Simulation Lab #2

EECS 170LC

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1 Introduction

A common-source and common-drain amplifier are simulated. Proper bias conditions are selected for each one. The effect of cascading a common-source amplifier with a common-drain amplifier is then analyzed.

2 Part 1

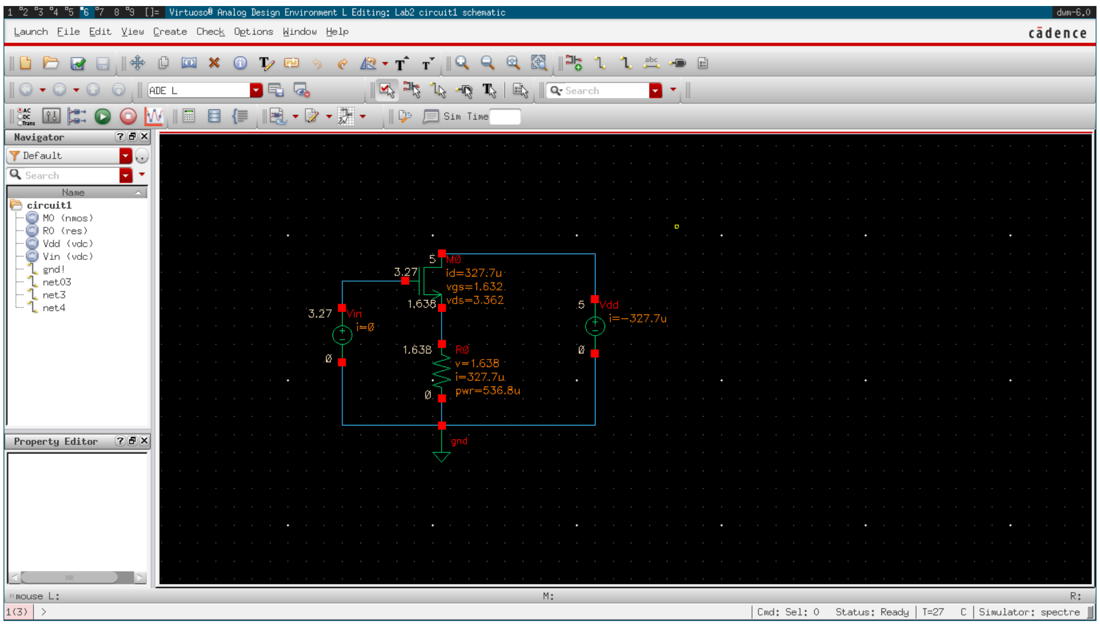

Figure 1: Common-Drain Amplifier

The circuit in figure (1)'s voltage transfer characteristic is acquired by sweeping V_{in} from 0V to 5V.

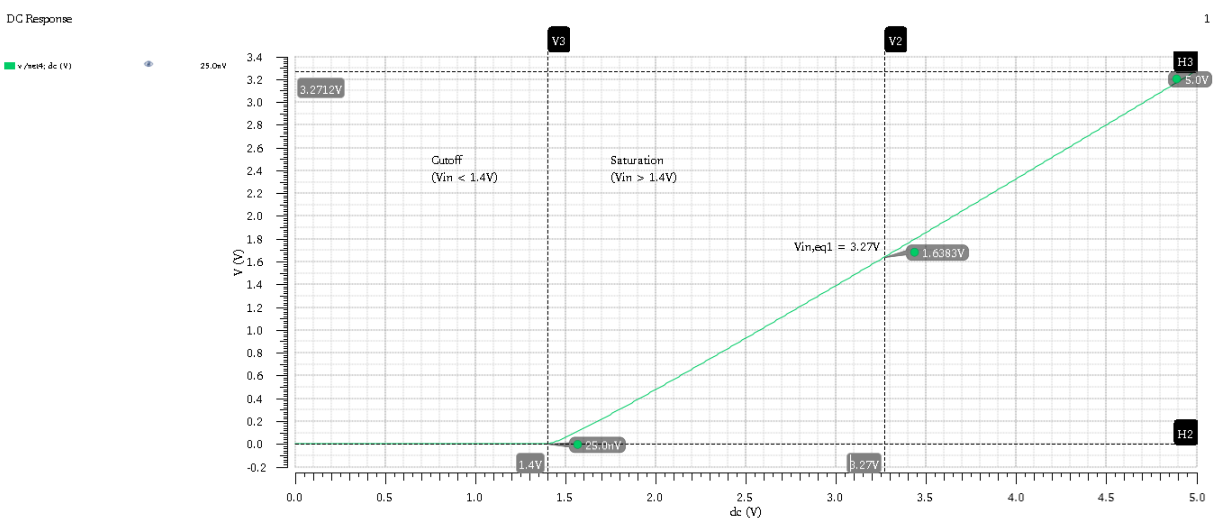

Figure 2: Common-Drain Amplifier Voltage Transfer Characteristic

Assume $0 < V_{in} < V_{tn}$. The transistor is in cutoff because the gate voltage is not high enough to form a channel. For $V_{in} > V_{tn}$, the transistor turns on. The transistor operates in saturation so long as $V_{GD} < V_{tn}$

(equivalent to $V_{DS} > V_{GS} - V_{tn}$). Because $V_{GD} = V_{in} - 5$V, the transistor is in saturation so long as $V_{in} < V_{tn} + 5$V. Since $V_{tn} > 0$V for enhancement-mode NMOSs, the transistor must be in saturation since V_{in} never exceeds 5V, and the transistor is not cutoff. Here, $V_{tn} \approx 1.4$V since that is the dividing line between cutoff and saturation.

Taking the average of the maximum and minimum values in the saturation region, $V_{in(eq1)} = 3.27$V. Figure (1) shows a DC operating point simulation at this bias point. g_m is given by $\frac{2I'_D}{V_{ov}}$, where I'_D is the saturation current not accounting for channel-length modulation and V_{ov} is the overdrive voltage. Here, the approximation $I'_D \approx I_D$ is used.

Table 1: g_m for the Common-Drain Amplifier

gm from Op Point Listing [mA / V]	Calculated gm [mA / V]	Error from Listing
2.83	2.83	0.11%

g_{ds} is simply the slope of the voltage transfer characteristic. A DC operating point listing provided by Virtuoso gives the value of g_{ds} for the transistor. r_o can then be acquired from $r_o = \frac{1}{g_{ds}}$. r_o can be calculated using $\frac{1}{\lambda I'_D} \approx \frac{1}{\lambda I_D}$.

Table 2: r_o for the Common-Drain Amplifier

ro from Op Point Listing [kiloohms]	Calculated ro [kiloohms]	Error from Listing
600.24	610.31	1.68%

An input signal of 10mV amplitude and 1MHz frequency biased at 3.27V is applied to the input of the common-drain amplifier.

