EXERCISE

5.10 Evaluate the gain expression found in Exercise 5.9 by using the values given in Example 5.6. Compare the result with the voltage gain found in the example.

Answer $A_v = -0.849$ without the bypass capacitor, compared to $A_v = -5.66$ with the bypass capacitor in place. Unbypassed impedance between the FET source terminal and ground greatly reduces the gain of a common-source amplifier.

5.6 THE SOURCE FOLLOWER

Another amplifier circuit, known as a source follower, is shown in Figure 5.33. The signal to be amplified is $v(t)$, and $R$ is the internal resistance of the signal source. The coupling capacitor $C_1$ causes the ac input signal to appear at the gate of the FET. The capacitor $C_2$ connects the load to the source terminal of the MOSFET. (In the midband analysis of the amplifier, we assume that the coupling capacitors behave as short circuits.) The resistors $R_5$, $R_1$, and $R_2$ form the bias circuit.

The Small-Signal Equivalent Circuit

The small-signal equivalent circuit is shown in Figure 5.34. The coupling capacitors have been replaced by short circuits, and the FET has been replaced by its small-signal equivalent. Notice that the drain terminal is connected directly to ground, because the dc supply becomes a short in the small-signal equivalent. Here, the FET equivalent circuit is drawn in a different configuration (i.e., with the drain at the bottom) from that illustrated earlier, but it is the same electrically.

Figure 5.33 Source follower.
**Figure 5.34** Small-signal ac equivalent circuit for the source follower.

Drawing the small-signal equivalent of an amplifier circuit is an important skill for electronics engineers. Starting from Figure 5.33, test yourself to see if you can obtain the small-signal circuit.

**Voltage Gain**

We now derive an expression for the voltage gain of the source follower. Notice that \( r_d \), \( R_s \), and \( R_L \) are in parallel. We denote the parallel combination by

\[
R'_L = \frac{1}{1/r_d + 1/R_s + 1/R_L} \quad (5.44)
\]

The output voltage is given by

\[
v_o = g_m v_{gs} R'_L \quad (5.45)
\]

Furthermore, we can write the following voltage equation:

\[
v_{in} = v_{gs} + v_o \quad (5.46)
\]

Using Equation (5.45) to substitute for \( v_o \) in Equation (5.46), we have

\[
v_{in} = v_{gs} + \frac{g_m v_{gs} R'_L}{1 + g_m R'_L} \quad (5.47)
\]

Dividing the respective sides of Equations (5.45) and (5.47), we obtain the following expression for the voltage gain:

\[
A_v = \frac{v_o}{v_{in}} = \frac{g_m R'_L}{1 + g_m R'_L} \quad (5.48)
\]

Notice that the voltage gain given in Equation (5.48) is positive and less than unity. Thus, the source follower is a noninverting amplifier with voltage gain slightly less than unity. So we get voltage gain \( \leq 1 \). What's the use? Answer next page.

**Input Resistance**

The input resistance is the resistance seen looking into the input terminals of the equivalent circuit. Hence, we have

\[
R_{in} = \frac{v_{in}}{i_{in}} = R_G \quad (5.49)
\]
Answer: This configuration is not used for amplification, it is used because 1) it's output resistance is very small and can be chosen to be very high (in MΩ range) by choosing R₁ and R₂ (i.e., R₂) very large.

\[ \begin{align*}
G\downarrow & \quad G\downarrow \\
\text{D} & \quad \text{D}
\end{align*} \]

**Figure 5.35** Equivalent circuit used to find the output resistance of the source follower.

### Output Resistance

To find the output resistance, we remove the load resistance, replace the signal source with its internal resistance, and look back into the output terminals. It is helpful to attach a test source \( v_x \) to the output terminals as illustrated in Figure 5.35. Then the output resistance is

\[ R_o = \frac{v_x}{i_x} \text{ output resistance} \]

where \( i_x \) is the current supplied by the test source as shown in the figure. The output resistance is given by

\[ R_o = \frac{1}{g_m + 1/R_S + 1/r_d} \]

This resistance can be quite low, and another reason for using a source follower is to obtain low output resistance.

