E6312: Problem Set 4

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To build the folded cascade OTA, I began by sizing transistors M0, M1, and M2 (see figure 1 for instance names). Because I want $160\mu A$ through transistor M9 and that transistor is sized with $W = 42\mu m$ and I want $320\mu A$ through transistor M2, I sized M2 at $84\mu A$. For the sake of convenience, I decided to use a $320\mu A$ current source so I sized transistors M0 and M1 at $84\mu A$ as well. In addition, because I will eventually put this circuit into feedback and I would like my output to be close to mid-rail, I set $V_{cm} = 800mV$ which is close to the ceiling of input voltage. This is an acceptable value because the small signal input will never be above 1V.

To bias V_{b1}, V_{b2}, and V_{b3} I utilized two branches of self-biasing current mirrors (see Figure 1). The first branch, which consists of one PMOS and four NMOS transistors, serves a number of purposes. The PFET (M21) mirrors current from M0 and cuts it in half (sized $42\mu A$). The four NMOS receive the $160\mu A$ of current and are sized as follows. M28 will have half the current of M14 and its gate voltage will bias V_{b1} so it must be half the width of M14, $10.5\mu m$. M29 will have the same current as M13 and its gate voltage will bias V_{b2} so it must be the same width as M13, $10.5\mu A$. M27 will also take the same width as M29 and M28. M20 will take one third of that width. Using a very similar methodology, I built the second self-biasing current mirror branch but this time mirroring the current with an NMOS and receiving the current with four PMOS transistors. M31 mirrors the current of $160\mu A$ so it is sized the same as M28. M44, M45, and M40 will all have the same current as M10 and the gate of M45 will bias V_{b3} so they are all sized the same as M10 at $42\mu A$. M4 is sized one third of that. As can be seen in Figure 2, the biasing is successful.

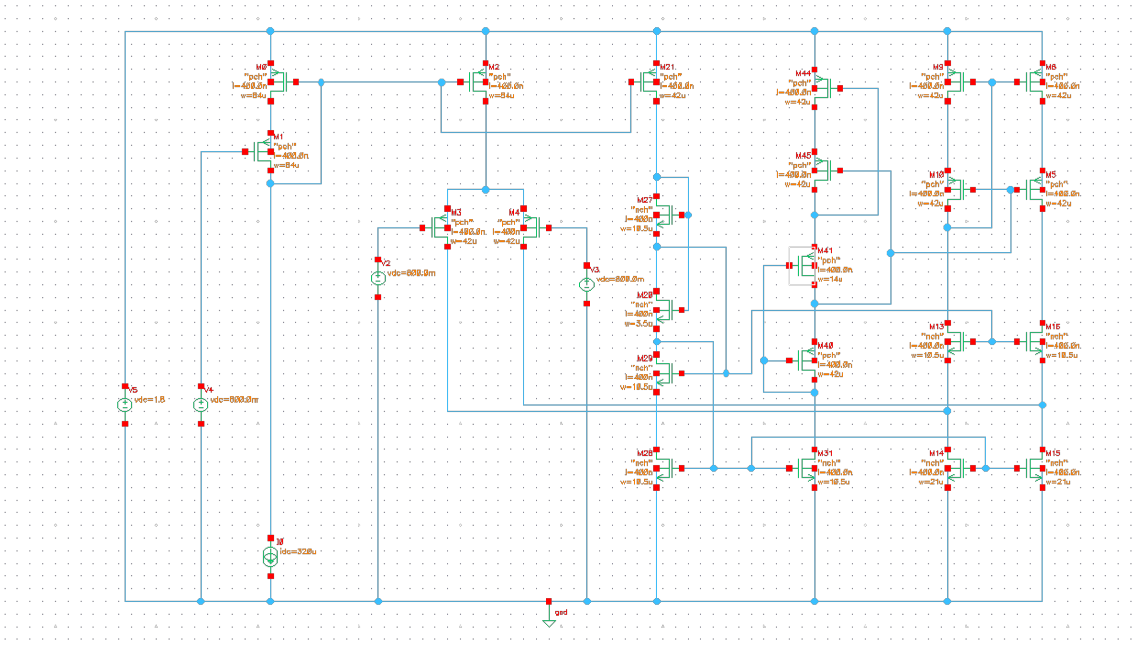

Figure 1: Schematic Diagram for the Folded Cascode OTA with Associated Biasing Circuitry