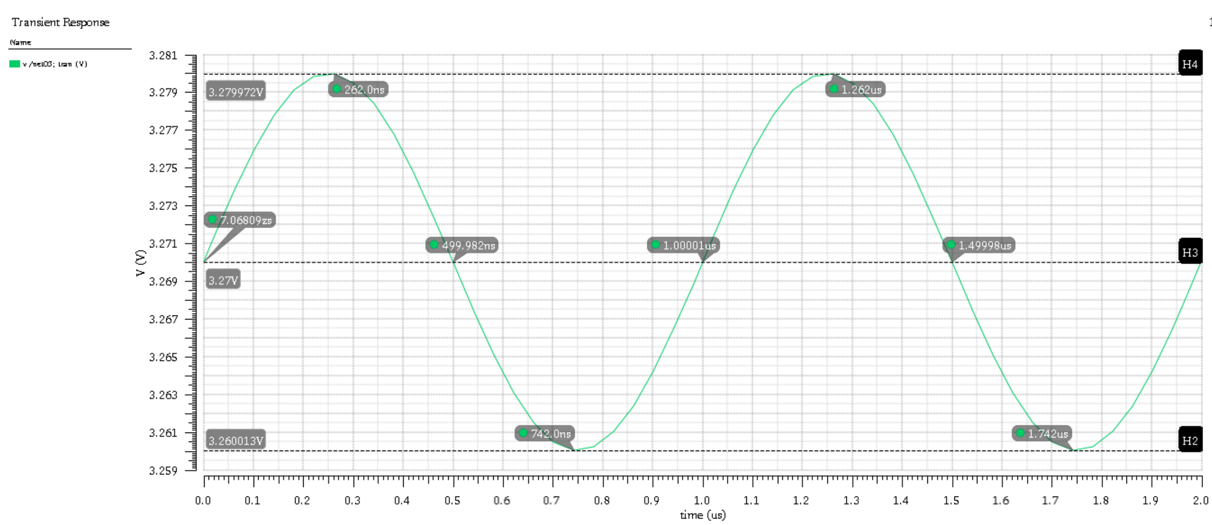

Figure 3: V_{in} for Small-Signal Analysis of Common-Drain Amplifier

A signal is then observed at the output of the amplifier.

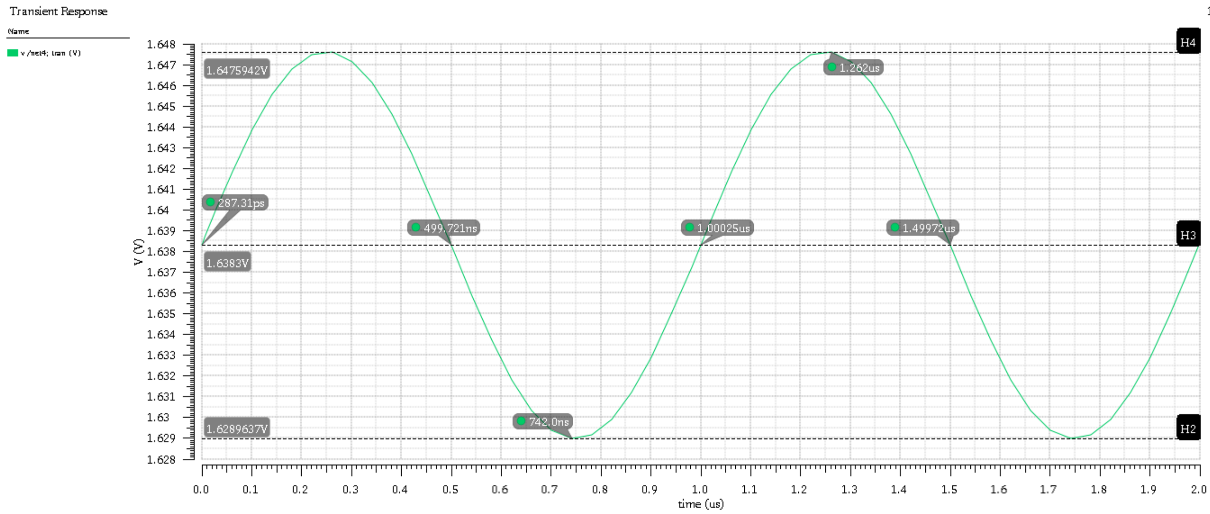

Figure 4: V_{out} for Small-Signal Analysis of Common-Drain Amplifier

The input and the output signals have the same amplitude. This is why the common-drain amplifier is often regarded as a "voltage follower". The bias at the output is simply the output voltage when V_{in} is biased at 3.27V, namely 1.64V.

10mV is then added to the input bias to take it from 3.27V to 3.28V.

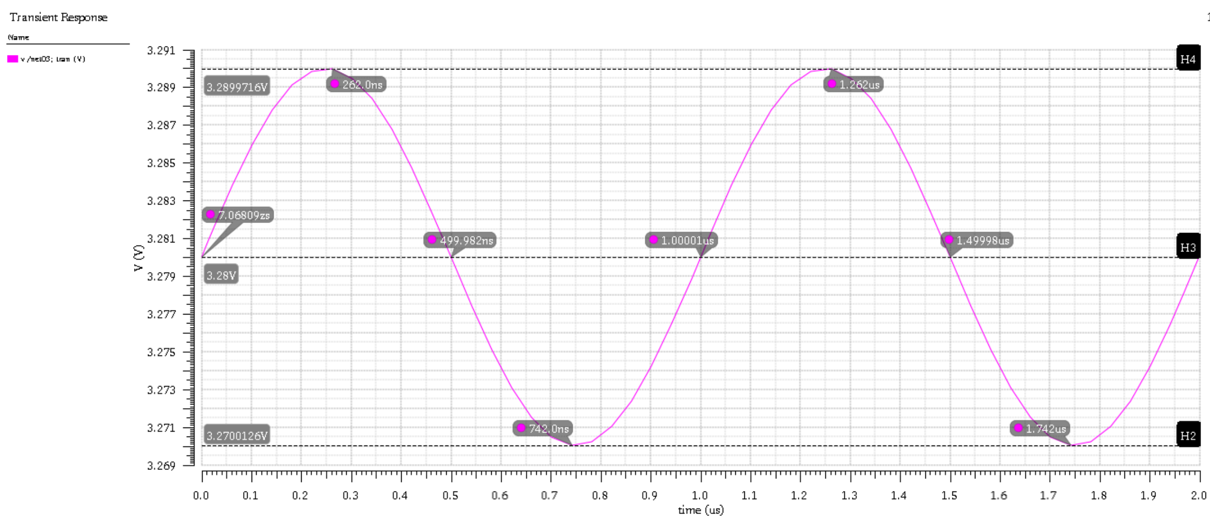

Figure 5: V_{in} for Small-Signal Analysis of Common-Drain Amplifier when Bias Increased by 10mV

