

*Laboratory 3: Configurable Amplifiers Using Small-Signal MOS Resistors*  
**Laboratory Exercises**

## **INTRODUCTION**

### **Objectives**

This lab attempts to illustrate the small-signal operation of a nonlinear device by demonstrating a gain-controllable inverting amplifier and bandwidth-controllable lowpass filter using a small-signal MOS resistor.

### **Summary of Procedures**

- (i) Using the Analog Discovery 2 oscilloscope, take sufficient data to determine the parameters needed to predict the small-signal resistance of two NMOS transistors under various gate bias voltages.
- (ii) Build a gain-controllable inverting amplifier using an op amp, a resistor, and one of the discrete NMOS transistors measured in (i).
- (iii) Measure the gain and bandwidth of the gain-controllable amplifier under various MOS resistor gate bias voltages.
- (iv) Build a bandwidth-controllable unity-gain amplifier with the same op amp and the same two NMOS transistors measured in (i).

### **Materials Required**

- AD2 USB Oscilloscope
- BNC Adapter Board
- LMC6482 Op Amp
- CD4007UB
- Oscilloscope Probes
- BNC Cables
- Digital Multimeter
- Breadboard
- Assorted Resistors and Capacitors
- CD4007UB 6-MOSFET CDIP Package

## PROCEDURE

### 1. Characterizing MOS Transistors

In this part of the lab, you will use the Analog Discovery 2 to measure the I-V characteristics of two NMOS transistors contained within the CD4007UB CDIP packages. For your reference, the data sheet (including the pinout) for the CD4007UB transistor DIP is online. Note that this chip contains NMOS and PMOS transistors connected as complementary pairs, as well as an inverter circuit. For this lab, take care to choose the two NMOS transistors that do not have their source and body terminals shorted together. Since you will repeat parts (a) – (i) below for the second MOSFET, you may want to complete each measurement on both transistors before moving to the next measurement.

- (a) First you will measure the MOSFET  $I_D$  vs.  $V_{DS}$  curves, which are generated by measuring the transistor drain current while sweeping its drain-to-source voltage,  $V_{DS}$ . This sweep is then repeated for various values of gate-to-source voltage,  $V_{GS}$ . You should not use the BNC adapter board for these measurements, so make all connections directly to the Analog Discovery 2 outputs with jumper wires. The first thing you will need to do is set up your sweep using the Analog Discovery 2 waveform generators.
  - (i) First, set up your  $V_{DS}$  sweep of 0 V to 5 V. Open a waveform generator instance and set Channel 1 (W1) to output a triangle wave with frequency of 240 Hz, amplitude of 2.5 V and offset of 2.5 V. This will create a voltage that repeatedly sweeps linearly from 0 V to 5 V and back to 0 V. In order to synchronize the two sweeps properly, set the phase of W1 to  $270^\circ$ , which will start the sweep at 0 V at time  $t = 0$  sec.
  - (ii) Next, you will create a function that steps  $V_{GS}$  from 0 V to 5 V in 1 V steps. To do this, enable the Channel 2 (W2) in your waveform generator by clicking the “Channels” dropdown at the top of the window (next to the button that says “Run All”) and make sure both W1 and W2 are checked.

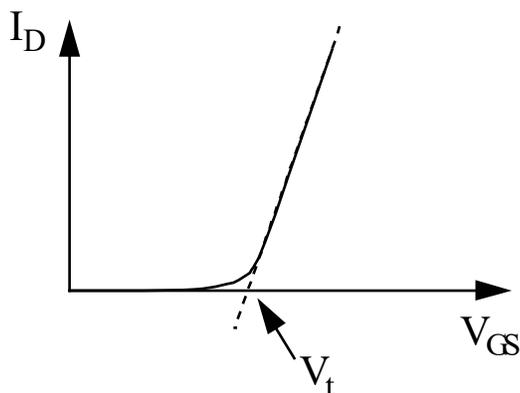
In the W2 window, click the dropdown menu that says “Simple” and change the waveform type to “Custom”. Click the button that says “New” to create a new custom waveform. In the new custom waveform window, click the tab that says “Values” and create six values from 0 to 5. Make sure the box in the bottom-left corner that says “Normalize” is checked and click the “Generate” button. In the plot window you should see a function that looks like a staircase with five steps (six values) spanning the entire vertical range of the window (-100% to 100%). Name your function to designate it as a stepped  $V_{GS}$  sweep and click “Save” to close the custom waveform window.