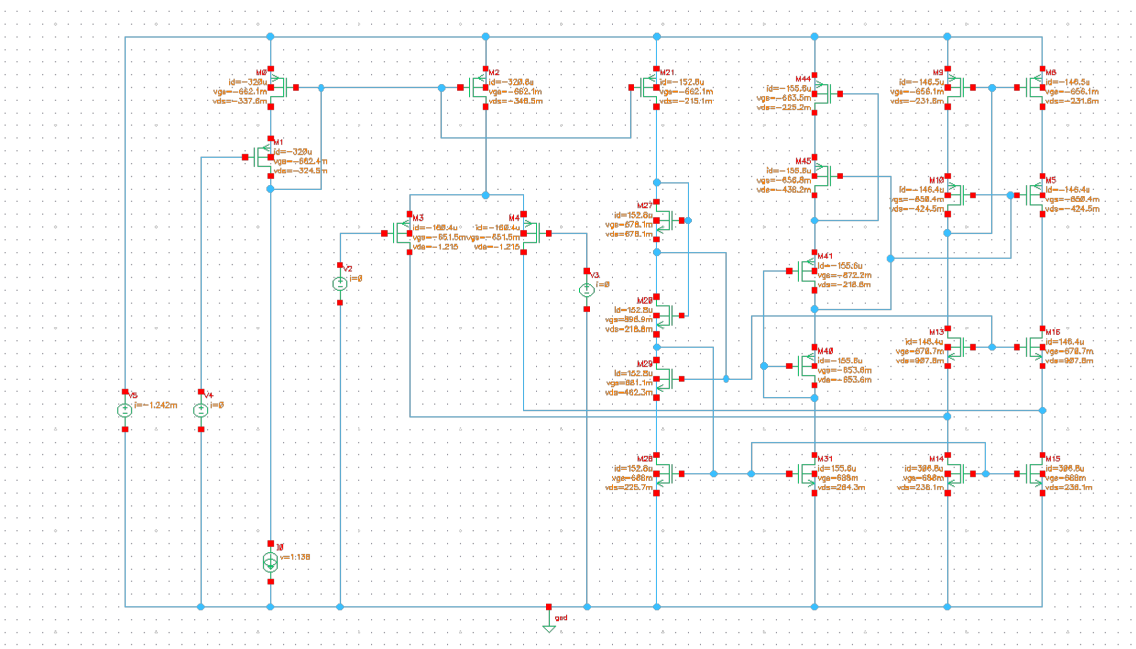

Figure 2: Schematic Diagram for the Folded Cascode OTA with Annotated DC Operating Point Values

3 Bullet Point 3

I performed a DC sweep of V_{out-OL} against V_{in-OTA} with the OTA in stand alone and the expected transfer function for a differential amplifier is attained (see Figure 3).

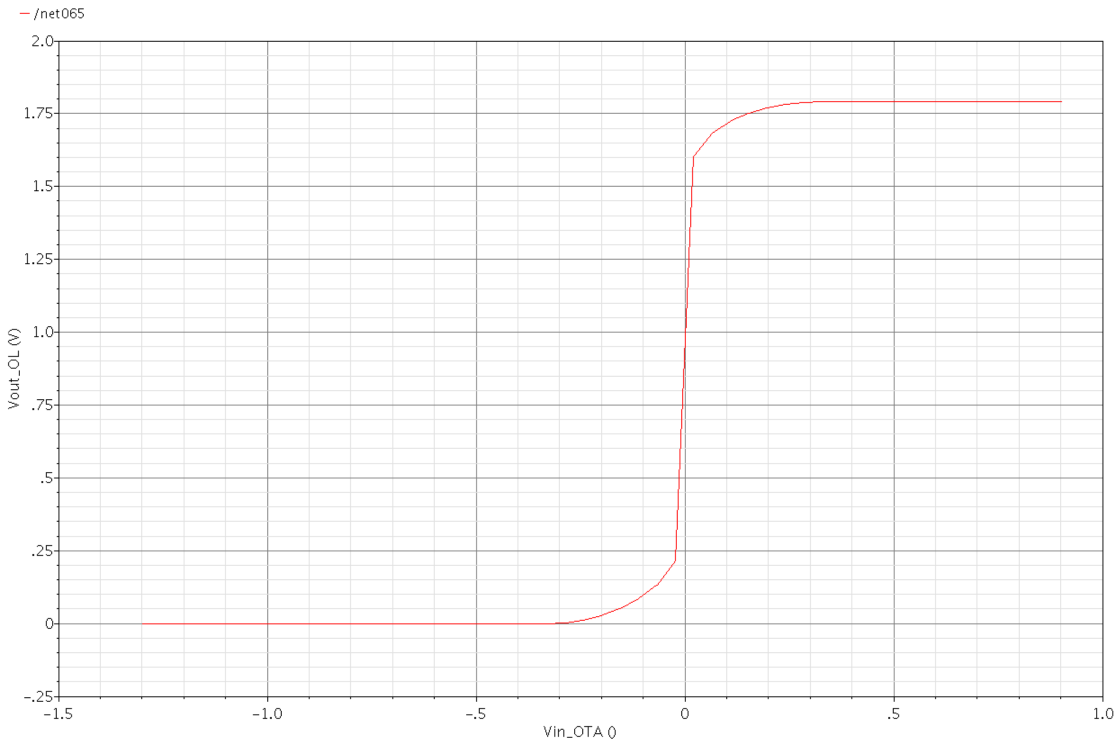

Figure 3: Voltage Transfer Characteristic for the Folded Cascode OTA in Stand Alone

4 Bullet Point 4

I applied a small-signal differential input as well as some DC feedback circuitry in order to simulate the open loop gain. Because the open loop gain does not consider small signal feedback, I wanted to build a circuit that would block all AC feedback. However, I wanted to use this feedback to bias V_{cm}. To do this I implemented an RC lowpass filter with a negligible cutoff voltage as can be seen in Figure 4. I performed an AC simulation of the open loop gain of the circuit (see Figure 5) and was able to attain $A(s) = 521.19\frac{V}{V} = 54.34dB$. Please note that since transistor M44 does not directly affect the biasing, I was able to reduce its size to $16\mu A$ and optimize my gain.