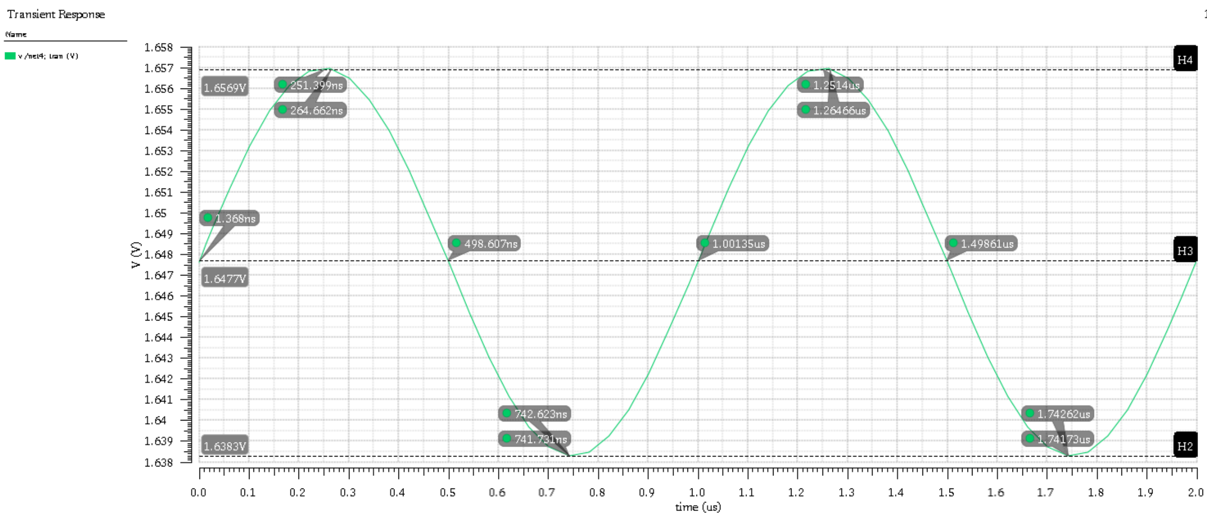

Figure 6: V_{out} for Small-Signal Analysis of Common-Drain Amplifier when Bias Increased by 10mV

Again, the output amplitude is the same as the input amplitude. The output bias shifts up by the same amount as expected, specifically from 1.64V to 1.65V. Again, this behavior is expected since the common-drain amplifier acts as a "voltage follower".

3 Part 2

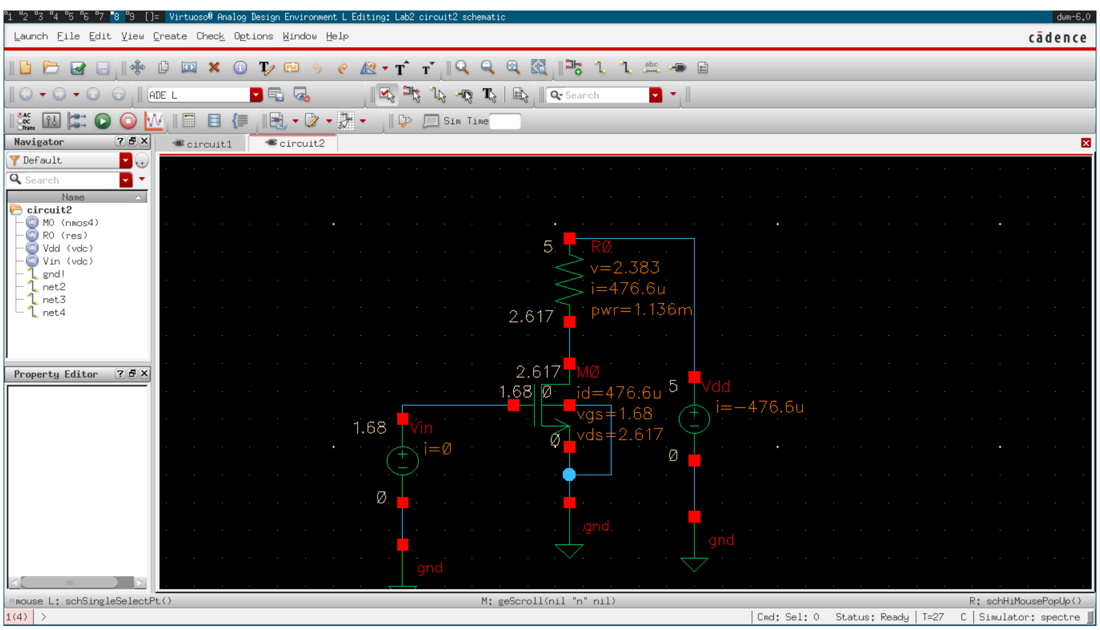

Figure 7: Common-Source Amplifier

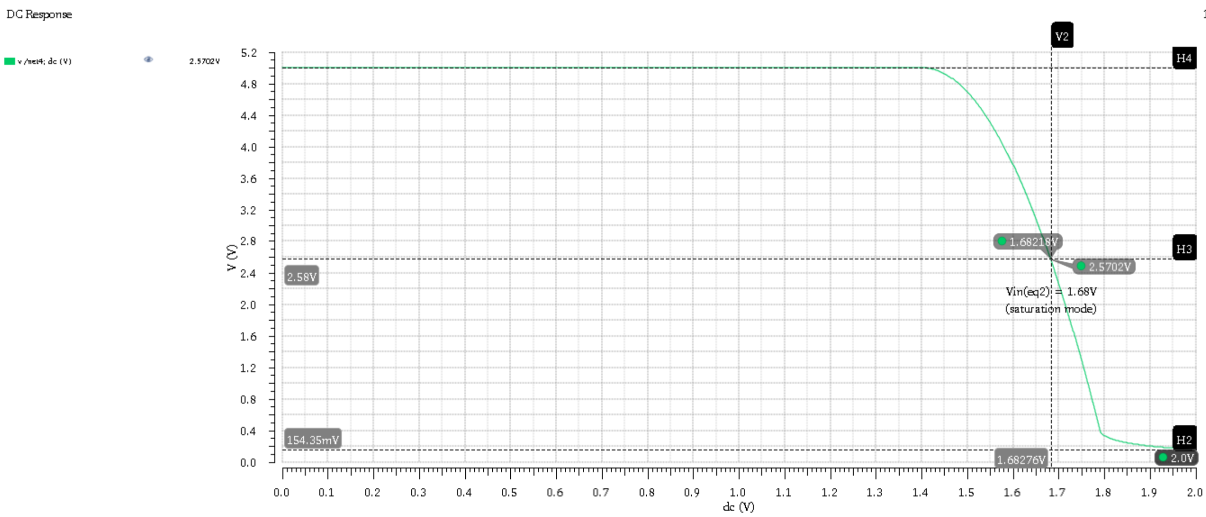

Figure 8: Voltage Transfer Characteristic for Common-Source Amplifier

$V_{in(eq2)} = 1.68$V for this particular amplifier. The transistor operates in the saturation region at this point. Common-source amplifiers start in cutoff mode for V_{in} below the threshold voltage V_{tn}. When V_{in} is too large, they typically enter the triode mode. For the region in between these two modes, the amplifier operates in saturation. Figure (7) shows the results of a DC operating point simulation. These results can be used to calculate g_m and r_o.