Now, back in the Channel 2 (W2) settings, set the frequency of the custom waveform to 40 Hz, the amplitude to 2.5 V and the offset to 2.5 V. Since we normalized the shape of this waveform to minimum and maximum values of -1 and +1, the resulting waveform will have minimum and maximum values of 0 V and 5 V, with steps of 1 V in between. The frequency is chosen such that for each step, the  $V_{DS}$  sweep controlled by W1 will complete a full 0 V to 5 V (and back to 0 V) sweep before W2 steps up to the next value of  $V_{GS}$ .

- (iii) Lastly, make sure to click the dropdown labeled “No synchronization” at the top of the window and change it to “Synchronized”. This will reveal some new settings right below the dropdown. Change the “Run” setting to 25 ms, which tells the Analog Discovery 2 how frequently to check and resynchronize the two waveform generator channels.
- (b) Now that you’ve set up your sweeps, find a  $100\ \Omega$  resistor and measure its actual value using your DMM. Then, connect the W1 output and the positive pin of the first oscilloscope channel (labeled 1+ on the Analog Discovery 2 enclosure) to the drain of your first MOSFET  $M_1$  through this resistor (i.e., put the resistor in series with the W1 output and the drain terminal). Connect the negative pin of the first oscilloscope channel (1–) to the other side of the resistor, which should be the drain terminal of  $M_1$ . You will use this measured voltage drop across the resistor along with its measured resistance value to calculate the drain current,  $I_D$ .
- (c) Connect the W2 output to the gate terminal of  $M_1$ . Connect the positive pin of the second oscilloscope channel (2+) to the drain terminal and the negative pin of the second oscilloscope channel (2–) to ground. Ground the source terminal and apply a body bias voltage  $V_B = -1\ \text{V}$  to the body terminal using the negative voltage supply of the Analog Discovery 2.
- (d) Turn on your waveform generator outputs and open an oscilloscope instance. You may want to trigger on W2, but feel free to play around and see what triggering gives you the most stable measurement. You need to create a new Math channel that scales the voltage measured across the  $100\ \Omega$  resistor in order to plot the current  $I_D$ . Click “Add Channel” on the right side of the window and choose “Math > Custom”. Simply change the expression to  $C1/R1$ , replacing R1 with your measured resistance value. Click “OK” and you should see a new channel called M1 that plots the drain current.
- (e) Even if you’ve done everything correctly up to this point, the waveforms may seem convoluted and difficult to interpret. To fix this, create a new XY plot by clicking “View > Add XY” in the top menu. This will open a new pane within your oscilloscope window. At the top of this pane set the  $x$ -axis to C2 and the  $y$ -axis to M1 (the math channel you created in (d), not transistor  $M_1$ ). This will plot  $I_D$  vs.  $V_{DS}$ . In order to line the sweeps up properly, set the time position to 12.5 ms with a base of 2.5 ms/div. You should now see a series of I-V curves that resemble the MOS  $I_D$ - $V_{GS}$  characteristics you’ve seen in lecture. You may need to adjust the Channel 1 and 2 vertical scales.
- (f) Once you’re satisfied with the display settings of your I-V curves, export the XY plot as both an image and as raw data (.csv). Use the data analysis software you’re most comfortable with to plot this data and measure the approximate slope of the I-V curve for  $V_{GS} = 5\ \text{V}$  in the linear region. The inverse of this slope is the small-signal resistance  $r_{ds1}$  of your linear-region MOSFET,  $M_1$ . Record the value of  $r_{ds1}$ .
- (g) Repeat steps (b) – (f) above for the second NMOS transistor,  $M_2$ .

