ECE4902 Lab 9 CMOS OP-AMP

PURPOSE:

The purpose of this lab is to measure the closed-loop performance of an op-amp designed from individual MOSFETs. This op-amp, shown in Fig. 9-1, combines all of the major circuit techniques we have been developing this term:

- Differential pair M1-M2 (input stage)
- Common source amplifier M5 (output stage)
- Current source with "bias rail" M6, M7, M8 (bias for differential pair and output stage)
- Current mirror load M3-M4 (for input stage high gain and single-ended to differential conversion)
- Active load M8 (for common source stage)
- Compensation using $R_Z$, $C_{COMP}$ and the Miller effect (for stability)

NOTE: Be sure to record ALL results in your laboratory notebook.

NOTE: This lab involves construction and measurement of circuits with very high gains. It is extremely important to use bypass capacitors $C_{BP1}$ and $C_{BP2}$ on the supply rail(s) to keep the power supply voltages clean. Also, keep wire leads as short as possible to prevent noise coupling into the circuit.

Figure 9-1
Figure 9-1.
CIRCUIT: CMOS OP-AMP

You’ll continue working with the CMOS op-amp shown in Figure 9-1. This is the one you built in lab 8 and tested open-loop, verifying a high gain >1000.

Figure 9-2.

UNITY GAIN BUFFER (UNCOMPENSATED)

L9-1. Configure the op-amp as a unity-gain buffer, shown in Fig. 9-2. Be sure the compensation capacitor \( C_{\text{COMP}} \) and zero resistor \( R_Z \) are not installed - so you see why you need them! Set the function generator to be a 1V peak, 100Hz sine wave.

The output of the op-amp should look something like a fuzzy sine wave. The reason is that the uncompensated op-amp is unstable, causing the output to oscillate. The oscillation should be approximately at the frequency at which \( 180^\circ \) of phase shift has accumulated around the feedback loop.

UNITY GAIN BUFFER (COMPENSATED)

L9-2. Add \( R_Z = 5.1k\Omega \) and \( C_{\text{COMP}}=100pF \) as shown in Fig. 9-1. You should see the op-amp output "calm down" as the oscillations disappear (or at least are greatly reduced). \( C_{\text{COMP}} \) is the Miller compensation capacitance discussed in class; resistor \( R_Z \) provides “lead compensation” to improve stability further as discussed in section 10.5 of Razavi and section 5.2 of Johns & Martin.

SLEW RATE LIMITING

L9-3. Using a ±4V square wave for \( v_s \), you should observe slew rate limiting on the output of the op-amp. Measure the positive-going and negative-going slew rate.

CLOSED LOOP BODE PLOT

L9-4. Go back to a sine wave input, and reduce the input amplitude to a small enough value (around 100mV peak) so that slew rate limiting does not occur. Determine the magnitude frequency response by measuring the input and output amplitudes over a range of frequencies from about 100Hz to over 1MHz. Use a logarithmic spacing on the frequency points; 1:3:10 or 1:2:5:10 is fine.
At each frequency, measure the input and output amplitudes and calculate the gain. Sketch the response as you go along. You may notice "peaking" in the magnitude plot (you definitely will if R_Z is not present!). The reason that R_Z is needed is that, with only C_COMP for compensation, the phase margin of this op-amp isn't as good as predicted from the simplified model of the Miller effect.

L9-5. Identify the closed loop bandwidth (3-dB frequency) f_{3dB}. Find the gain-bandwidth product (easy in this case since the closed loop DC gain is unity).

![Figure 9-3](image)

CLOSED LOOP GAIN OF 11 AMPLIFIER

L9-6. Reconfigure the op-amp for a gain of 11 as shown in Fig. 9-3.

To get a better feeling for the signals in a closed loop op-amp, use the multiple-channel capability of your scope to “follow” the signal along the path from input to output. Using a separate scope channel for each, look at the signal at the input (V_+), first stage output (V_G5), output V_{out}, and signal fed back to the inverting input (V_-). Note the polarity, amplitude, and DC bias level at each point.

CLOSED LOOP BODE PLOT

L9-7. With the input amplitude small enough (around 100mV peak) so that slew rate limiting does not occur, determine the magnitude frequency response by measuring the input and output amplitudes over a range of frequencies from about 100Hz to over 1MHz.

L9-8. Calculate the gain at each frequency, and sketch the response as you go along. You probably won't see "peaking" in this case. The reason is that the attenuation of the 1MΩ/100kΩ feedback network reduces the loop gain Aβ, thus improving the phase margin.

L9-9. Identify the closed loop DC gain, the closed loop bandwidth (3-dB frequency) f_{3dB}, and the gain-bandwidth product.
BANDWIDTH-RISE TIME RELATIONSHIP

L9-10. Change to a small signal (≈ 100mV peak-to-peak) step at the input. Measure the 10%-to-90% rise time $t_r$ (making sure that the output is not slew rate limited!). Using this measurement and the bandwidth x rise time = 0.35 relationship, estimate the bandwidth. How well does this agree with your measurement from the magnitude plot (frequency domain) results?

Lab Writeup

Your writeup should describe the measured performance relative to a hand analysis and simulation of the circuit. For the open-loop op-amp (comparator):

W9-1. Measurement:

• Show the waveforms from the uncompensated (L9-1) and compensated (L9-2) cases.
• Report the measured slew rate from L9-3.
• Show the Bode plots for closed-loop magnitude response from L9-4 and L9-7.
• Report the calculated gain-bandwidth products from L9-5 and L9-9.

Hand analysis vs. Measurements

W9-2. When comparing your measured results to what you would expect from a theoretical hand analysis, be sure to address the following in particular:

• How well does the gain-bandwidth product from the gain of 11 amplifier match that from the unity gain case? Ideally they would be the same - try to come up with an explanation for any difference.

• In each case, how close is the gain-bandwidth product to the prediction of $g_m/2\pi C_{COMP}$? You will have to "back into" the value of $g_m$, using the measured bias current and your CD4007 parameters.

• How close are the slew rate measurements to the prediction of $I_{SS}/C_{COMP}$? Try to come up with an explanation for any difference.

W9-3. Be sure to calculate the actual small signal parameters (such as the transconductance and output resistances $r_o$) from the measured DC bias conditions.

Simulation

S9-3. Compare the results of AC and transient simulations to your measured and calculated results for closed-loop frequency response, gain-bandwidth product, and slew rate limit.