Table 3: g_m for Common-Source Amplifier

gm from Op Point Listing [mA / V]	Calculated gm [mA / V]	Error from Listing
3.41	3.40	0.02%

Table 4: r_o for Common-Source Amplifier

ro from Op Point Listing [kiloohms]	Calculated ro [kiloohms]	Error from Listing
414.08	419.64	1.34%

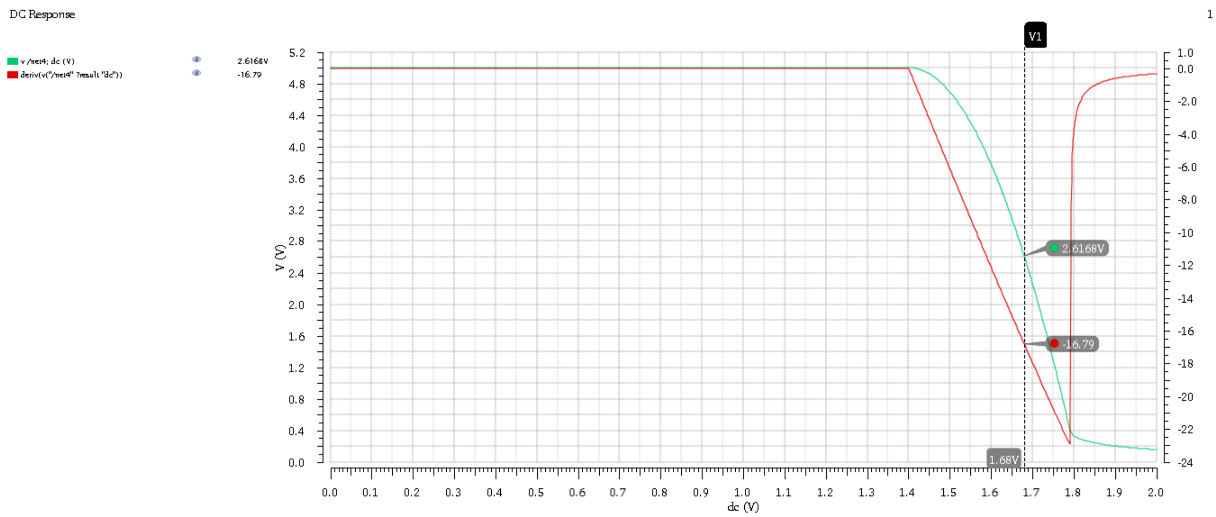

Figure 9: Common-Source Amplifier Voltage Transfer Characteristic with $\frac{dV_{out}}{dV_{in}}$ in Red

At $V_{in(eq2)}$, the gain $\frac{dV_{out}}{dV_{in}}$ turns out to be about -16.79. The gain can be calculated using the expression $A_v = -g_m(R_D||r_o)$.

Table 5: Common-Source Amplifier Gain

Gain from Graph [V/V]	Gain from Theory [V/V]	Error from Theory
-16.79	-16.82	0.17%

The small-signal behavior of the common-source amplifier is then analyzed. A 1mV amplitude, 1MHz sine wave is applied at the gate when the transistor is biased at $V_{in(eq2)}$.

