

# Transmit filter designs for ADSL modems

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## 1. Objectives

- Design a filter from a given topology and cutoff frequency specifications.
- Analyze the characteristics of the designed filter.
- Use SPICE to verify circuit designs before building the circuit.
- Experimentally verify the characteristics of the designed filter.
- Compare analytical, SPICE, and experimental filter response.

## 2. Reference

The opamp characteristics and circuits are covered in the textbook. Make sure you know how to analyze circuits using the simple ideal opamp model.

Review the materials on Bode plots which include gain (in dB) and phase shift vs. log frequency.

**Review the procedure to compute the transfer function and corner frequencies (3dB points) of a circuit.**

Review the usage of the dual power supply that can set two tracked supply values (e.g. +10V and –10V). The convention is to use  $V_{CC}$  to denote the positive supply and  $V_{EE}$  to denote the negative supply.

The only knowledge required for this experiment is: time-domain analysis, basic opamp circuit analysis, impedance of components, frequency-domain analysis, plotting gain (dB) and phase as function of frequency, and transfer function. No general knowledge of filters is required.

Also see:

Analysis of the Sallen-Key Filter Topology. TI Application Report.

<<http://focus.ti.com/lit/an/sloa024b/sloa024b.pdf>>

### 3. Circuits

You will design, analyze, simulate, and test the circuit in Figure 1.

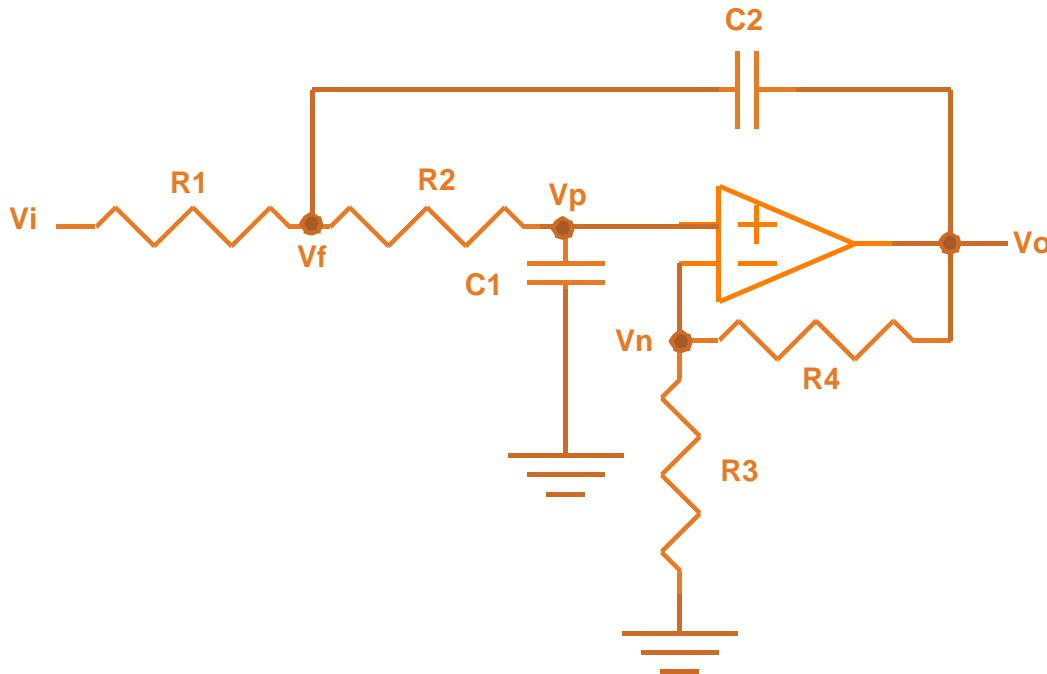


Figure 1. Low Pass Sallen-Key filter.

### 4. Components and specifications

The components to be used are resistors, capacitors, and operational amplifiers. Resistors and capacitors come in pre-determined sizes, so their values cannot be arbitrarily selected. **When you select a component value, make sure that the component of this specific value is available from the stockroom.**

Opamp specifications are available from the laboratory web site of this course or manufacturers' web sites. Check your component and download the appropriate specifications.

### 5. Discussion

Asymmetric-digital-subscriber-line (ADSL) modems are commonly used for internet connections with speed up to 100 times faster than 56K modems on existing phone lines. They also permit simultaneous phone and modem usage. The transmit filter at the front end of the ADSL modem is a very important circuit performing the following functions:

1. The transmit filter pre-processes the signal to limit its bandwidth (frequency range). The filter output drives the digital-to-analog converter interfacing with the telephone line.
2. The transmit filter usually is a bandpass filter to eliminate low-frequency noise and to reduce interference in the receive band.

The starting point of all transmit filters in ADSL modems is the basic Sallen-Key filter depicted in Figure 1. It has a minimum number of components and is simple to design. The standard

specifications are a passband from 1.7 KHz to 119 KHz, with a very steep slope at higher frequencies to reduce interference.

To simplify the design for this laboratory, we will design a low-pass filter instead of a bandpass filter. Several design procedures exist to select the component values to realize a given specification. We will choose the simplest of these design procedures in this experiment.

## 6. Pre-lab

### 6.1 Recording specified opamp parameters for analysis and design

Go over the specifications of the opamp to be used and write down the typical values of the opamp parameters. Include the frequency dependence of the open loop gain, slew rate, input and output impedance, etc.

