ECEN 325 Lab 11: MOSFET Amplifier Configurations

Objective

The purpose of this lab is to examine the properties of the MOS amplifier configurations. DC operating point, voltage gain, and input and output impedances of common-source and common-drain topologies will be studied.

Introduction

MOSFET DC Biasing

Figures 1(a) and (b) show typical resistive biasing circuits for NMOS and PMOS transistors, respectively.

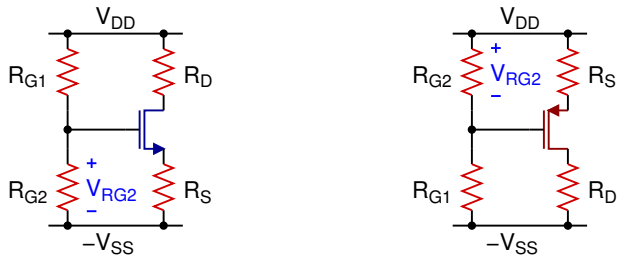


Figure 1: Resistive DC biasing circuit for (a) NMOS (b) PMOS

Assuming that the transistors are active, DC solutions for Figs. 1(a) and (b) can be found as

$$\textbf{NMOS:} \quad \left.\begin{aligned} I_D &= \frac{k_n'}{2}\frac{W}{L}(V_{GS}-V_{tn})^2 \\ V_{RG2} &= \frac{R_{G2}}{R_{G1}+R_{G2}}(V_{DD}+V_{SS}) = V_{GS}+I_D R_S \end{aligned}\right\} \Rightarrow \frac{V_{RG2}-V_{GS}}{R_S} = \frac{k_n'}{2}\frac{W}{L}(V_{GS}-V_{tn})^2 \qquad (1)$$

$$\textbf{PMOS:} \quad \left.\begin{aligned} I_D &= \frac{k_p'}{2}\frac{W}{L}(V_{SG}-|V_{tp}|)^2 \\ V_{RG2} &= \frac{R_{G2}}{R_{G1}+R_{G2}}(V_{DD}+V_{SS}) = V_{SG}+I_D R_S \end{aligned}\right\} \Rightarrow \frac{V_{RG2}-V_{SG}}{R_S} = \frac{k_p'}{2}\frac{W}{L}(V_{SG}-|V_{tp}|)^2 \qquad (2)$$

Both quadratic equations above have two solutions, where the solution satisfying $V_{GS} > V_{tn}$ and $V_{SG} > |V_{tp}|$ should be chosen for the NMOS and PMOS circuits, respectively. After determining V_{GS} or V_{SG}, I_D can be calculated from the linear equation. To verify that the transistors are active, the following should be satisfied

$$\textbf{NMOS:} \quad V_{DS} \geq V_{ov} \Rightarrow V_{DD}+V_{SS}-I_D(R_D+R_S) \geq V_{GS}-V_{tn} \qquad (3)$$

$$\textbf{PMOS:} \quad V_{SD} \geq V_{ov} \Rightarrow V_{DD}+V_{SS}-I_D(R_D+R_S) \geq V_{SG}-|V_{tp}| \qquad (4)$$

MOSFET Small-Signal AC models

Figure 2 shows the AC small-signal models for NMOS and PMOS transistors in the active region. Small-signal parameters in Fig. 2 can be calculated as

$$g_m = k'\frac{W}{L}V_{ov} = \sqrt{2k'\frac{W}{L}I_D} \qquad r_o = \frac{1}{\lambda I_D} \qquad (5)$$

where λ is the channel length modulation parameter. For typical discrete MOSFET circuit implementations, r_o will not have a significant impact, therefore will be ignored. For small-signal AC analysis, π-model and T-model provide identical results, however the T-model allows more intuitive analysis with simpler calculations. Table 1 shows node impedances and node-to-node gains for generic MOSFET configurations, which are derived by substituting the transistor with its T-model, where $r_o = \infty$.

