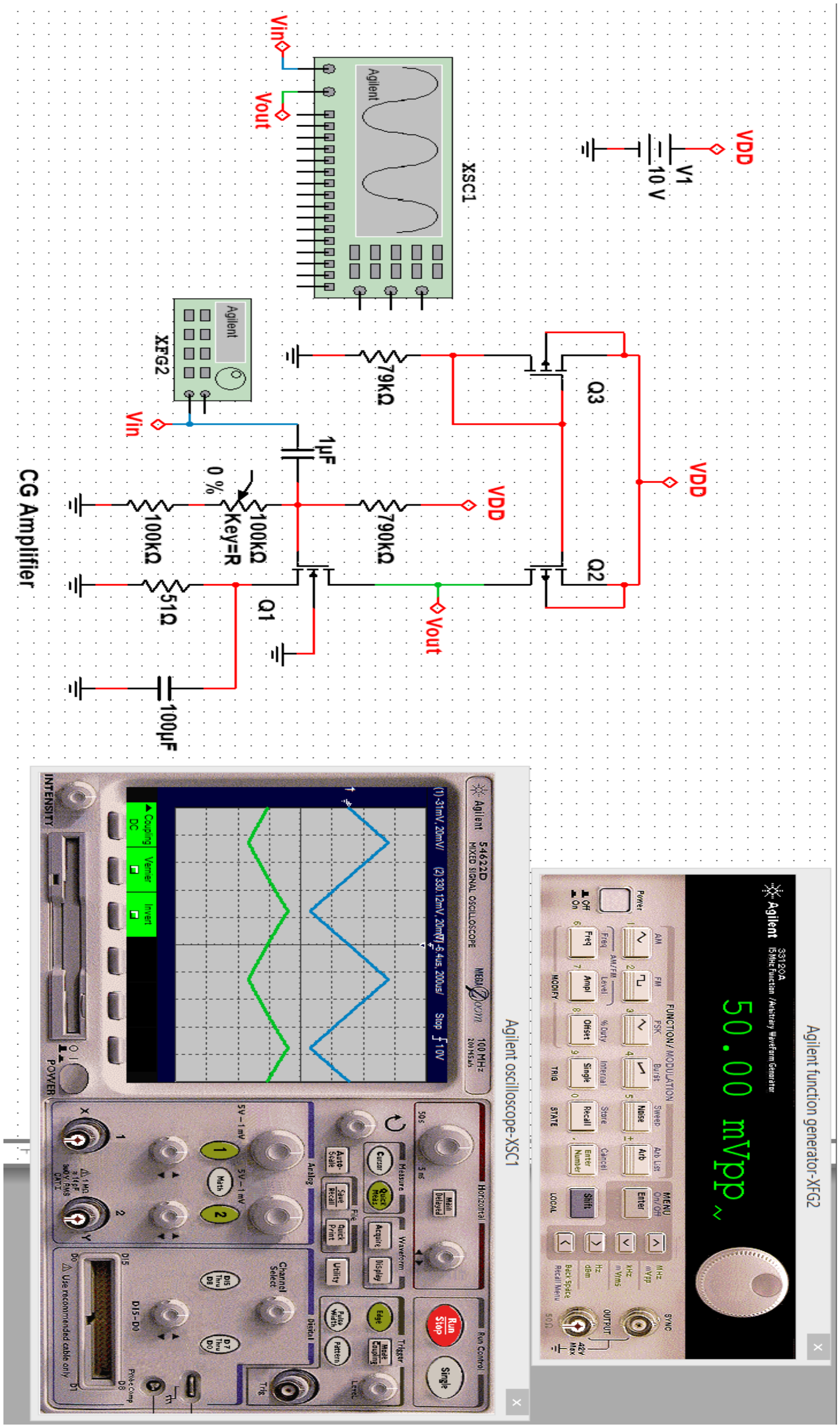
$R_{out} = r_{o1}//r_{o2}$

$\mathbf{R_{out} = 564\ k\Omega}$

$A_v = v_o/v_i = -g_{m1}v_{gs}R_{out}/v_{gs} = -g_{m1}R_{out}$

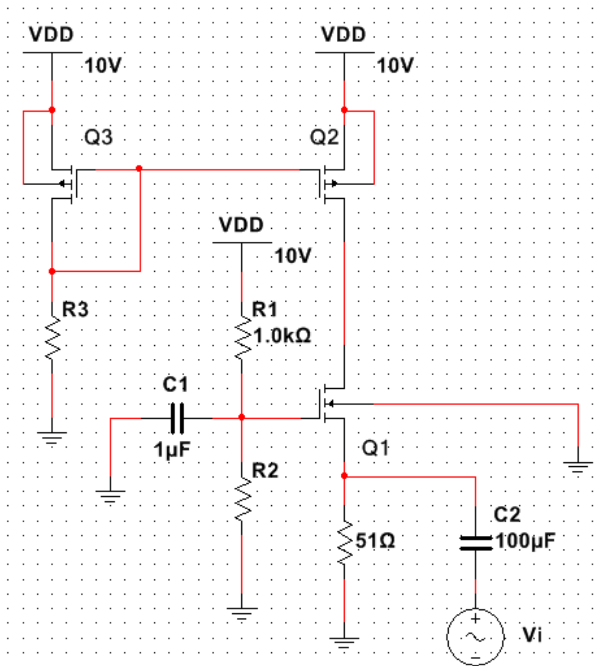
$\mathbf{A_v = -211.5\ V/V}$ **(theoretical)**

Measuring the Voltage Gain in Multisim (fig 3 in handout)

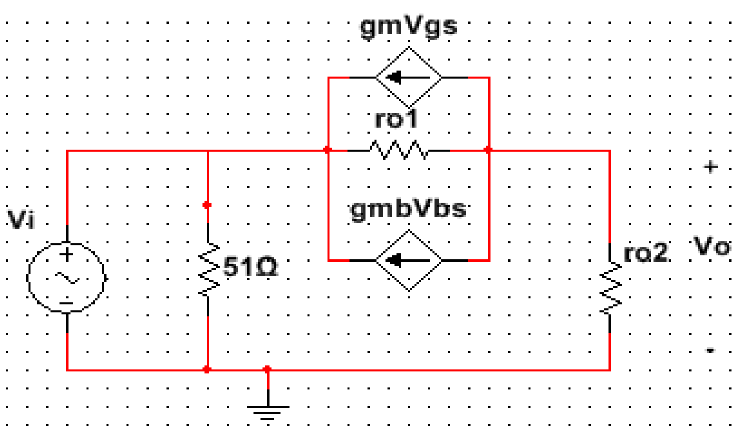


Task 5: Common-Gate (CG) Amplifier Circuit

A Common-Gate configuration is easily created using the Common-Source circuit with a few modifications to transistor Q1. In particular, the gate terminal was grounded and the signal was connected to the source terminal. The same Q-point was used for this circuit.



CG Amplifier w/ Active Load



CG Small-signal equivalent

Data/Calculations:

$\mathbf{R_{in} = 51\Omega}$ (by inspection)

$\mathbf{R_{out}}$ = $r_{o1}//r_{o2}$ = $\mathbf{564\ k\Omega}$

$A_v = v_o/v_i$

$v_o = r_{o2}[-g_{m1}v_{gs1} - g_{mb1}v_{bs1} + (v_i - v_o)/r_{o1}]$

$= r_{o2}v_i[g_{m1} + g_{mb1} + 1/r_{o1}] - (r_{o2}/r_{o1})v_o$

$v_i = v_{gs}$

$A_v = (g_{m1} + g_{mb1} + 1/r_{o1})R_{out}$

$\mathbf{A_v = 264.25\ V/V}$ **(theoretical)**

<u>Task 6:</u> Deducing Values for the Body Effect

In this task we had to use the difference in gain magnitudes between the CS and CG configurations, find a value for g_{mb} (transconductance parameter), and find a value for η (body effect parameter) for the NMOS transistor biased at the previously described Q-point.