### 6.2 Basic Sallen-Key filter specifications

The filter will be designed to be a low-pass filter, with a 3-dB frequency of 1 KHz and low-frequency gain of 2. Be sure you understand what is meant by the 3-dB frequency. At the 3-dB frequency, also called the cutoff frequency,  $\omega_c$ , the magnitude of the gain (in dB) is 3dB below the maximum gain (in dB)

$$|H(j\omega_c)|_{dB} = |H_{max,dB}| - 3dB$$

### 6.3 Design procedure

For the circuit in Figure 1 with power supplies  $V_{CC} = 12\text{ V}$ ,  $V_{EE} = -12\text{ V}$ , and assuming an ideal opamp, answer the following questions:

1. Derive the transfer function  $H(s)$  of the filter. Hint: write KCL at the nodes  $V_f$ ,  $V_p$ , and  $V_n$ .
2. From the equation in item 1 above, select the values of  $R_3$  and  $R_4$  so that the low-frequency gain of the circuit is 2.(from the gain specification in section 6.2).
3. To simplify the design procedure, assume  $R_1=R_2=R$  and  $C_1=C_2=C$ . Simplify the equation in item 1 above.
4. From the simplified equation in item 3, what is the expression for the 3-dB frequency in terms of  $R$  and  $C$ ? Since the 3-dB frequency is specified in section 6.2 to be 1 KHz, select the component values for  $R$  and  $C$ . Hint: since the available capacitor values are more restricted than the available resistor values, pick the capacitor value first then pick the resistor value to satisfy the frequency specification.

At this point, the design is completed since you have selected values for all the components of the circuit in Figure 1. Be sure to remember that the tolerance of a typical resistor and capacitor are 5% and 50% respectively.

5. Plot the gain (dB) and phase shift of the circuit as function of frequency from 10 Hz to 50 KHz. From this plot, does your design have the correct values for the low-frequency gain and the 3-dB frequency as specified? If it does not, it is not a good design and will need to be re-designed. Mark the cutoff frequency, passband, and stopband in the plot.

6. Simulate the design with SPICE, still assuming an ideal opamp, to make sure the circuit works as designed. Use SPICE AC analysis to plot gain (dB) and phase shift as function of frequency from 10 Hz to 50 KHz. From this plot, does your design have the correct values for the low-frequency gain and the 3-dB frequency as specified? If it does not, it is not a good design and will need to be re-designed. Overlay this data onto your plot in 6.3.5. Clearly mark the 3dB frequency, passband, and stopband on your plots.

## **7. Experimental procedures**

### **7.1 Instruments needed for this experiment**

The instruments needed for this experiment are: a power supply, a function generator, a multimeter, and an oscilloscope.

Review the characteristics of ideal and non-ideal opamps and the proper handling of integrated circuit packages. In this lab, do not apply signals that exceed the slew rate limitation of the opamp.

### **7.2 Basic Sallen-Key filter**

1. Build the circuit in Figure 1 using power supplies  $\pm 12$  V and the component values from your design in the Pre-lab. Be sure to measure the exact component values, especially capacitance.
2. Use a sine wave input with small amplitude so that the output is not affected by the slew rate in this part. From the starting input frequency of 10 Hz and varying it using 1-2-5 sequence up to 50 KHz (i.e. set input frequency to 10 Hz, 20 Hz, 50 Hz, 100 Hz, 200 Hz, ... up to 50 KHz). Display the input and output waveforms (2 complete cycles) on the scope. For each frequency setting above, measure the gain and estimate the phase shift of the circuit.
3. Near the specified 3-dB frequency take extra gain and phase shift measurements so that the 3-dB frequency can be estimated within 50Hz
4. Use a table to store the frequency, gain, and phase shift data from the measurements in items 2 and 3 above. You will eventually overlay the experimental and analytical transfer response.
5. Get a hardcopy output from the scope display with both waveforms for each of these 3 frequencies: 100 Hz, 1 KHz, and 10 KHz. Turn these 3 hardcopies in as part of your lab report.

## **8. Data analysis**

### **8.1 Basic Sallen-Key filter**

1. From the table of data in item 4 section 7.2, plot the gain (dB) and phase shift of this circuit versus frequency. Be sure to use and label Hz, dB, and degrees as the units.
2. Overlay the gain and frequency shift plots in item 1 above with the calculated gain and phase shift plots from the pre-lab (item 5 section 6.3) and as simulated by SPICE (item 6 section 6.3). Explain any differences between these plots.
3. Is the measured value of the 3-dB frequency the same as the frequency specification in section 6.2? Explain any difference.

4. Is the measured value of the low-frequency gain the same as the gain specification in section 6.2? Explain any difference.

## 9. Further research

1. Select the resistors R3 and R4 so that the low-frequency gain of the circuit in the lab is much larger than 2. Build the circuit and see what it does (it does a very interesting thing!).
2. Look up the design of the same Sallen-Key filter in any opamp cookbook but use the bandpass case. Pick the component values and build the bandpass circuit used in ADSL modems. Push the performance limits (slew rate, frequency, different input signal types, etc.) and see what the circuit does when the opamp no longer operates in the ideal region. Measure the waveforms in the lab and correlate with the opamp characteristics.

## 10. Self-test

1. Apply a large signal to any of the circuit in this lab and see when the slew rate limitation begins to show up. At what amplitude if the frequency is low? At what frequency if the output amplitude is kept fixed (say at  $\pm 5$  V)?
2. Use the digital multi-meter in the RMS measurement mode and see if you can measure the gain of an amplifier as function of frequency. Set the input frequency and measure the output RMS value at that frequency. From this RMS output value, calculate the gain, then from the data points (frequency, gain) as the frequency varies, reproduce the gain plot. How is this plot compared to the plots obtained from hand calculation, SPICE simulation, and scope data?