Now you will use a similar test setup to measure the  $I_D$ - $V_{GS}$  characteristic of both  $M_1$  and  $M_2$  for various body-bias values  $V_B$ . The sweep parameters are given below, and your job is to modify the setup used for parts (a) – (g) in order to measure the  $I_D$ - $V_{GS}$  characteristics.

- (h) Measure the  $I_D$ - $V_{GS}$  characteristics by sweeping  $V_{GS}$  from 0 V to 5 V for values of  $V_B$  ranging from  $-5$  V to 0 V in 1 V increments (with  $V_{DS} = 500$  mV). Save an image of your curves. If you want, you may do the following analysis in a separate program by first exporting the data as a .csv file.
- (i) Since you cannot create cursors in the XY plot, you can instead use cursors in the main oscilloscope window to determine the approximate threshold voltage for the case where  $V_B = 0$  V, which we call  $V_{T0}$ . If you extend a line downwards from the region where the transistor is turned on (i.e., not in cutoff, the steep part of the curve), the point where this line crosses the  $x$ -axis is defined as the threshold voltage. This is shown in Fig. L3.1. Unless you are analyzing your data in a separate program, you may approximate the threshold voltage by using cursors to find the voltage  $V_{GS}$  where the drain current  $I_D$  drops to zero. Note that this requires you to understand which curve corresponds to which body-bias value. Save an annotated version of the plot and cursors you use to take your measurement.
- (j) Repeat steps (h) & (i) for  $M_2$ .

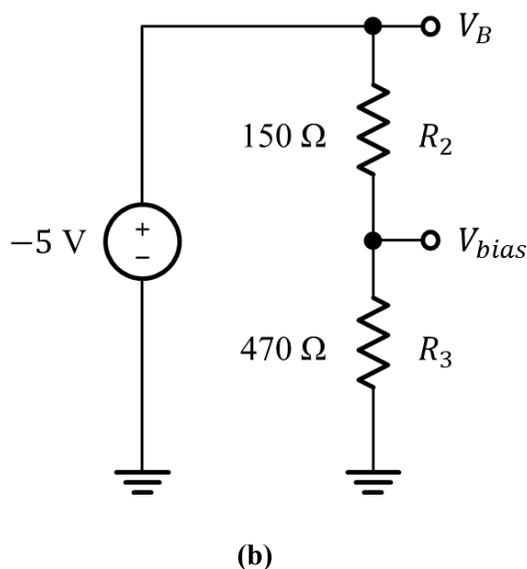
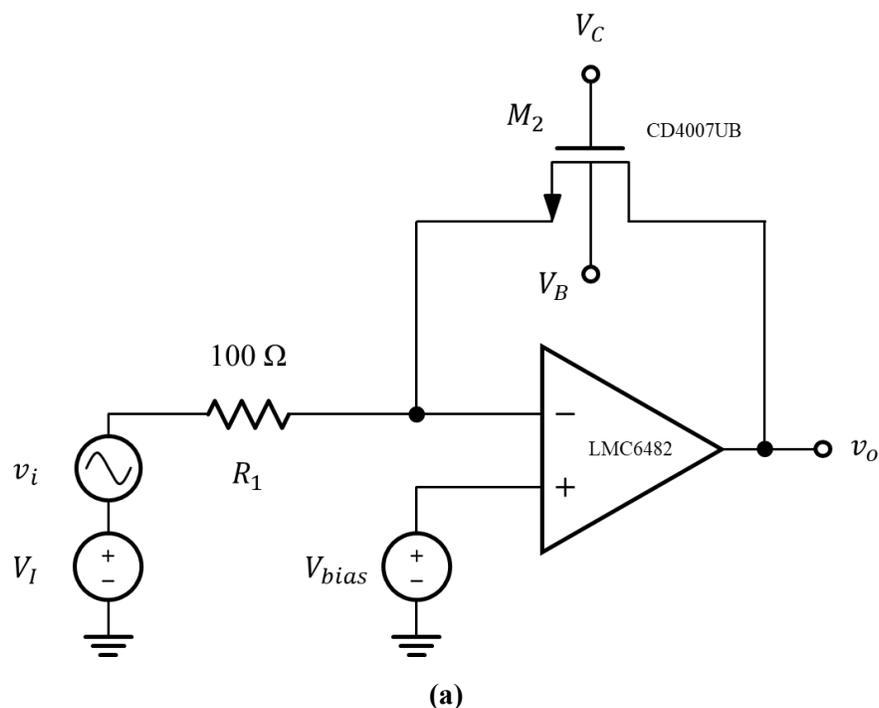