Data/Calculations:

$|A_v(CS)| / |A_v(CG)| = 1/(1+\eta)$

$(46.2\ V/V) / (73\ V/V) = 1/(1+\eta)$

$\mathbf{\eta = .580}$

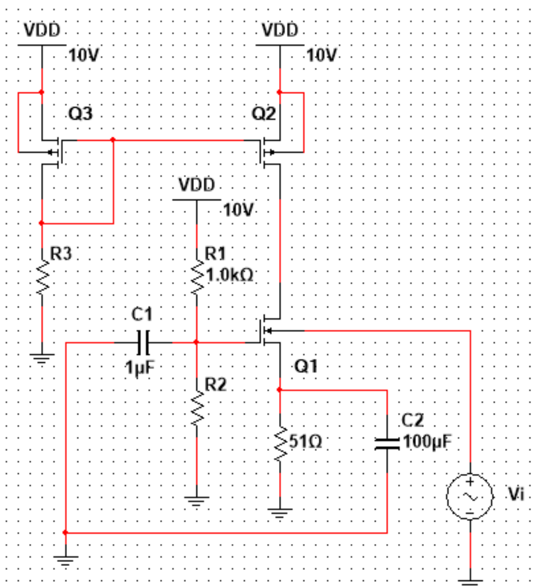
$g_{mb} = \eta g_{m1}$

$g_{mb} = (0.580)(0.375\ mA/V)$

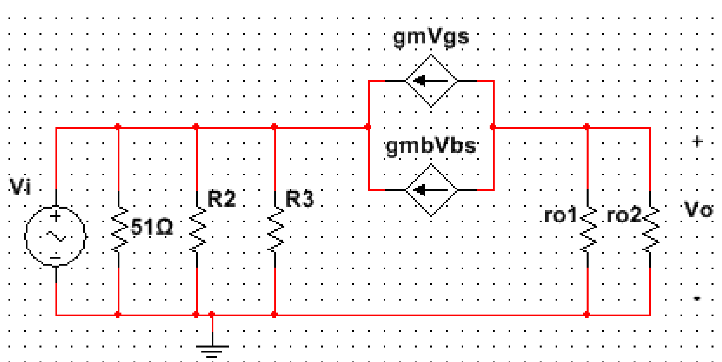
$\mathbf{g_{mb} = 217\ \mu A/V}$

Task 7: Directly Measuring the Body Effect

From the CG Amplifier, we saw that the body effect enhanced the small-signal voltage gain which is directly related to the body effect parameter (η). For this task, we had to develop an alternative test scheme to measure this body effect. If we connected the gate and source to ground, and connected the signal to the body, the output voltage was proportional to the NMOS transistor's transconductance parameter in the resulting circuit. The same bias conditions were used for this circuit as the previous circuits. Next, we developed a small signal model and did some analysis.



Directly Measuring the Body Effect



Body Effect Small-signal equivalent

Data/Calculations:

r_{o1} = 634 kΩ

r_{o2} = 5.1 MΩ

g_m = 0.375 mA/V

$A_v = (g_m+g_{mb})(r_{o1}//r_{o2}) - g_m(r_{o1}//r_{o2})$

A_v (from following plot) = 1.517 V / 25.52 mV = 59.4 V/V

g_{mb} = 205 µA/V (measured)

η = 1.59

Discussion:

- The reasoning for the circuit in Task 7 and how it works was explained in the Task 7 section.
- *Questions from Lab Handout:*
    - Why is the 10X probe needed to measure v_o? *(Task 3)*

    We always have to be very careful of loading effects because the load can draw too much current away from the circuit causing malfunctions and errors in measurements.

    - How does the calculated gain compare with the experimental gain? *(Task 4)*

    The calculated gain is more than 4 times as much as the experimental gain. Once we removed noise from the plot, the experimental gain was about -46 and the calculated gain was about -212. This difference could be due to incorrect parameter values from Lab 4, namely the channel-length modulation parameter. This would cause R_{out} to be incorrect which is a factor in the equation for gain.