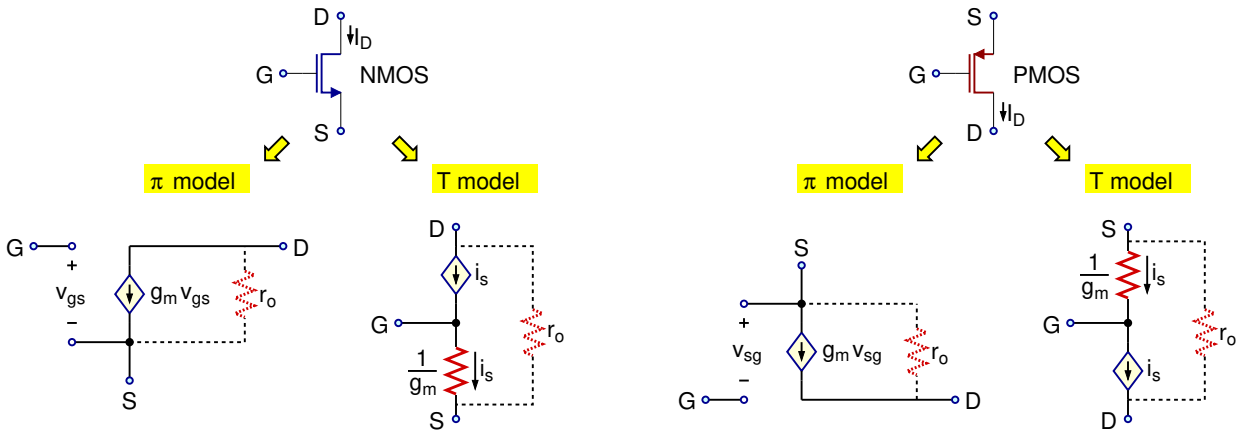
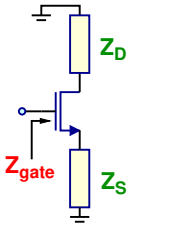
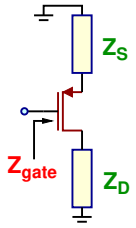
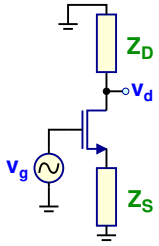
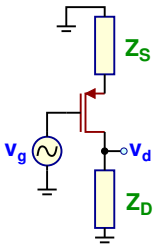
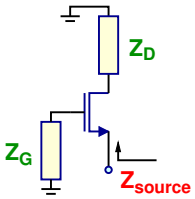
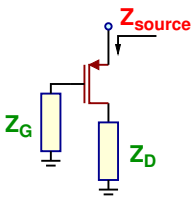
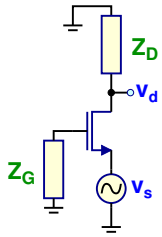
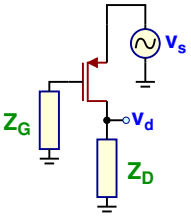
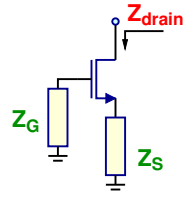
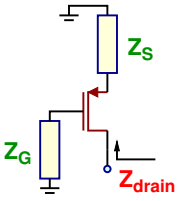
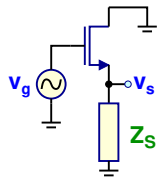
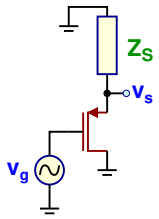


Figure 2: Small-signal AC models for NMOS and PMOS transistors

Table 1: MOSFET Node Impedances and Node-to-Node Gains when $r_o = \infty$

NMOS	PMOS	Impedance	NMOS	PMOS	Gain
		$Z_{gate} = \infty$			$\frac{v_d}{v_g} = \frac{-Z_D}{\frac{1}{g_m} + Z_S}$
		$Z_{source} = \frac{1}{g_m}$			$\frac{v_d}{v_s} = \frac{Z_D}{Z_{source}}$
		$Z_{drain} = \infty$			$\frac{v_s}{v_g} = \frac{Z_S}{\frac{1}{g_m} + Z_S}$

MOSFET Amplifier Configurations

Common-Source Configuration

Figures 3 and 4 show the common-source configurations for NMOS and PMOS transistors, respectively. AC analysis of this configuration yields

$$A_v = \frac{V_{o,ac}}{V_i} = -\frac{R_D}{\left(\frac{1}{g_m}\right)} = -g_m R_D \qquad R_i = R_G = R_{G1} \parallel R_{G2} \qquad R_o = R_D \tag{6}$$