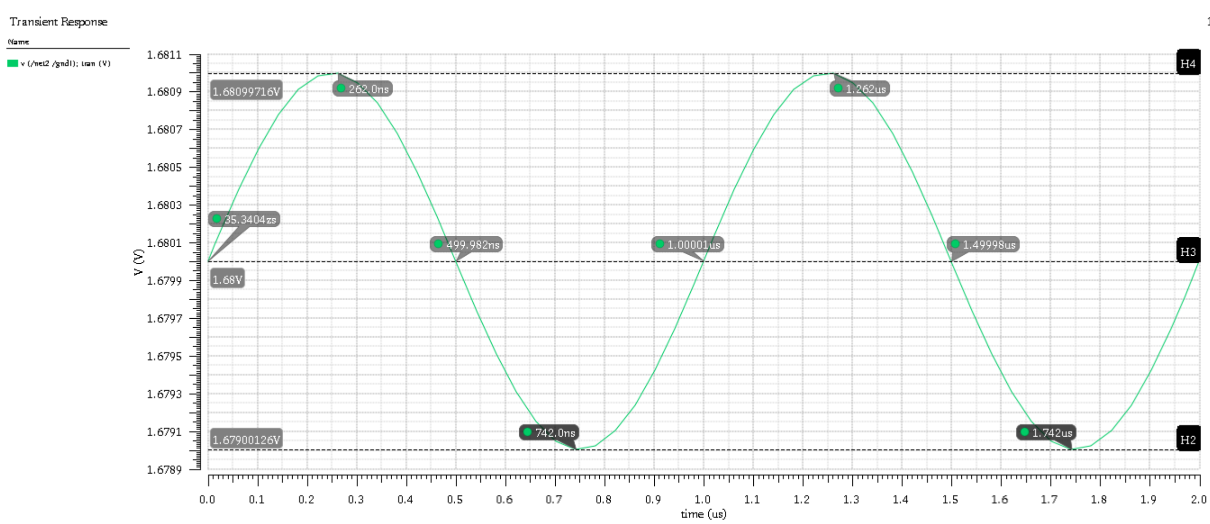

Figure 10: V_{in} Small-Signal Test of Common-Source Amplifier

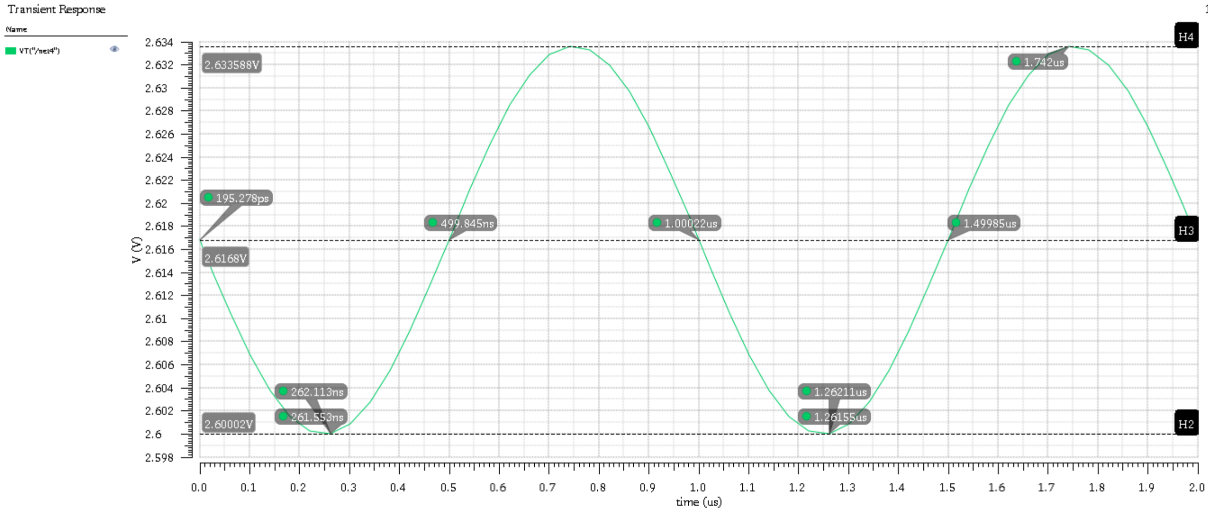

Figure 11: V_{out} Small-Signal Test of Common-Source Amplifier

The output signal is biased at the output voltage when $V_{in(eq2)}$ is applied at the gate of the transistor, whereas the input signal is biased at $V_{in(eq2)}$. The ratio of the output signal's amplitude to the input signal's amplitude is about 16.8, in line with the theoretical gain prediction and gain acquired from simulation plots. The output signal is also out of phase by 180^o, which is consistent with the fact that the gain is negative.

The input bias is then increased by 10mV.

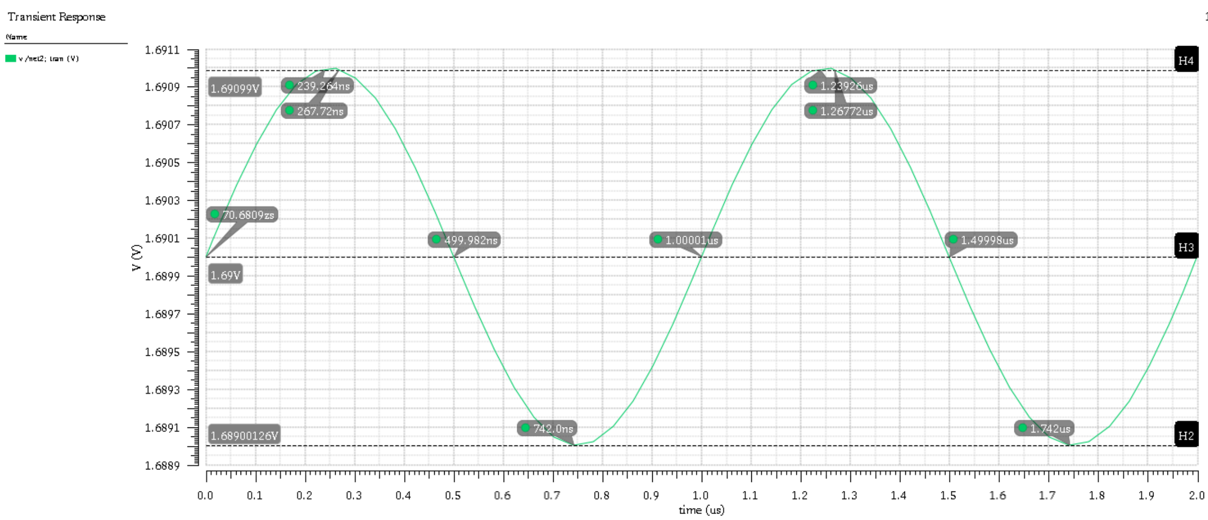

Figure 12: V_{in} for Small-Signal Test of Common-Source Amplifier after Increasing Input Bias by 10mV

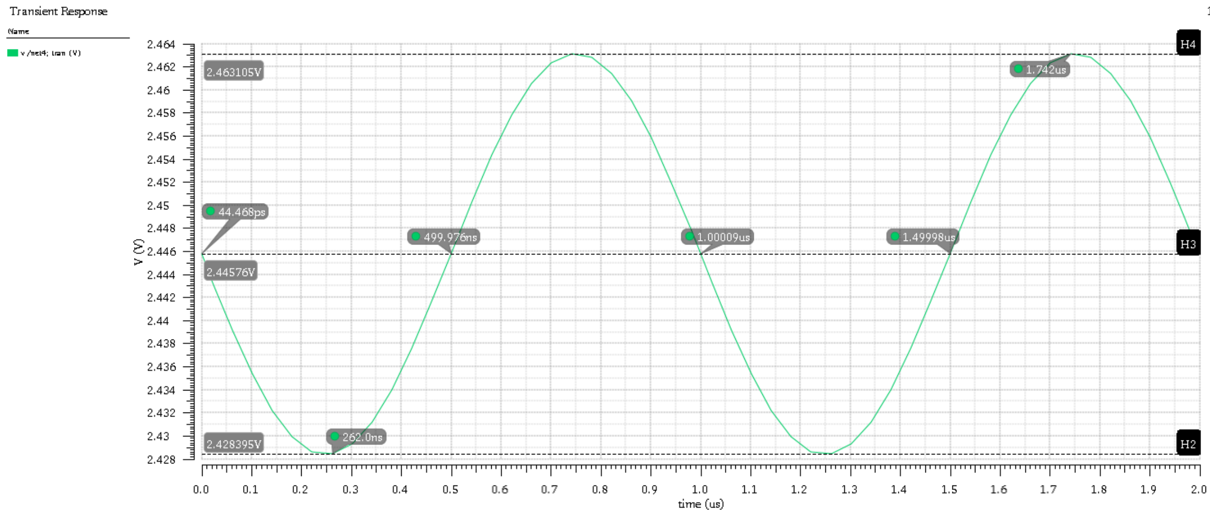

Figure 13: V_{out} for Small-Signal Test of Common-Source Amplifier after Increasing Input Bias by 10mV

The output bias drops by roughly the gain of the amplifier times the change in the input bias 10mV, precisely the behavior that is expected since the gain is directly related to the slope of the voltage transfer characteristic. However, the gain appears to have increased in magnitude to about -17.4. Thus, the gain of a common-source amplifier increases as the bias voltage is increased past the midpoint. It should be noted that this is at the expense of output voltage swing.