    - How does the calculated gain compare with the experimental gain? *(Task 5)*

    The calculated gain is more than twice as much as the experimental gain. Once we removed noise from the plot, the experimental gain was about 90 and the calculated gain was about 264. This difference could be due to incorrect parameter values from Lab 4, namely the channel-length modulation parameter. This would cause R_{out} to be incorrect which is a factor in the equation for gain.

- Why is the gain magnitude of the CG Amp larger than the CS Amp? *(Task 5)*

The gain magnitude is larger for the CG amplifier because of the body-effect on the circuit. By comparing the gain equations, you can see how the body effect increases the gain. There is an additional term that gets added, then multiplied by R_{out}*. Therefore, the gain for the CG Amplifier will be larger than that of the CS Amplifier.*

- How do the experimental values of g_{mb} and η compare to those previously determined? *(Task 7)*

Our value for g_{mb} *was very close to what we expected. As far as our* η *value, it could be off because of noise in our plots which would affect the gain.*

- Is there a reason why an experimental approach is preferred in terms of accuracy and simplicity? *(Task 7)*

An experimental approach is preferred because it takes into account the variances of components (5% resistors, etc.) whereas the theoretical approach considers ideal values. Also it is much easier to look at plots to determine gain rather than calculate it by hand.

Comparing Theoretical, Experimental, Simulated Values and Error Analysis:

Task 1:

V_{SG2} *(theoretical)* = **2.10 V**

Task 2:

V_{GS1} *(theoretical)* = **1.75 V**

Task 3:

V_{SG2}*(measured)* = **2.09 V** *and* V_{GS1}*(measured)* = **1.56 V**

Task 4:(CS)

Av (calculated) = **-211.5**, *Av(measured)* = **-46.2**, *Av(simulated)* = **-16.5**

-Simulated gain is hard to see here. It was easier to see in Multisim.

Task 5: (CG)

Av (calculated) **264.25** = *and Av(measured)* = **73**

Task 6:

g_{mb}*(calculated)* = **217 µA** *and* η*(calculated)* = **0.580**

Task 7:

g_{mb}*(measured)* = **205 µA** *and* η*(measured)* = **1.59**

Error Analysis:

1) % error = {(theoretical – experimental) / theoretical} x 100

2) % error = {(experimental – simulated) / experimental} x 100

V_{SG2}: % error = {(2.10V – 2.09V) / 2.10V} x 100 = **0.48 %**

V_{GS1}: % error = {(1.75V – 1.56V) / 1.75V} x 100 = **10.86%**

Av(CS): % error = {(211.5 – 46.2) / 211.5} x 100 = **78.16%**

2) % error = {(46.2 – 16.5) / 46.2} x 100 = **64.29%**

Av(CG): % error = {(264.25 – 73) / 264.25} x 100 = **72.37%**

-Reasons for such large error was given in the above 'Discussion'

g_{mb}: % error = {(217 – 205) / 217} x 100 = **5.53%**

η: % error = {(0.580 – 1.59) / 0.580} x 100 = **17.4%**

Summary and Conclusions:

In this lab we learned about NMOS amplifying devices with Active Loads. These were accomplished using transistors which are preferred over resistive circuits because of the size advantage. We investigated the gain of the Common-Source configuration and the Common-Gate configuration and saw various properties come into play like the input and output resistances of the transistors themselves. We also learned about the body effect and how that can change the gain of the amplifier. Errors in device parameters can cause very large discrepancies between measured/simulated/theoretical values as shown in this lab. Next time, we will take extra care to make sure these parameters are calculated correctly to ensure more accurate results, leading to less error.

This lab was difficult, but taught us a lot about the various configurations and the advantages they possess. Certainly it is easier to plot input voltage vs. output voltage rather than developing small signal models and calculating a theoretical gain but it is definitely a useful skill to be able to do both.