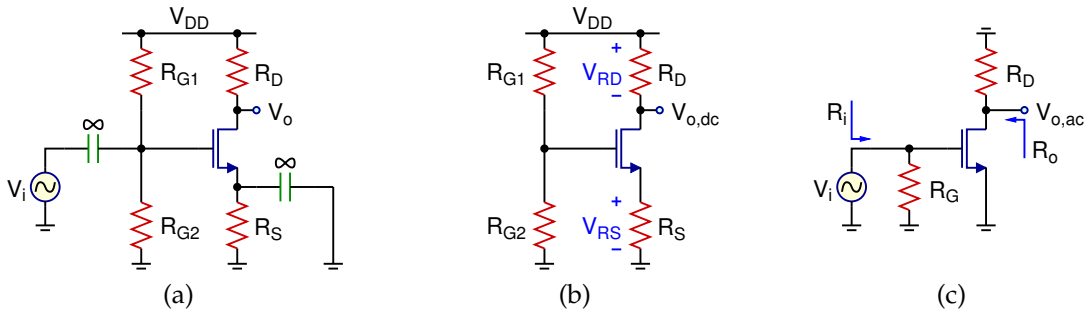


Figure 3: (a) NMOS Common-Source Configuration (b) DC equivalent (c) AC equivalent

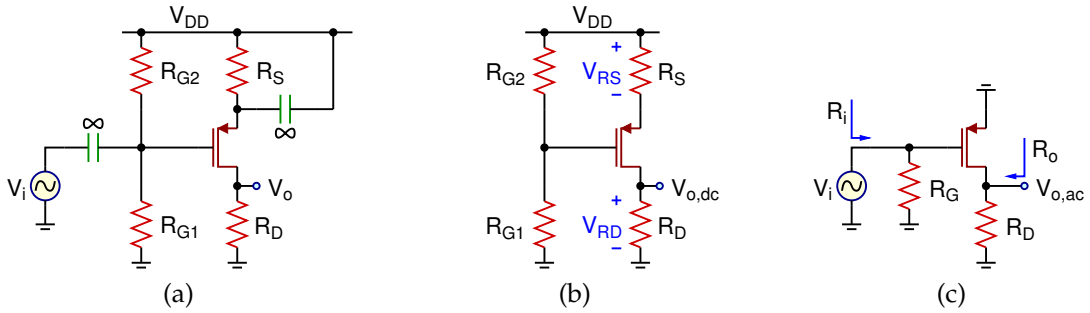


Figure 4: (a) PMOS Common-Source Configuration (b) DC equivalent (c) AC equivalent

Typical design specifications for the common-source configuration includes:

- 0-to-peak unclipped output voltage swing: $\hat{V}_o$
- Voltage gain: $A_v = \dfrac{V_{o,ac}}{V_i}$
- Input and output resistances: R_i and R_o
- THD at the maximum output level

Based on the typical specifications, design procedure for the common-source amplifiers in Figs. 3 and 4 can be given as follows:

➪ Choose $V_{RS} \approx 1V$ to reduce the variation of I_D as a function of V_t.

➪ To have an unclipped output swing of $\hat{V}_o$, V_{RD} should be chosen such that $(V_{DD} - \hat{V}_o - V_{RS} - V_{ov}) \geq V_{RD} \geq \hat{V}_o$. Choice of V_{RD} does not only affect the available signal swing at the output, but also determines the gain as well as the linearity of the amplifier as follows:

☆ $|A_v| = g_m R_D = g_m \dfrac{V_{RD}}{I_D} = \cancel{K'}\dfrac{W}{\cancel{L}}\cancel{V_{ov}}\dfrac{V_{RD}}{\frac{\cancel{K'}}{2}\frac{W}{\cancel{L}}V_{ov}^{\cancel{2}}} = \dfrac{2V_{RD}}{V_{ov}}$

☆ Small-signal condition: $\hat{v}_{gs} \ll 2V_{ov} \Rightarrow \dfrac{\hat{V}_o}{2V_{RD}} V_{ov} \ll 2V_{ov} \Rightarrow \hat{V}_o \ll 4V_{RD}$

To maximize the available gain and linearity, choose $V_{RD} = V_{DD} - \hat{V}_o - V_{RS} - V_{ov}$. Since $V_{ov} = \dfrac{2V_{RD}}{|A_v|}$,

$$V_{RD} = \frac{V_{DD} - \hat{V}_o - V_{RS}}{1 + \dfrac{2}{|A_v|}}$$

To avoid clipping or distortion due to possible variation of V_t, V_{RD} may be chosen slightly less than the value given in the equation above.