**Figure L3.1** Determination of  $V_{T0}$  from the  $I_D$  vs.  $V_{GS}$  curve for a linear MOSFET.

## 2. Gain-Controllable Amplifier

- (a) First, build the circuits in Fig. L3.2.
  - (i) Reconnect the BNC adapter board to your Analog Discovery 2. Build the circuit in Fig. L3.2(a), using the power supplies to generate  $\pm 5$  V rails for the LMC6482 op amp. Use the same negative power supply to power the voltage divider in Figure L3.2(b), the outputs of which you will connect to the body terminal of  $M_1$  ( $V_B$ ) and the noninverting terminal of your op amp ( $V_{bias}$ ). As always, make sure to measure all actual resistor values. Measure and record the generated bias voltage  $V_{bias}$ .

- (ii) Use the waveform generators (in 0- $\Omega$  mode) to supply  $V_C$  and the input signal  $v_i = V_I + v_i \sin(2\pi \cdot 100t)$ , setting the input amplitude  $v_i$  to 50 mV and the DC input voltage  $V_I$  to the same bias voltage  $V_{bias}$  you measured in part (i). You may want to use the waveform generators in “Basic” mode (as opposed to



**Figure L3.2** Gain-controllable amplifier circuit showing: (a) the op amp circuit with NMOS transistor  $M_2$  in feedback, input bias voltage  $V_I$ , and bias voltage  $V_{bias}$ ; and (b) the voltage divider circuit used to generate  $V_B$  and  $V_{bias}$

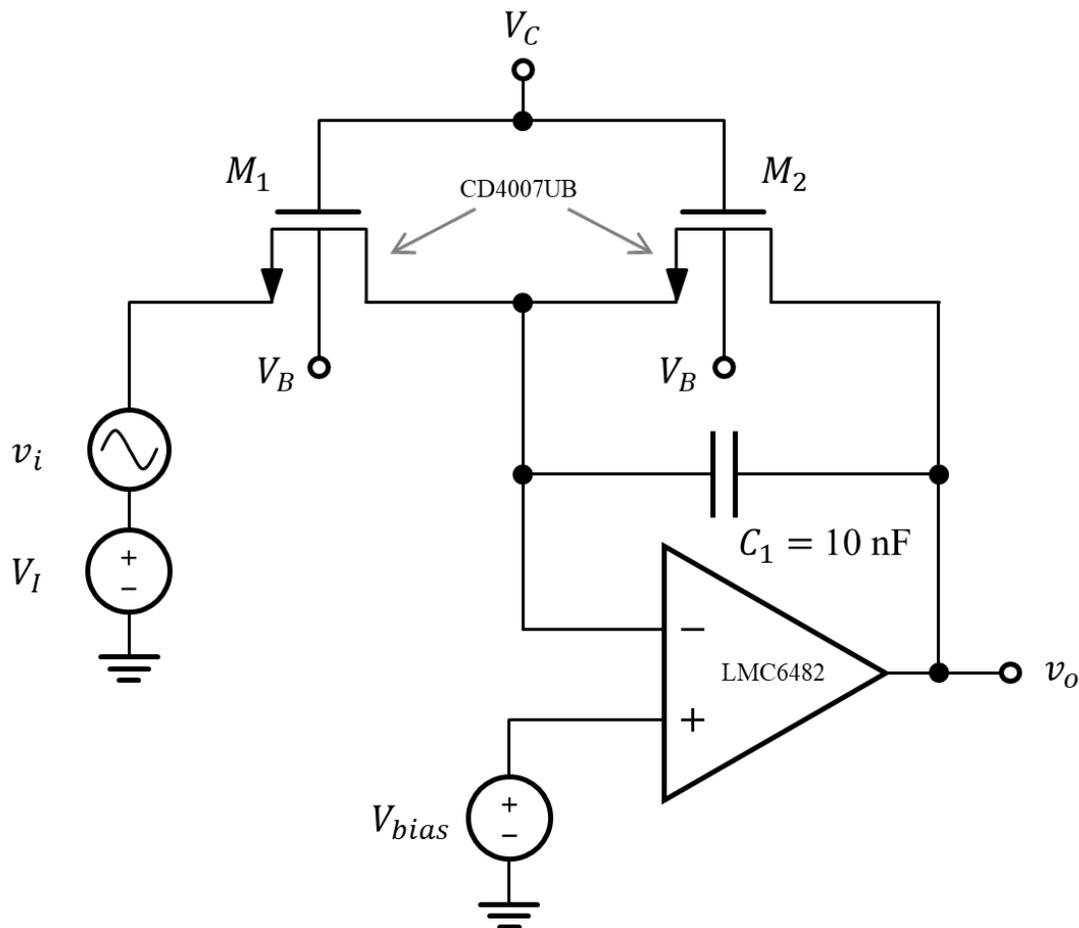
“Simple” or “Custom”) so that you can fine-tune the DC input voltage and amplitude.