From the phase plot of my optimized open loop circuit (Figure 5), I estimate that there are poles at $227kHz$ and $471MHz$ and a zero at 945MHz. I estimate the gain-bandwidth product (taken at -3dB from the maximum gain) to be $72.2MHz$.

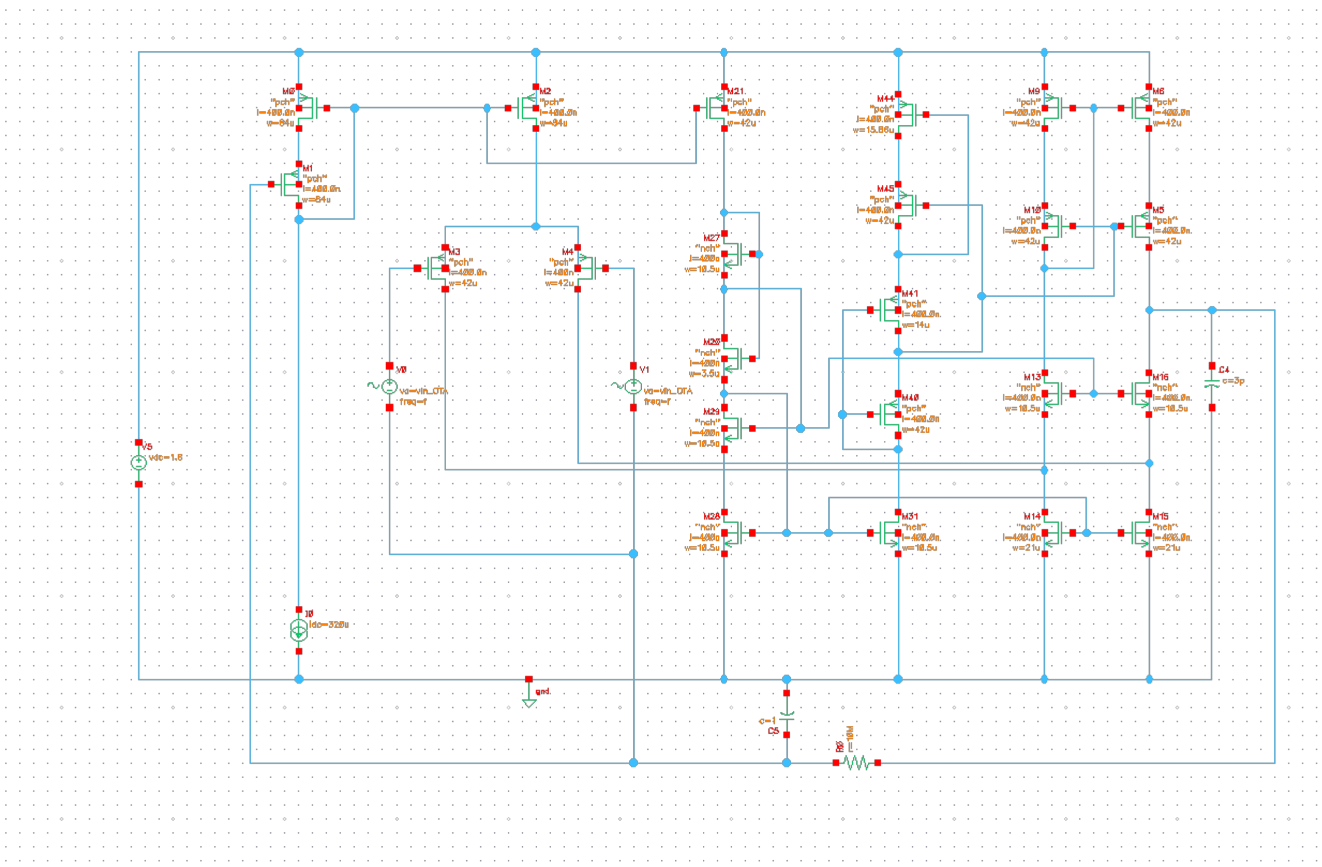

Figure 4: Schematic Diagram for the Folded Cascode OTA for Open Loop Gain Simulation