- Calculate $V_{ov} = \dfrac{2V_{RD}}{|A_v|}$, then $I_D = \dfrac{k'}{2}\dfrac{W}{L}V_{ov}^2$.
- Calculate $R_D = \dfrac{V_{RD}}{I_D}$ and $R_S = \dfrac{V_{RS}}{I_D}$
- Find R_{G1} and R_{G2} such that $V_{RG2} = V_{RS} + |V_t| + V_{ov}$ and $R_{id} = R_{G1} \| R_{G2}$, which yields

$$R_{G1} = \frac{R_{id} V_{DD}}{V_{RS} + |V_t| + V_{ov}} \qquad R_{G2} = \frac{R_{G1} R_{id}}{R_{G1} - R_{id}}$$

where R_{id} is the desired input resistance.

Common-Drain (Source Follower) Configuration

Figures 5 and 6 show the common-drain configurations (also known as source follower) for NMOS and PMOS transistors, respectively. DC analysis of this configuration can be performed using the same equations given in (1) and (2), whereas AC analysis yields

$$A_v = \frac{V_{o,ac}}{V_i} = \frac{R_S}{\dfrac{1}{g_m} + R_S} \qquad R_i = R_{G1} \parallel R_{G2} \qquad R_o = R_S \parallel \frac{1}{g_m} \tag{7}$$

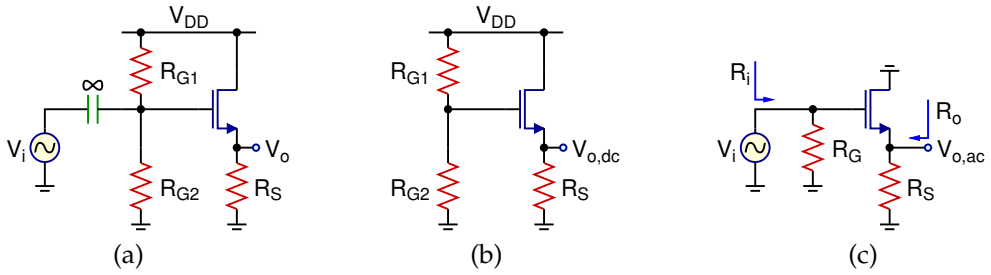


Figure 5: (a) NMOS Common-Drain (Source Follower) Configuration (b) DC equivalent (c) AC equivalent

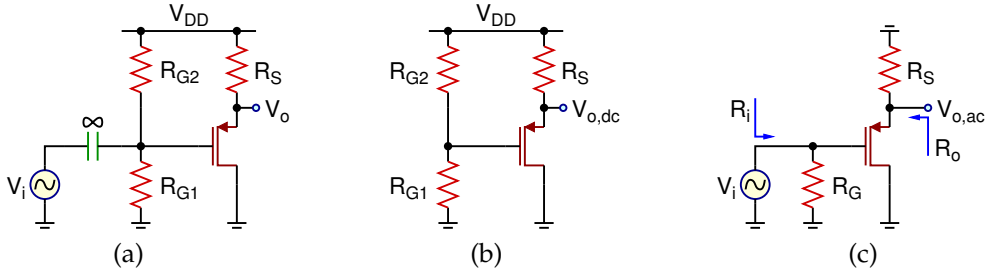


Figure 6: (a) PMOS Common-Drain (Source Follower) Configuration (b) DC equivalent (c) AC equivalent

In typical multi-stage amplifiers, source follower is directly connected to a gain stage, such as a common-source amplifier, without the extra biasing resistors R_{G1} and R_{G2}. Therefore, DC voltage levels in a source follower is typically dependent on the previous amplifier stage.