4 Part 3

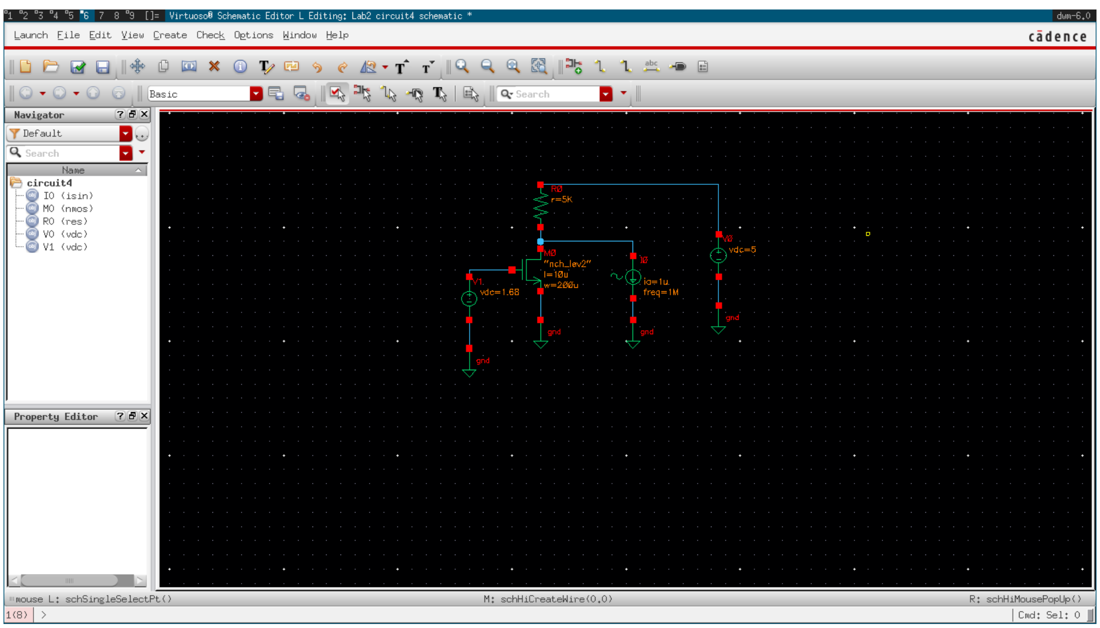

Figure 14: Circuit 3

The amplitude V_x can be acquired by analyzing the results of a transient simulation.

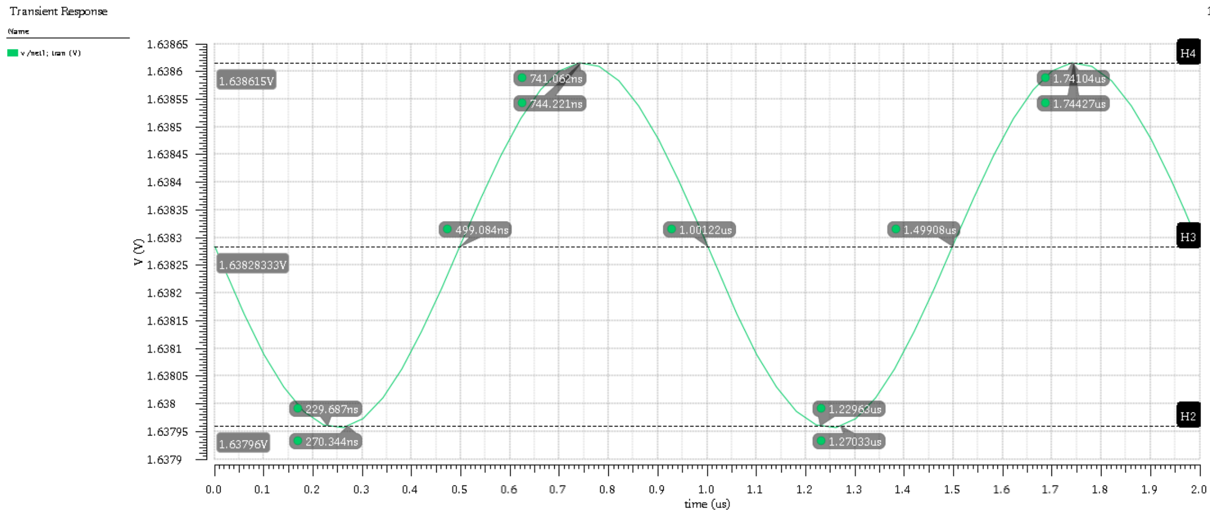

Figure 15: V_x Plot for Circuit in Figure (14)

The output resistance can be calculated simply by observing the amplitude of the waveform in figure (15), also known as V_x, and dividing it by the input current amplitude, which is 1µA in this case. The output resistance can be theoretically calculated for a common-drain amplifier using $r_{out} = R_s || \frac{1}{g_m} || r_o$. Clearly, the simulation result is consistent with theory.

Table 6: r_{out} for the Common Drain Amplifier

rout from Simulation [Ohms]	rout from Theory [Ohms]	Error from Theory
327.50	330.40	0.88%