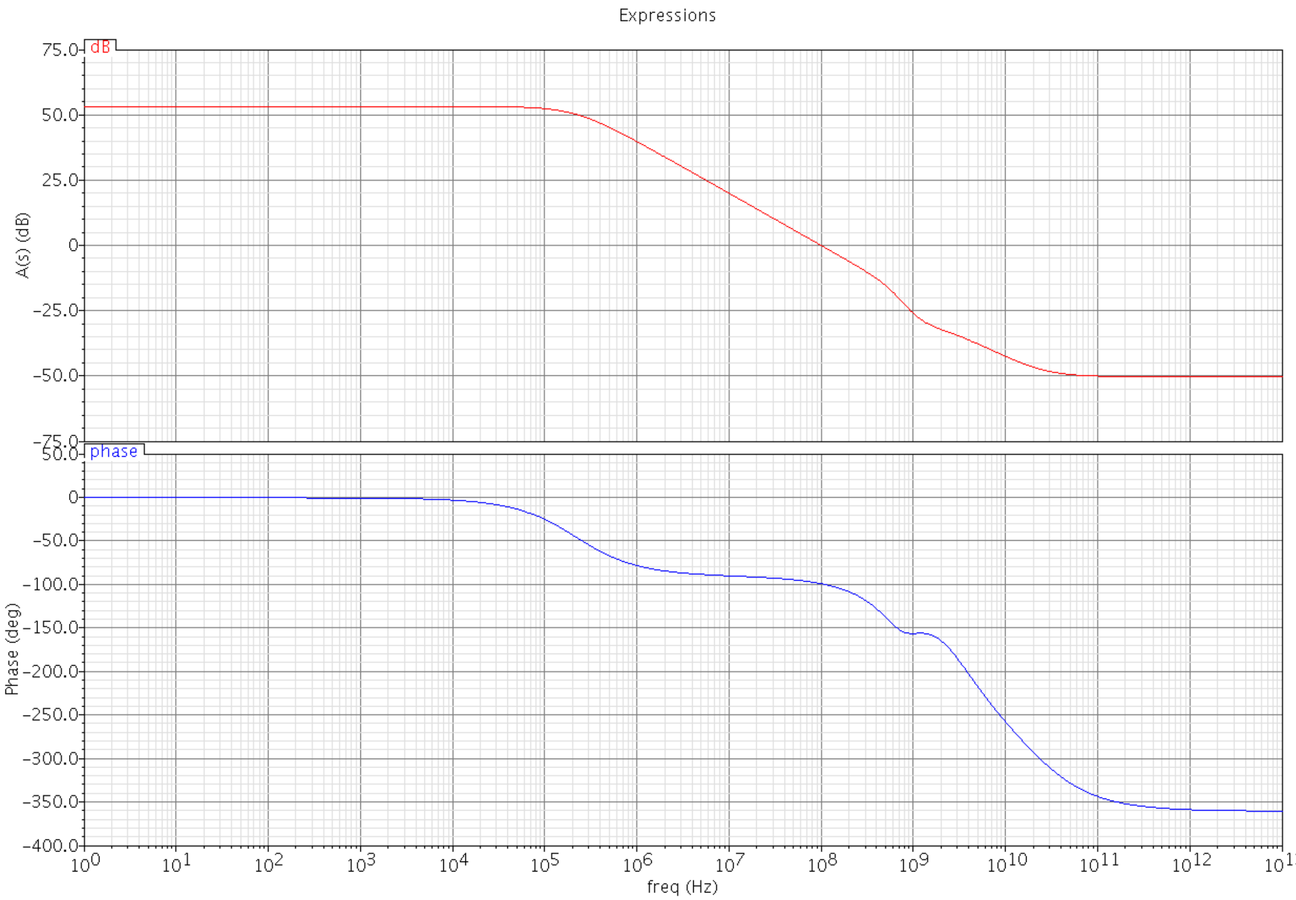

Figure 5: Bode Plot of the Open Loop Gain of the OTA

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I placed my OTA in AC feedback as shown in Figure 6 with $V_{cm} = 0.8V$. To find the feedback factor, β, from this configuration, I plotted the current through the feedback resistor over the voltage at the output (see Figure 7).

$$\beta = \frac{I_f}{v_{out}} \tag{1}$$

From my simulation, I attained a value of $\beta = 0.577mA/V$. This is comparable to the ideal value of

