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Experiment #8
## MOSFET filtering

Introduction:
Now that the MOSFET has been explored in static and dynamic operation, the MOSFET, combined with what has been already presented, may be used as a filter. This lab will explore utilizing the canonic cells combined with capacitors to realize very simple low-pass, band-pass, or high-pass filters.

Theory:
The canonic cell learned in previous labs can be easily modified to create simple filters.

Low-pass filter:
A low-pass filter is realized by tying the output of the canonic cell to AC ground via a capacitor. The time constant resulting can be easily calculated by finding the output resistance of the canonic cell and the load resistance. In figure 11.1 a low-pass filter using a common-source is shown, it is assumed that the transistor is biased in the saturation region of operation, so biasing is neglected. You should use a MOSFET instead of the BJT in the schematic diagram.
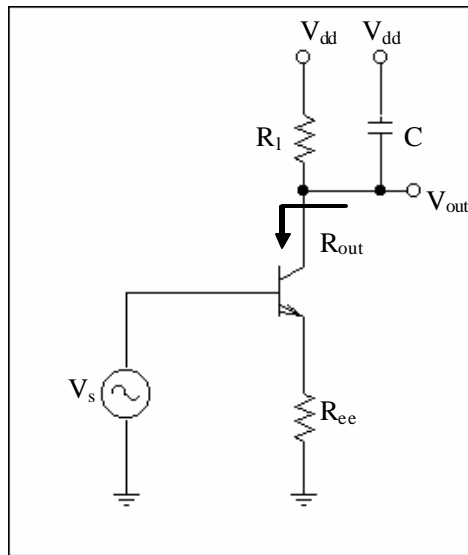
Figure 11.1 A simple low-pass filter.

Assuming any parasitics from the MOSFET are insignificant for the frequency range of interest, the time constant and, in this case, the 3-dB bandwidth if frequency is approximately equal to

$$f = \frac{1}{2\boldsymbol{p}(R_{out} \parallel R_l)C}$$ (11.1)

So this filter will have a first order roll-off caused by the capacitor tied to the output. The circuit in figure 11.1 can by inspection be determined a low-pass filter. As the frequency of the signal is increased the capacitor acts more and more like a short circuit to AC ground. Hence the output at high frequencies will go to zero volts. The transfer function of the low-pass filter featured in figure 11.1 can be found using Laplace transform and techniques learned in experiment #6 and is given below.

$$A_v = \frac{-gm(R_{out} \| R_l)}{[1 + sC(R_l \| R_{out})](1 + gmRss)} \quad (11.2)$$

Notice how the transfer function is almost identical to the transfer function of a normal common-emitter canonic cell that was give in experiment #5, except for the pole that was added by introducing the capacitor to the topology. This left-half plane pole is what gives the circuit its low-pass response.

High-pass filter:

A high-pass filter can be achieved by simply putting a capacitor in series with the signal. You have already built and worked with high pass filters and may have not realized it. Coupling capacitors are nothing more than high-pass filters that are used to block DC or very low frequency signals. An example of a high-pass filter is shown in figure 11.2 assuming the BJT schematic is a MOSFET, once again biasing has been neglected.
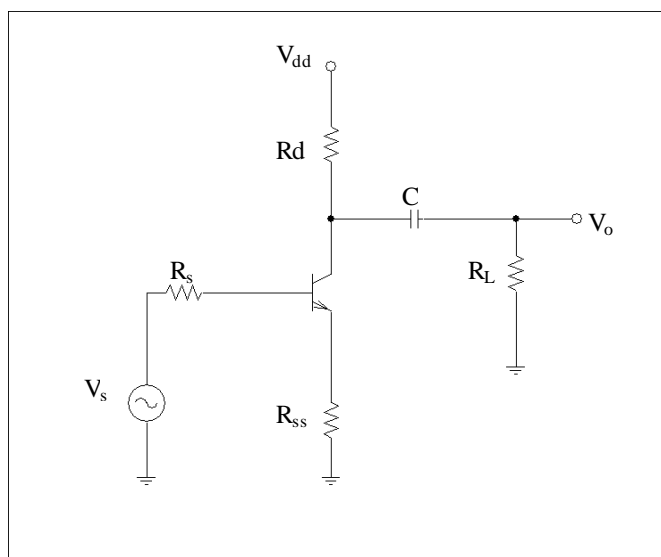
**Figure 11.2** A simple high-pass filter.

An analysis on figure 11.2 yields the following transfer function:

$$A_V = \frac{-gm(r_o \| R_D)sCR_L}{(1 + sC(r_o \| R_D + R_L))(1 + gmR_{ss})} \quad (11.3)$$

Notice that the transfer function is the about the same as a normal common-source amplifier, except this time a left-half plane pole and an s term in the numerator. This is what gives the high pass filter it unique feature. By inspection you can determine that equation 11.3 is a transfer function of a high-pass filter. If you take the limit as s goes to infinity, you can see the transfer function reduces the gain magnitude to the parallel combination of R_{out} and R_L times the original Gm of the circuit. Taking what was learned from experiment #6, this is exactly what you would expect from this topology if the capacitor was shorted. One quick note, there is no way to realize a true high-pass filter. The transistor parasitics will dominate at really high frequencies and the transfer function magnitude will diminish.