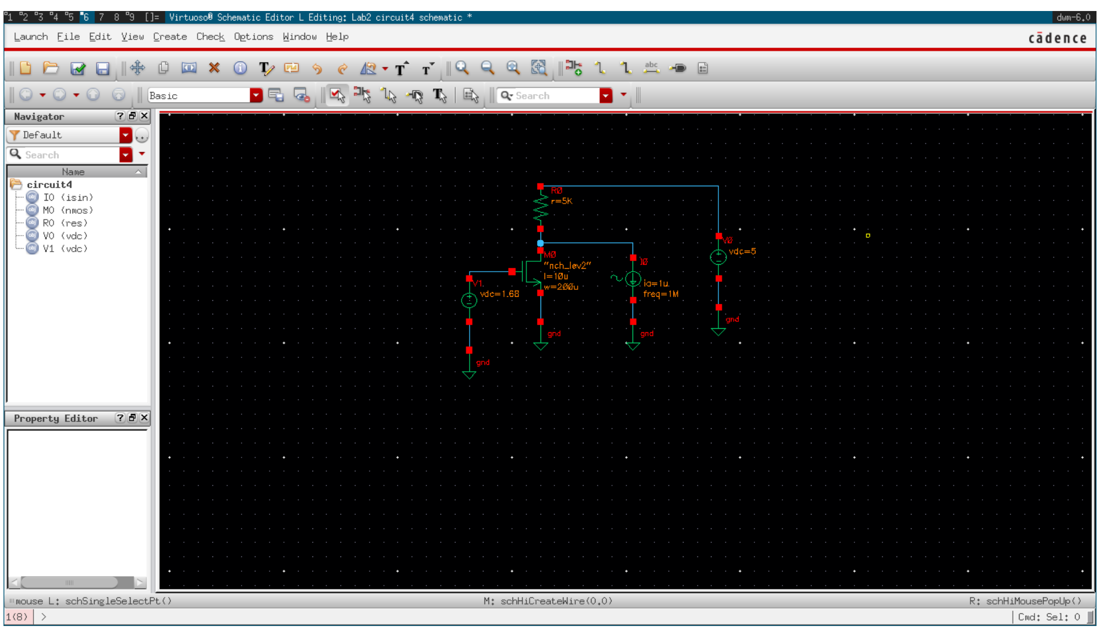

Figure 16: Circuit 4

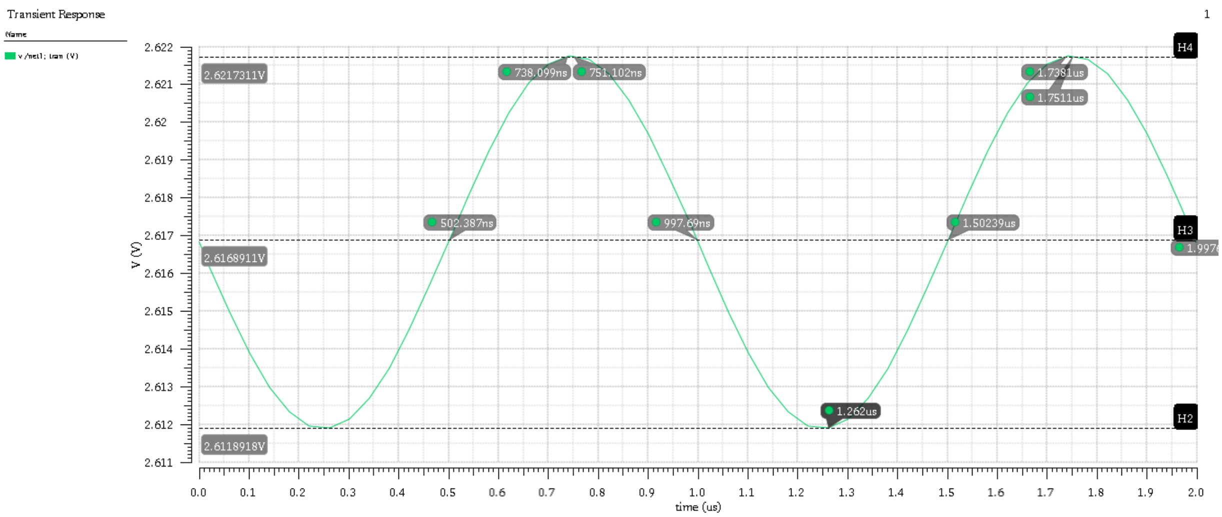

Figure 17: V_x Plot for Circuit in Figure (14)

Table 7: r_{out} for the Common Source Amplifier

rout from Simulation [Ohms]	rout from Theory [Ohms]	Error from Theory
4919.65	4940.35	0.42%

From these results, it is clear that the common-drain amplifier has a much lower output resistance.