$$\beta_{ideal} = \frac{1}{R_f} = 0.4mA/V \tag{2}$$

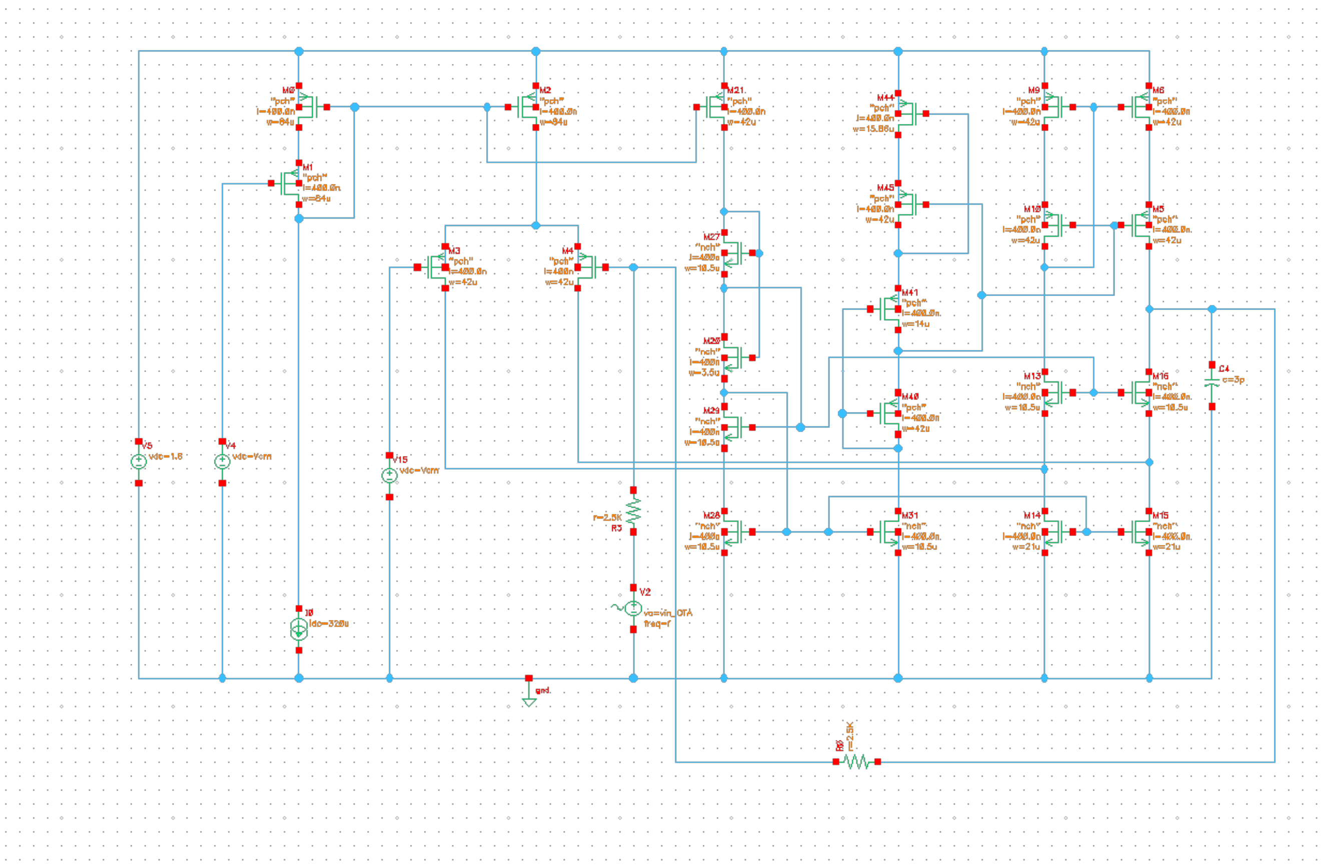

Figure 6: Schematic Diagram for the Folded Cascode OTA for Closed Loop Gain Simulation