Calculations

1. Using the 2N7000G transistor, design the common-source amplifier in Fig. 3(a) with the following specifications:

Supply Voltage, V_{DD}	5V
0-to-Peak Output Swing, $\hat{V}_o$	$\geq 1V$
Voltage Gain, $\lvert A_v \rvert$	25
Input Resistance, R_i	$\geq 10k\Omega$
THD for 5kHz 1V (0-to-peak) Sine Wave Output Voltage, V_o	$\leq 5\%$

   Show your design procedure and all your calculations.

2. Using 2N7000G and the same R_{G1}, R_{G2} and R_S values from your common-source amplifier, calculate A_v, R_i and R_o for the source follower in Fig. 5.

Simulations

For all simulations, provide screenshots showing the schematics and the plots with the simulated values properly labeled.

1. Draw the common-source amplifier schematic in Fig. 3(a) using the calculated component values and 2N7000G transistor.
   - **(a)** Perform **DC operating point** or **interactive simulation** to obtain the **DC solution** for V_{RG2}, V_{RS}, V_{RD}, $V_{o,dc}$ and I_D.
   - **(b)** Perform **AC simulation** to obtain A_v and R_i.
   - **(c)** Apply a 5kHz 40mV sine wave signal to the input V_i and obtain the **time-domain waveforms** for the input and output voltages using **transient simulation**. Perform **Fourier simulation** to measure the **total harmonic distortion (THD)** on the output waveform.
   - **(d)** Increase the input amplitude to measure the clipping levels at the output voltage V_o.
2. Draw the source follower schematic in Fig. 5(a) using the calculated component values and 2N7000G transistor.
   - **(a)** Perform **DC operating point** or **interactive simulation** to obtain the **DC solution** for V_{RG2}, V_{RS} and I_D.
   - **(b)** Perform **AC simulation** to obtain A_v, R_i and R_o.
   - **(c)** Apply a 5kHz 0.8V sine wave signal to the input V_i and obtain the **time-domain waveforms** for the input and output voltages using **transient simulation**. Perform **Fourier simulation** to measure the **total harmonic distortion (THD)** on the output waveform.

Measurements

For all measurements, provide screenshots showing the plots with the measured values properly labeled.

1. Build the common-source amplifier in Fig. 3(a) using the simulated component values and 2N7000G transistor.
   - **(a)** Measure the **DC** values for V_{RG2}, V_{RS}, V_{RD}, $V_{o,dc}$ and I_C using the **voltmeter** or **scope**.
   - **(b)** Measure A_v and R_i using the **network analyzer**.
   - **(c)** Apply a 5kHz 40mV sine wave signal to the input V_i and obtain the **time-domain waveforms** for the input and output voltages using the **scope**. Measure the **total harmonic distortion (THD)** on the output waveform using the **spectrum analyzer**.
   - **(d)** Increase the input amplitude to measure the clipping levels at the output voltage V_o using the **scope**.

2. Build the source follower circuit in Fig. 5(a) using the simulated component values and 2N7000G transistor.
   (a) Measure the **DC** values for V_{RG2}, V_{RS} and I_D using the **voltmeter** or **scope**.
   (b) Measure A_v, R_i and R_o using the **network analyzer**.
   (c) Apply a 5kHz 0.8V sine wave signal to the input V_i and obtain the **time-domain waveforms** for the input and output voltages using the **scope**. Measure the **total harmonic distortion (THD)** on the output waveform using the **spectrum analyzer**.

Report

1. Include calculations, schematics, simulation plots, and measurement plots.
2. Prepare a table showing simulated and measured results.
3. Compare the results and comment on the differences.

Demonstration

1. Build the common-source amplifier in Fig. 3(a) and the source follower in Fig. 5(a) on your breadboard and bring it to your lab session.
2. Your name and UIN must be written on the side of your breadboard.
3. Submit your report to your TA at the beginning of your lab session.
4. For the common-source amplifier in Fig. 3(a):
   - Measure A_v and R_i using the network analyzer.
   - Apply a 5kHz 40mV sine wave input and show the time-domain output voltage using the scope.
   - With the 5kHz 40mV sine wave input, measure the THD at the output using the spectrum analyzer.
5. For the source follower in Fig. 5(a):
   - Apply a 5kHz 0.8V sine wave input, and show the time-domain waveforms at the input and the output using the scope.