5 Part 4

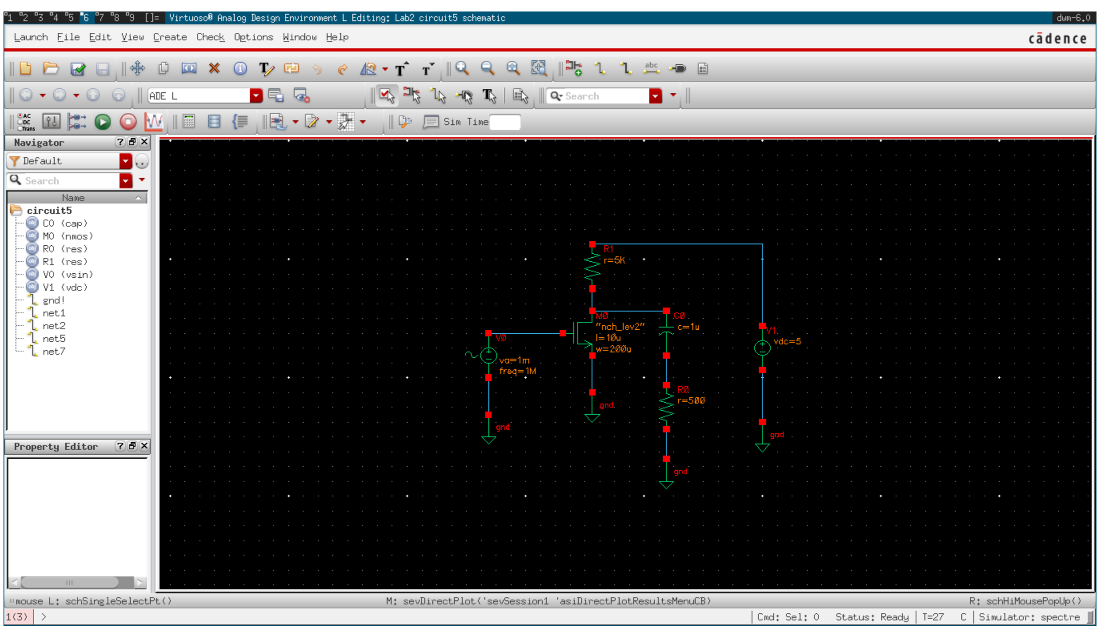

Figure 18: Circuit 5

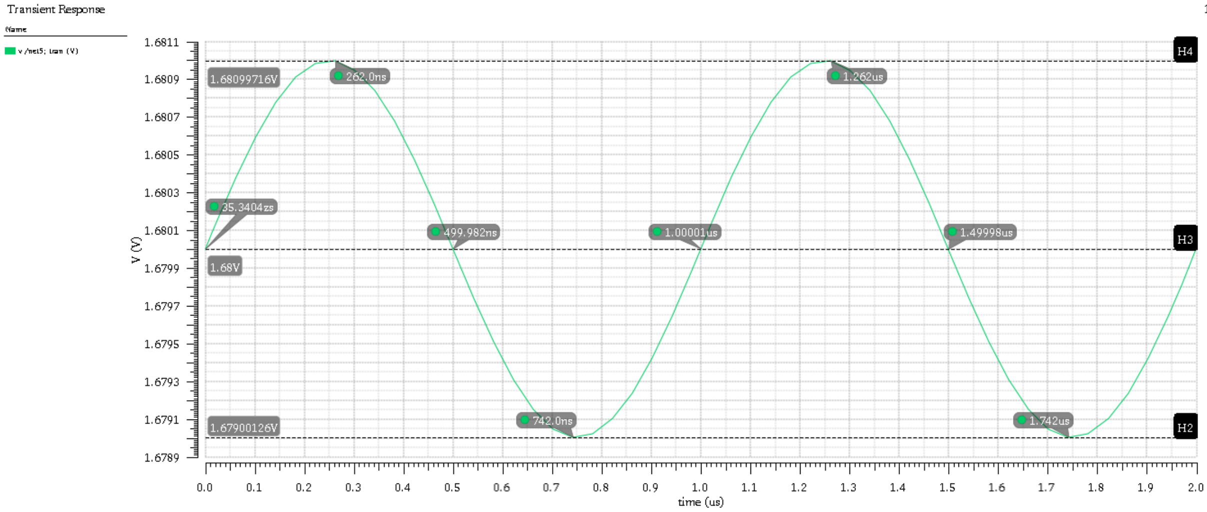

Figure 19: V_{in} for Small-Signal Test of Circuit 5

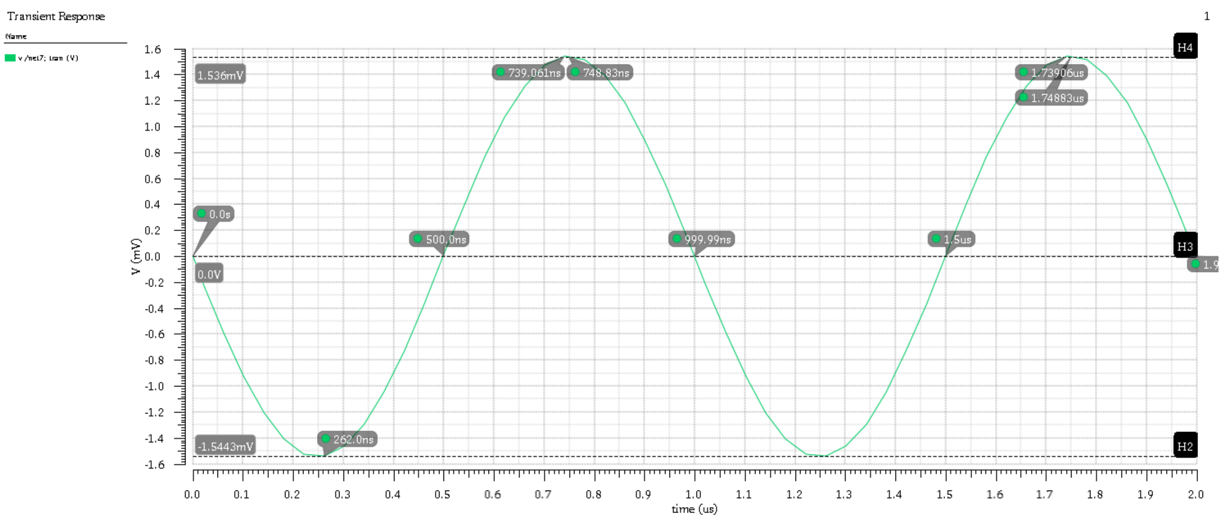

Figure 20: V_{out} for Small-Signal Test of Circuit 5

The small-signal gain can simply be acquired by taking the ratio of the amplitude of V_{out} to the amplitude of V_{in}. This should also be multiplied by a factor of -1 since the signals are out of phase by 180^o. The gain can be determined theoretically from $-g_m(R_D||R_L||r_o)$. Note that the capacitor at the output eliminates the DC bias voltage and passes an unbiased small signal to the output of the amplifier.

Table 8: Common-Source Amplifier Gain

Measured Gain [V/V]	Theoretical Gain [V/V]	Error from Theoretical
-1.54	-1.55	0.15%

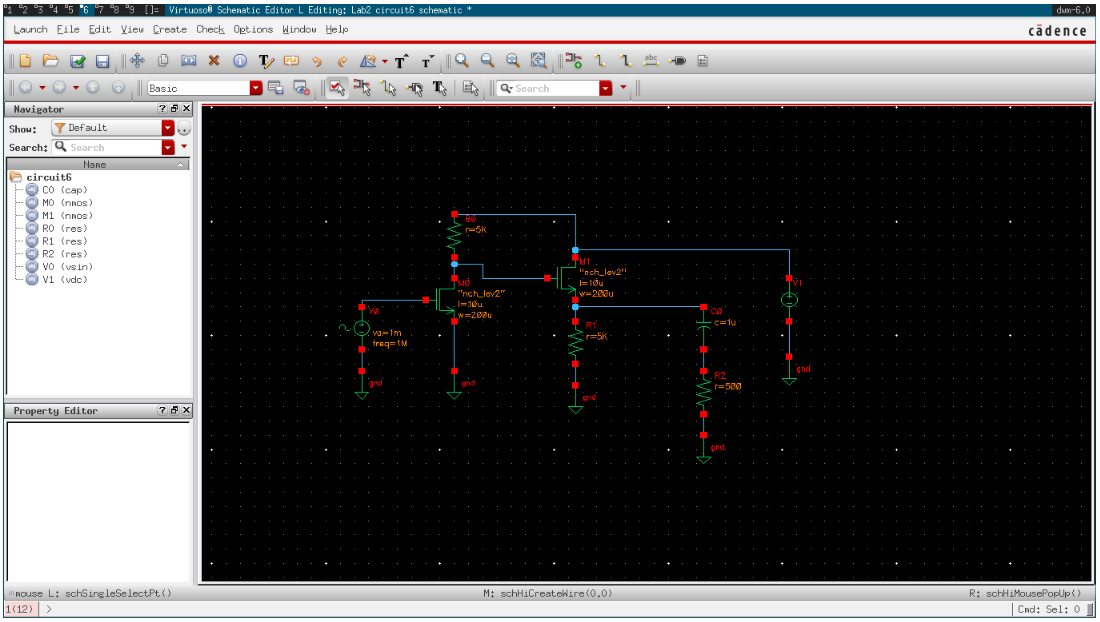

Figure 21: Cascaded Two-Stage Amplifier

The common-drain amplifier at the output will present nearly the same output voltage, but with a much lower output resistance. The theoretical gain can be calculated by multiplying a common-source gain with a common-drain gain (usually about 1) and then applying the voltage division equation.

$$A_{cascade} = \frac{A_{CSA} A_{CDA} R_L}{r_{out,CDA} + R_L} \tag{1}$$

Table 9: Gain of Cascaded Amplifier

Measured Gain [V/V]	Theoretical Gain [V/V]	Error from Theoretical
-8.50	-9.45	10.12%

A discrepancy exists between the theoretical value of the cascaded gain and the actual simulation result. The simulation likely accounts for parameters that are difficult to capture in theoretical calculations, such as the nonideal effects of the decoupling capacitor in the circuit. What is clear from either result is that the gain of the amplifier increases. This is because the common-drain amplifier's lower output resistance decreases the significance of the loading effect. So, instead of the load resistance causing the gain to drop as a result of a voltage divider effect, the load resistance receives a greater portion of the voltage drop because the output resistance of the amplifier has decreased.

6 Conclusion

The common-drain amplifier exhibits a "voltage follower" behavior. The small-signal output voltage of the amplifier simply tracks the small-signal input voltage of the amplifier. The common-source amplifier is to be used a voltage amplifier. By increasing the bias voltage past the midpoint, a higher gain can be achieved. However, this is at the cost of output voltage swing. For the same series resistor, the common-drain amplifier has a much lower output resistance than the common-source amplifier. Thus, by cascading a common-source amplifier as the voltage amplification stage followed by a common-drain amplifier that follows its voltage, a higher gain can be achieved for a given load simply because the output resistance drops considerably.