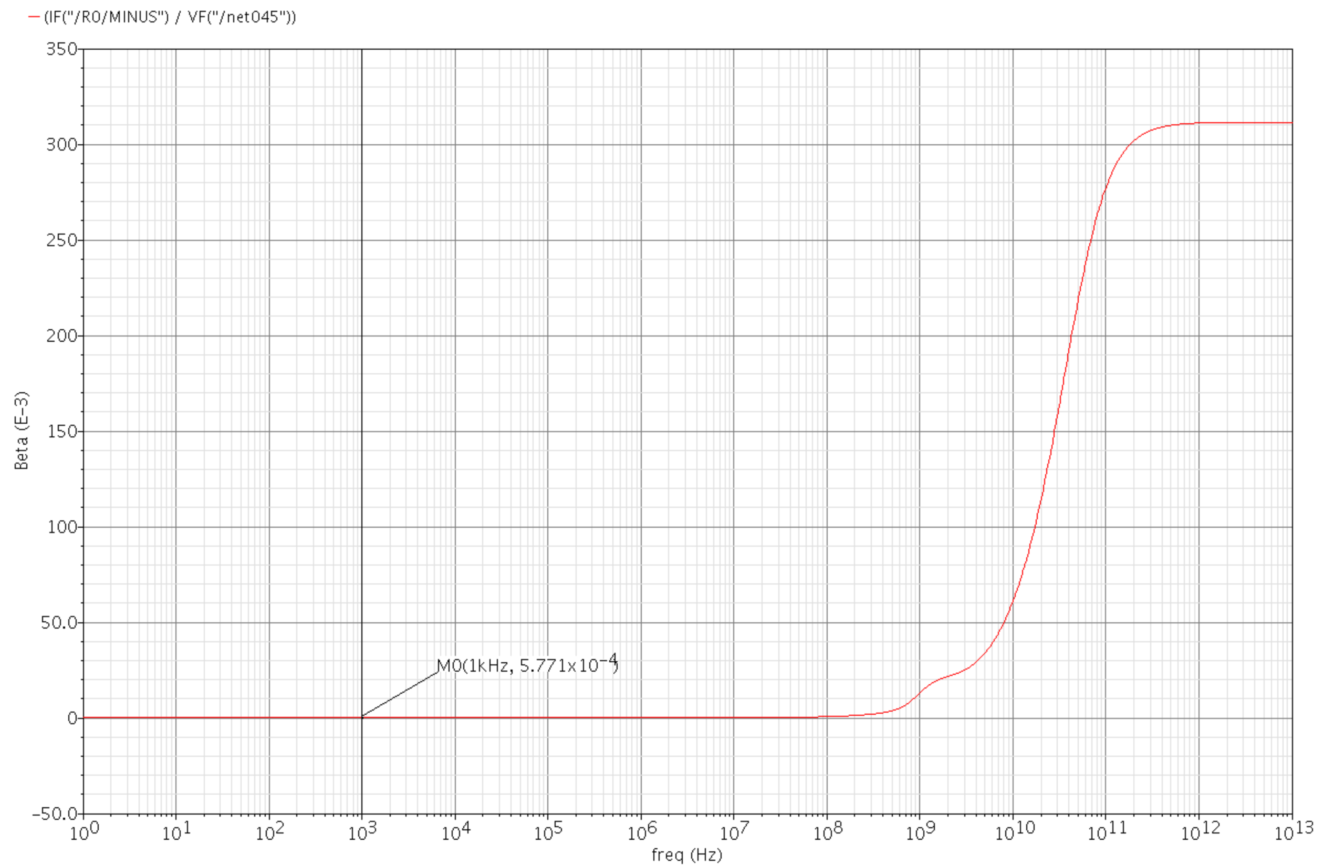

Figure 7: Frequency Response of the Feedback Network

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With an ideal op-amp (infinite gain and bandwidth), a small-signal step at the input should cause an immediate small-signal step at the output. The reason for this is that with infinite bandwidth, τ is defined as

$$\tau = \frac{1}{2\pi f_{3dB}} = \infty. \tag{3}$$

To determine the output function, we use the equation

$$v_{OUT} = \mu(t)\{1 - e^{\frac{-t}{\tau}}\} = \mu(t). \tag{4}$$

Therefore, with a small-signal step function at the input, we will observe a small-signal step function at the output.

11 Bullet Point 11

To determine the ideal output step for the various small-signal step inputs, I first had to simulate the closed loop gain of my circuit. To do this I constructed the circuit shown in Figure 8 and acquired a gain of $A_{closed-loop} = 0.53V/V = -5.51dB$ (see Figure 9). I then set out to simulate the step response at various input magnitudes and sample at times 2τ and $100Ts$. My transient step responses can be seen in Figure 10 and my voltage transfer characteristic for V_{ideal}, V_{out1}, and V_{out2} can be seen in Figure 11.

The absolute and percent errors are shown in the Chart 1.