- (iii) Set both oscilloscope channels to DC coupling and connect two compensated probes to  $v_i$  and  $v_o$  respectively (you may want to use your probes in  $10\times$  mode). Measure the low-frequency gain,  $v_o/v_i$ , and 3-dB bandwidth for values of  $V_C$  ranging from -1 V to 5 V (in steps of 1 V), increasing the dc input voltage  $V_I$  and decreasing the input amplitude  $v_i$  as needed to eliminate any distortion at the output. For each value of the control voltage  $V_C$ , make sure you measure the actual DC value of the gate-to-source voltage  $V_{GS}$  (you can use your DMM for this). Tabulate your data using the “measured” sections of Table L3.1 in the *Results Sheet for Laboratory Exercises*, then plot the gain vs.  $V_{GS}$  and the 3-dB bandwidth versus  $V_{GS}$  on separate graphs.
- (b) [Note: You can do this part after the lab period, if necessary.] Extract values for  $K_n$  and  $V_{TN}$  from your part 1 measurements and use these to fill in the “calculated” portions of Table L3.1 in the *Results Sheet for Laboratory Exercises*. Then plot the gain versus  $V_C$  and 3-dB bandwidth versus  $V_C$  on the same graphs as your measured data, being sure to delineate which graph is which. Comment on any discrepancies between measured and calculated data.
- (c) Next, with  $V_C$  set to 5 V, adjust your DC input voltage  $V_I$  about its nominal value,  $V_{bias}$ , until you see distortion of the output waveform. Do you see the same distortion when you increase  $V_I$  as when you decrease  $V_I$ ? Attach plots of the ensuing output waveforms. Why do you think the waveforms look the way they do? Explain in detail what you think may be happening.