Band-pass:

The band-pass presented here is nothing more than a combination of the low and high pass filters presented above. It can be seen in figure 11.3.
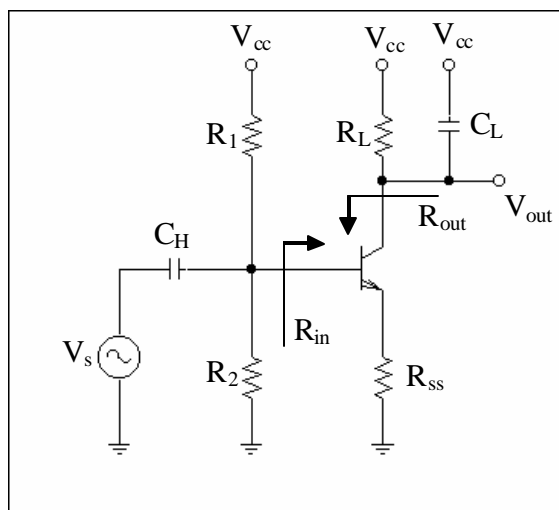
Figure 11.3 A simple band-pass filter

This band-pass uses a single pole roll-up and roll-off response for frequency rejection, thus the Q of this topology is very limited. The analysis of figure 11.3 is left as a prelab exercise.

Conclusion:

The filters presented in this experiment are very elementary and not useful for most applications. The utility is limited by the inherently low Q that is associated when using filter with a single order response. Every filter presented only produces a 20dB/dec transitions from the pass band to the stop-band. The Sallen and Key filters presented in experiment #3 perform much better due to the higher order responses. The mini project found in the prelab also introduces the problems associated with biasing. Thus far in the examples presented for MOSFET dynamic operation, the transistor was assumed to biased in its saturation region. However, biasing does affect the ac response due to the elements needed to establish the correct Q-point. One will find when designing circuits that these elements can have an effect on gain and the time constants of the circuits. Thus careful design and analysis is needed to correctly model the true behavior of a topology.

Reference reading

1) John Choma, Jr. *EE348 lecture notes*. University of Southern California. Spring 2001.

2) David Johns & Ken Martin. *Analog integrated Circuit Design*. John Wiley & Sons, Inc., New York, 1997.

3) Paul R. Gray & Robert G. Meyer. *Analysis and Design of Analog Integrated Circuits*. John Wiley & Sons, Inc., New York, 1993.

Pre-lab

1)   Design a low-pass filter that has a 3-dB bandwidth of 50kHz. The MOSFET should be biased into saturation and supply a gain of 1. Discrete resistors can only be used for biasing. Remember you can use different configurations of transistors to realize resistance. Use $R_{ss}=0$ and V_{dd}=5V. Verify your design in Spice.

2)   Determine the 3dB point and transfer function for the high-pass filter pictured in figure 11.2.

3)   Using a 5V supply, design a high-pass filter whose time constant is located at 15KHz. The MOSFET should be biased into saturation and supply a gain of 1. Once again, resistors may only be used for biasing. Verify your design in Spice.

4)   In previous labs, the common-source canonic cell was used as an amplifier. It was shown in this experiment that a common-source could be used as a filter. You will now use what you have learned to design a filter with gain.   For this exercise, you will first need to filter the signal, and then apply a gain to it. A system diagram is shown below.

Input signal | Filter | Amplifier | Output signal | Load
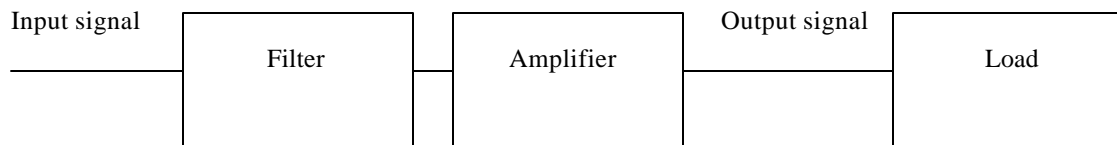
With what you have learned so far, would it be adequate to just replace the boxes with the appropriate canonic cells?

5a)   Design the following system using the appropriate MOS canonic cells to explore, identify, and address any design concerns or issues that maybe present.

5b)   Modify the above system diagram and present a new system diagram to account for and overcome any design concerns that you discovered.

5c)   Redesign the system diagram, build the necessary circuitry to implement this system and verify your suspicions in Spice.

Example of one design issue: Might it be possible to merge the Filter and Amplifier into the same cell circuit? Why not?

Design Specs:

Low pass filter: Bandwidth of 50kHz with unity gain. (A = 1)

Amplifier: Gain of 20
                 Drain current cannot exceed 1mA

Load: 1 kiloOhm

Supply: ± 5V

Signals: Input and output signals are both sinusoidal voltages
                 Input signal needs a magnitude of 10mV (You will actually build this, so you may need
                 to design a resistor divider to attenuate the output of the function generator if the actual
                 generator that you will use in lab has a min magnitude that is higher than 10mV)

Spice models: Use spice and the MOSFET models that were given in previous labs.

Lab Exercise

1) Build the low-pass filter that you designed in question #1 of the prelab. Verify it has correct dc biasing and is in the saturation region of operation. Do a detailed frequency sweep and plot its ac response. Does your data match with 10% to what you simulated in Spice? If not, explain why? Make sure, if you are following figure 11.1, that you give a dc offset voltage to the frequency generator that you use, or use a resistor divider and a coupling capacitor, so the transistor is properly biased in linear operation.

2) Repeat the procedure in the last question for the high-pass filter you designed for question #3 of the prelab. Once again make sure the transistor is biased properly.

3) Build and test the circuit you designed in part 5 of the pre-lab. Are your results with in ±15% of the design specs? If not use the remaining mount of lab time to tweak your design. Try to get your results to as close to a ±15% as possible. Report any difficulties that you come across as well as any solutions you came up with.