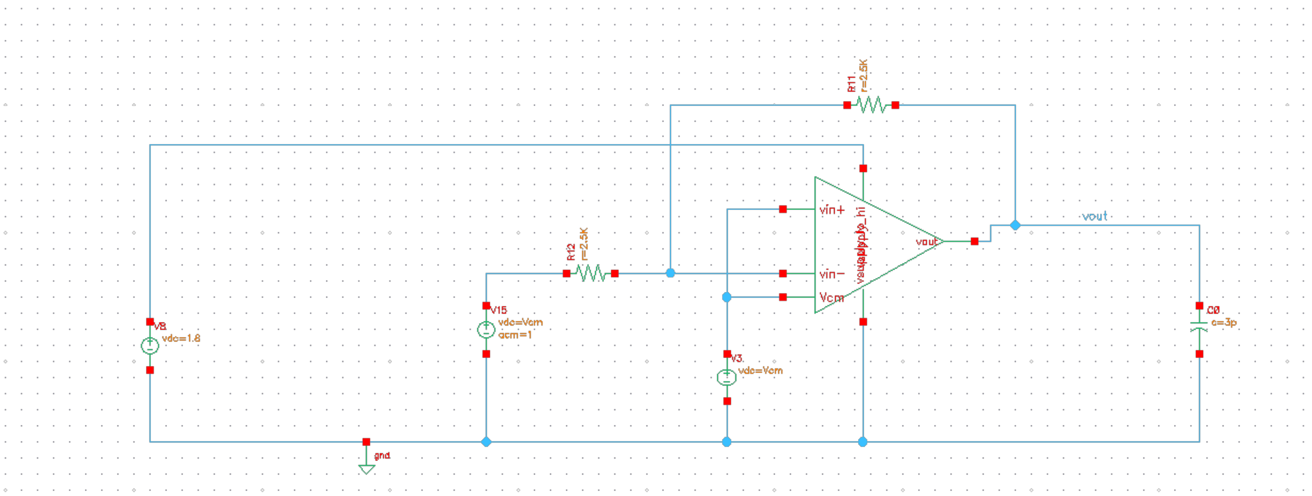

Figure 8: Schematic to Measure Closed Loop Gain

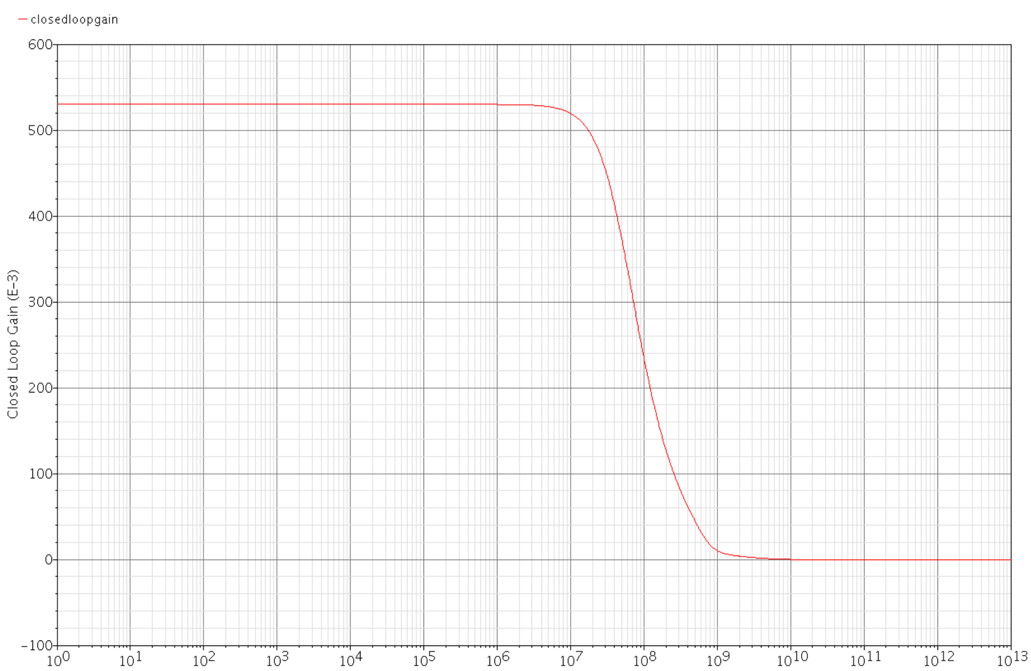

Figure 9: Closed Loop Frequency Response of the OTA in Feedback

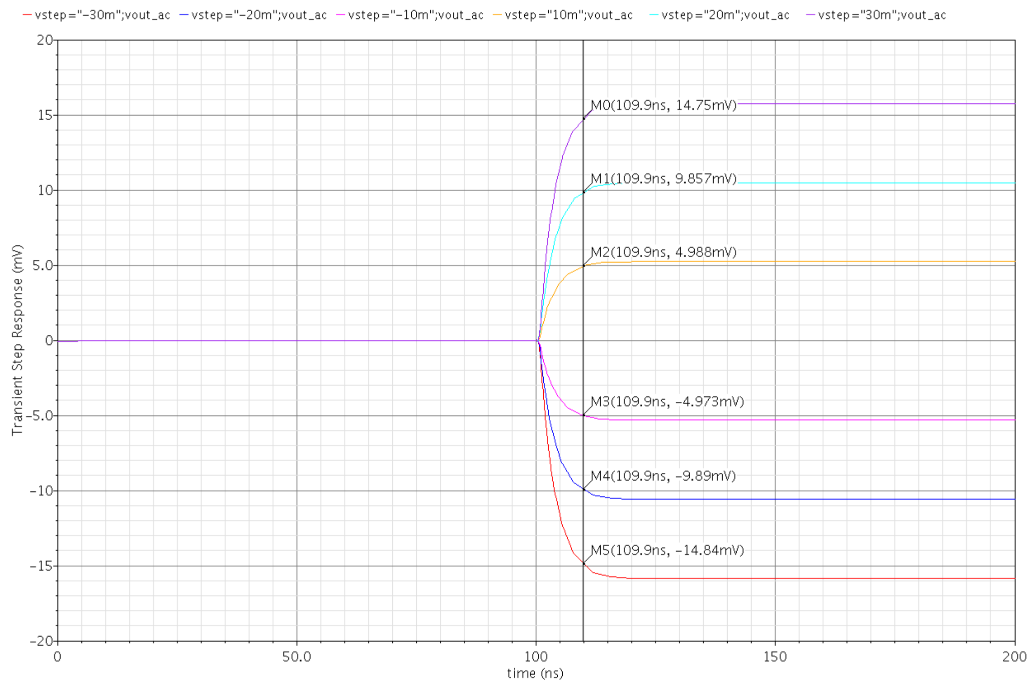

Figure 10: Step Responses for Various Small-Signal Input Step Sizes

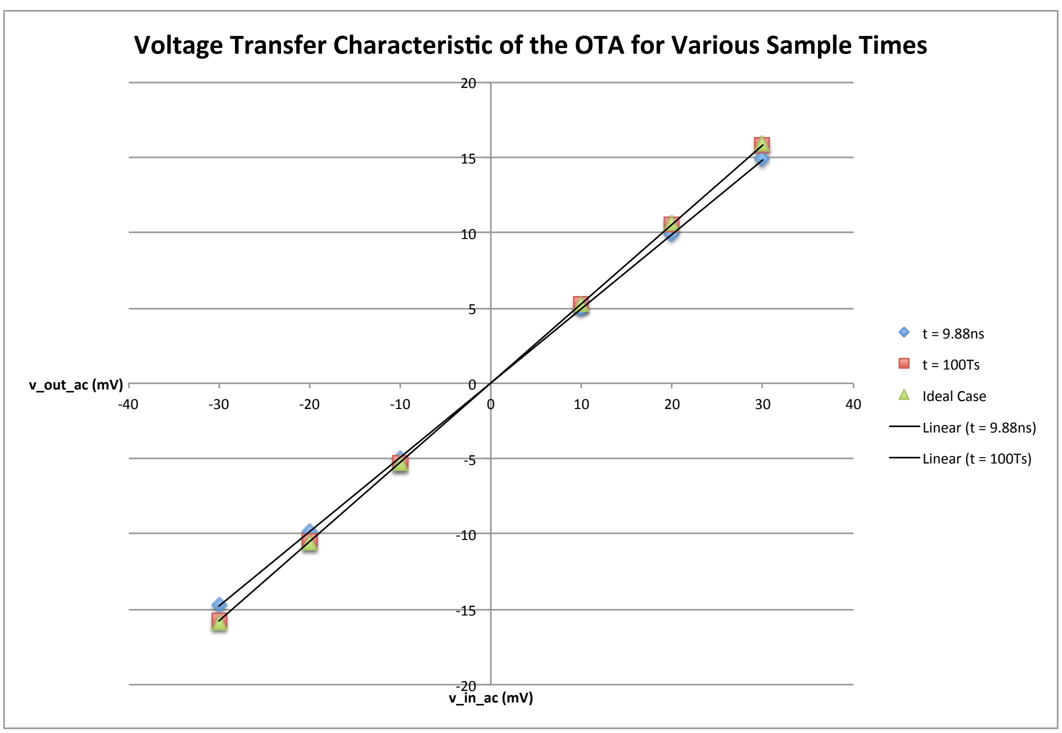

Figure 11: Transfer Function of the OTA Step Response

v_{in}[mV]	v_{ideal}[mV]	Absolute Error at $t = 2\tau$[mV]	Percent Error at $t = 2\tau$[%]	Absolute Error at $t = 200Ts$[mV]	Percent Error at $t = 200Ts$[%]
10	5.30	0.33	6.17	0.03	0.51