### 3. Bandwidth-Controlled (Unity-Gain) Filter

- (a) Hook up the circuit in Fig. L3.3 using the same voltage divider connected to the body terminals of your MOSFETs and the noninverting input of your op amp, being sure to measure the actual value of  $C_I$  using the capacitance meter on your DMM. Using the waveform generator, apply a 200 mV<sub>PP</sub>, 1-kHz sine wave to the input of the circuit, again setting the offset  $V_I$  to be equal to the measured value of  $V_{bias}$ . Use the oscilloscope or the network analyzer to measure the low frequency gain  $v_o/v_i$  and 3-dB bandwidth of this amplifier for values of control voltage  $V_C$  ranging from 0 V to 5 V, in steps of 1 V. Again, be sure to record the actual DC gate-to-source voltage  $V_{GS}$  for each value of  $V_C$ . Even if you choose to use the network analyzer, you must include at least one scope plot for each value of  $V_C$  to verify your waveforms are not distorted. If they are, you may adjust your input signal’s offset voltage and amplitude to try and eliminate any distortion. Tabulate your data using the “measured” sections of Table L3.2 in the *Results Sheet for Laboratory Exercises*, then plot the gain versus  $V_C$  and 3-dB bandwidth versus  $V_C$  on separate graphs.
- (b) [Note: You can do this part after the lab period, if necessary.] Extract values for  $K_n$  and  $V_{TN}$  from your part 1 measurements and use these to fill in the “calculated” portions of Table L3.2 in the *Results Sheet for Laboratory Exercises*. Then plot the gain versus  $V_C$

and 3-dB bandwidth versus  $V_C$  on the same graphs as your measured data, being sure to delineate which graph is which. Comment on any discrepancies between measured and calculated data.



**Figure L3.3** Bandwidth-controlled unity-gain amplifier circuit biased with the same scheme as the gain-controllable amplifier.

**Laboratory 3: Configurable Amplifiers Using Small-Signal MOS Resistors**  
**Results Sheet for Laboratory Exercises**

NAME: \_\_\_\_\_

LAB SECTION: \_\_\_\_\_

**1. Characterizing MOS Transistors**

- (a) Attach annotated XY plot of  $I_D$  vs.  $V_{DS}$  curves for both  $M_1$  and  $M_2$ . Show all calculations on the plot.

$$r_{ds1} \text{ (for } M_1 \text{ with } V_{GS1} = 5 \text{ V)} = \underline{\hspace{4cm}}$$

$$r_{ds2} \text{ (for } M_2 \text{ with } V_{GS2} = 5 \text{ V)} = \underline{\hspace{4cm}}$$

- (b) Attach annotated XY plot of  $I_D$  vs.  $V_{GS}$  curves for both  $M_1$  and  $M_2$ . Show all calculations on the plot.

$$V_{t1} \text{ (for } M_1) = \underline{\hspace{4cm}}$$

$$V_{t2} \text{ (for } M_2) = \underline{\hspace{4cm}}$$

**2. Gain-Controllable Amplifier**

- (a) Measured values:

$$R_1 = \underline{\hspace{2cm}}, R_2 = \underline{\hspace{2cm}}, R_3 = \underline{\hspace{2cm}}$$

$$V_{bias} = \underline{\hspace{2cm}}$$

Fill in the columns associated with the “measured” portions of Table L3.1. Attach the required annotated plots.

- (b) Fill in the columns associated with the “calculated” portions of Table L3.1. Plot your results as required on the same graph as the measured data.
- (c) Attach an annotated plot of the output waveforms and provide a possible explanation for what you observed.

$V_C$ [V]	$V_{GS}$ [V]	Gain, $v_o/v_i$ [V/V]		3-dB BW [Hz]	
		2(a) Measured	2(b) Calculated	2(a) Measured	2(b) Calculated
-1					
0					
1					
2					
3					
4					
5					

Table L3.1 Gain-Configurable Amplifier Characteristics

### 3. Bandwidth-Controlled (Unity-Gain) Filter

- (a) Measured value of  $C_1 =$  \_\_\_\_\_
- (b) Fill in the columns associated with the “measured” portions of Table L3.2. Attach the required annotated plots.
- (c) Fill in the columns associated with the “calculated” portions of Table L3.2. Plot your results as required on the same graph as the measured data.

$V_C$ [V]	$V_{GS}$ [V]	Gain, $v_o/v_i$ [V/V]		3-dB BW [Hz]	
		3(a) Measured	3(b) Calculated	3(a) Measured	3(b) Calculated
0					
1					
2					
3					
4					
5					

Table L3.2 Bandwidth-Configurable Amplifier Characteristics