### Example 5.8 Gain and Impedance Calculations for a Source Follower

Consider the source follower illustrated in Figure 5.33, given that \( R_L = 1 \text{kΩ} \) and \( R_1 = R_2 = 2 \text{MΩ} \). The NMOS transistor has \( K_P = 50 \mu\text{A/V}^2 \), \( \lambda = 0 \), \( L = 2 \mu\text{m} \), \( W = 160 \mu\text{m} \), and \( V_{th} = 1 \text{V} \). Find the value required for \( R_S \) to achieve \( I_{DF} = 10 \text{mA} \). Then compute the voltage gain, input resistance, and output resistance.

**SOLUTION** From Equations (5.3) and (5.5), we have

\[ K = \left( \frac{W}{L} \right) \frac{K_P}{2} = 2 \text{mA/V}^2 \]

\[ I_{DF} = K(V_{GSO} - V_{th})^2 \]

Solving the latter equation for \( V_{GSO} \) and substituting values, we obtain

\[ V_{GSO} = \sqrt{I_{DF}/K + V_{th}} = 3.236 \text{V} \]

This small output resistance is typical and large input resistance makes the circuit useful.

\[ R_S \approx 1000 \text{kΩ} \]

\[ R_L \approx 1 \text{MΩ} \]

\[ g_m \approx 10 \text{mS} \]

\[ r_d \approx 1 \text{kΩ} \]

\[ R_o = \frac{1}{g_m + 1/R_S + 1/r_d} \approx 10 \text{kΩ} \]
The dc voltage at the gate terminal is given by

\[ V_G = V_{DD} \times \frac{R_2}{R_1 + R_2} = 7.5 \text{ V} \]

The dc voltage at the source terminal of the NMOS is

\[ V_S = V_G - V_{GSQ} = 4.264 \text{ V} \]

Finally, we find the source resistance:

\[ R_S = \frac{V_S}{I_{DQ}} = 426.4 \text{ } \Omega \]

(Of course, in a discrete circuit, we would choose a standard nominal value for \( R_S \). However, we will continue this example using the exact value computed for \( R_S \).)

Next, we use Equation (5.30) to find the transconductance of the device:

\[ g_m = \sqrt{2}K\sqrt{W/L}\sqrt{I_{DQ}} = 8.944 \text{ mA} \]

Because we have \( \lambda = 0 \), the drain characteristics are horizontal in the saturation region, and \( r_d = \infty \).

Next, we substitute values into Equation (5.44):

\[ R'_L = \frac{1}{1/r_d + 1/R_S + 1/R_L} = 298.9 \text{ } \Omega \]

Then the voltage gain is given by Equation (5.48):

\[ A_v = \frac{V_o}{V_{in}} = \frac{g_m R'_L}{1 + g_m R'_L} = 0.7272 \]

The input resistance is

\[ R_{in} = R_1 || R_2 = 1 \text{ M} \Omega \]

The output resistance is given by Equation (5.51):

\[ R_o = \frac{1}{g_m + 1/R_S + 1/r_d} = 88.58 \text{ } \Omega \]

This is a fairly low output resistance compared with that of other single-FET amplifier configurations.

The current gain can be found by the use of Equation (1.4):

\[ A_i = A_v \frac{R_{in}}{R_L} = 727.2 \]

The power gain is given by

\[ G = A_v A_i = 528.8 \]

Even though the voltage gain is less than unity, the output power is much greater than the input power because of the high input resistance.

In summary, a source follower configuration is very useful as it provides a module with high input resistance, low output resistance, AND high current gain.
In the preceding section and in this one, we have considered two of the most important single-stage FET amplifiers: the common-source amplifier and the source follower. Later in the book, we discuss other amplifier configurations that use FETs, multistage amplifiers, and amplifiers that use both FETs and BJTs.

**EXERCISE**

5.11 Derive Equation (5.51). [See page 322]

**EXERCISE**

5.12 Derive expressions for the voltage gain, input resistance, and output resistance of the common-gate amplifier illustrated in Figure 5.36.

**Answer** The small-signal equivalent circuit is shown in Figure 5.37. $A_V = g_m R_L$ in which $R_L = R_D || R_L$; $R_{in} = 1/(g_m + 1/R_S)$; $R_o = R_D$. 

[Figure 5.36: Common-gate amplifier.]

[Figure 5.37: See Exercise 5.12.]