20	10.60	0.71	6.70	0.05	0.47
30	15.90	1.06	6.67	0.07	0.44
-10	5.30	0.31	5.89	0.04	0.79
-20	10.60	0.74	7.00	0.08	0.82
-30	15.90	1.15	7.23	0.14	0.86

Table 1: Error Values for Small Signal Step Response

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I extended my step response plot for input steps of $\pm 100mV$, $\pm 200mV$, and $\pm 500mV$ to show the effects of slewing. As can be seen in Figure 12, slewing is most obvious in the 500mV response.

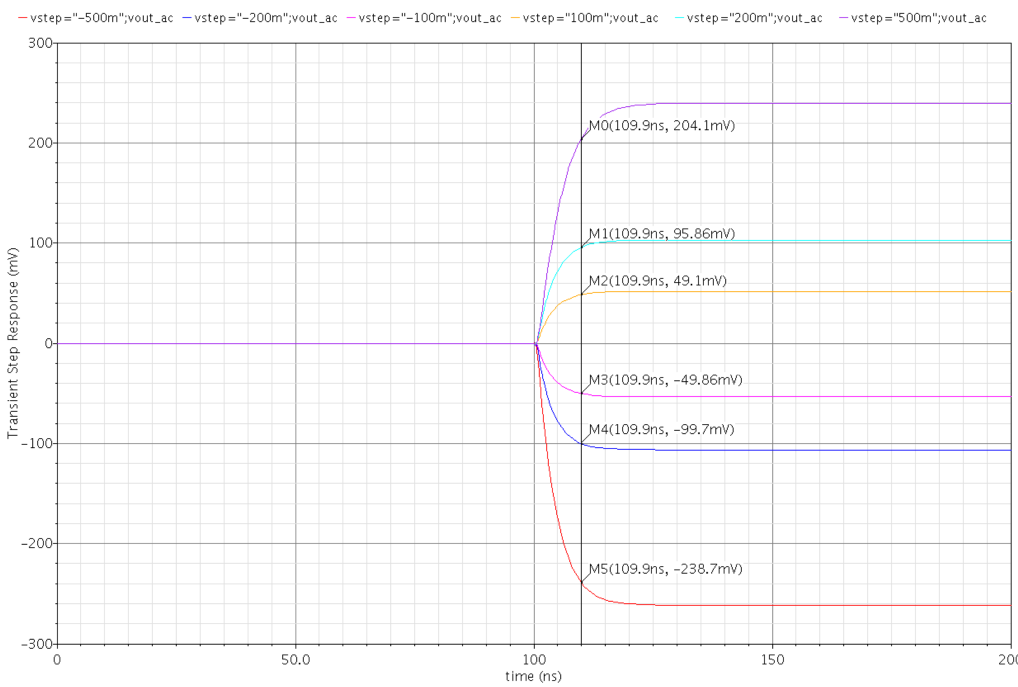

Figure 12: Step Responses for Various Large-Signal Input Step Sizes