Signal Amplifier

The signal amplifier to be constructed in this assigment must conform to the following parameters:

Input Impedance = 15kHz
Max Amplification = 44dB
Lower Cutoff Freq. = 60Hz
Lower Cutoff Freq. = 50kHz

In order to achieve the bandpass character specified, the amplifier will consist roughly of the following stages:

Input → High-Pass filter → Cascaded amplifier stages → Low-Pass filter → Output

Amplifier Stage

The easiest place to begin is the with the cascaded amplifier stages. Immediately, however, we run into the issue that a single amplifier stage is bandwidth limited by the internal frequency compensation of the TL072, as seen in figure 1.

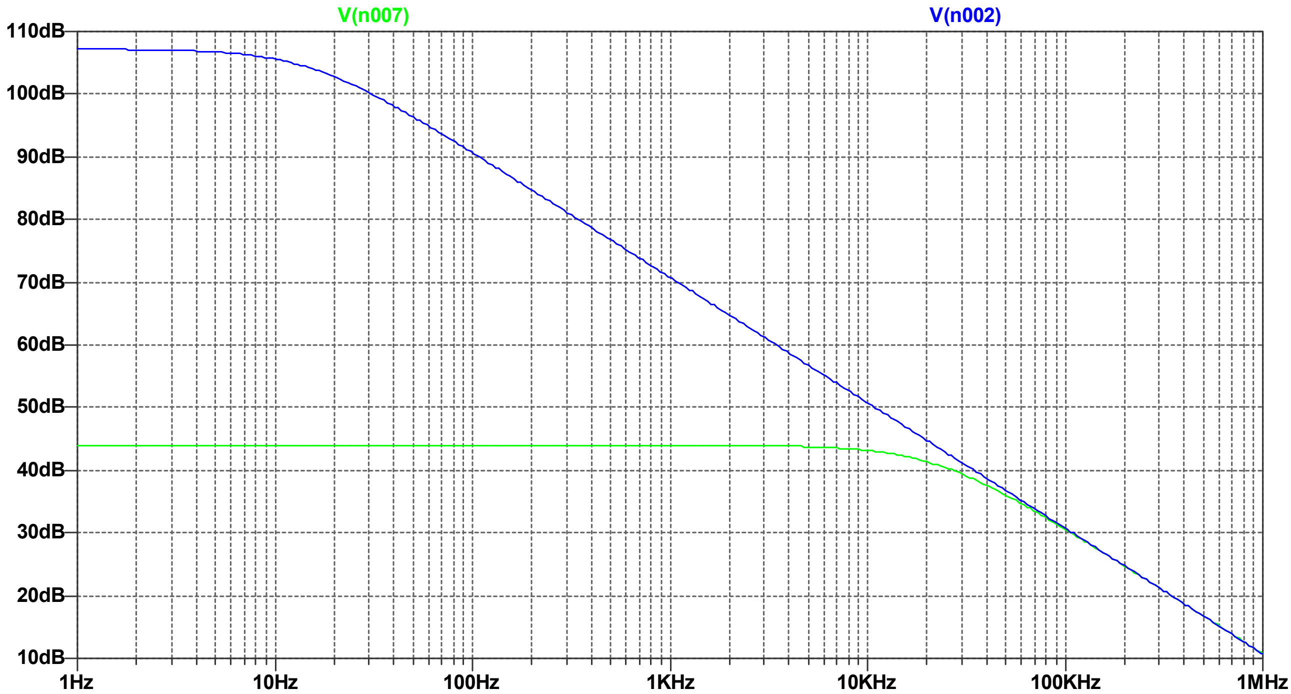

Figure 1: *'Raw' or open-loop amplification in blue, giving the characteristic 'gain-bandwidth' product. Closed-loop amplification in green. The bandwidth of the closed loop amplifier is clearly limited by the open-loop bandwidth at a given gain.*

In order to construct an amplifier with the required bandwidth at the specified gain (that is, 50kHz at 44dB), a single amplifier with the required bandwidth can first be designed and then multiple 'copies' can be cascaded to increase the gain without significantly diminishing the bandwidth.

Using the Gain-Bandwidth Product (GBWP)

$$A_u \cdot \mathrm{B} = 3\mathrm{MHz} \tag{1}$$

we can calculate the approximate bandwidth of a single amplifier stage at 44dB (or x158,5) i.e.

$$\frac{3\mathrm{MHz}}{158,5} \approx 19\mathrm{kHz} \tag{2}$$

This is clearly too low and therefore multiple stages will be needed. After a few iterations it can be determined that three stages with a gain of $\frac{44\text{dB}}{3} = 14,67\text{dB} = 5,41$ each gives a bandwidth of approximately $\frac{3\text{MHz}}{5,41} \approx 555\text{kHz}$ which is enough to give a completely flat frequency response across he bandwidth we are interested in.

To implement the amplifier we use three cascaded non-inverting amplifier circuits. These will also function as a buffer between the two filter stages. As the three stages are identical we need only calculate for one of them using the the formula

$$A_u = 1 + \frac{R_2}{R_1} \tag{3}$$

If we arbitrarily choose $R_1 = 10\text{k}\Omega$ then

$$R_2 = (5,41 - 1) \cdot 10\text{k}\Omega = 44,1\text{k}\Omega \tag{4}$$

The final amplifier stage is presented in the complete circuit diagram in figure 3.

Low-Pass Filter Stage

In order to ensure a reliable and flat frequency response in the pass band of the filter a 2nd order butterworth configuration is used with the Sallen-Key architecture.

A generic LP 2nd order Butterworth filter is given by the following transfer function:

$$H_{LP}(s) = \frac{1}{1 + s\frac{1,414}{\omega_0} + \frac{s^2}{\omega_0^2}} \tag{5}$$

where ω_0 is the cutoff frequency. The equivalent transfer function of a LP Sallen-Key filter is

$$H_{LP}(s) = \frac{1}{1 + s(R_1 + R_2)C_2 + s^2 R_1 R_2 C_1 C_2} \tag{6}$$

If we begin by arbitrarily choosing $C_2 = 1\text{nF}$ and $R_1 = R_2$ then

$$R_1 = R_2 = \frac{1,414}{1\text{nF} \cdot 2\pi 50\text{kHz}} = 2250\Omega \tag{7}$$

Using these three values we can work out C_1 using the coefficient of s^2 in the above equations:

$$C_1 = \frac{1}{(2\pi 50\text{kHz})^2 \cdot 1\text{nF} \cdot 2250^2\Omega} = 2\text{nF} \tag{8}$$

High-Pass Filter Stage

A Sallen-Key high pass filter is mathematically very similar to its low-pass counterpart, the variables are simply exchanged i.e. $R_1 \leftrightarrow C_1$, $R_2 \leftrightarrow C_2$ and an extra s^2 term is added in the numerator.

The generic transfer function for a high-pass 2nd order butterworth is

$$H_{HP}(s) = \frac{\frac{s^2}{\omega_0^2}}{1 + s\frac{1,414}{\omega_0} + \frac{s^2}{\omega_0^2}} \tag{9}$$

where ω_0 is the cutoff frequency. The transfer function of a high-pass Sallen-Key filter of this order is

$$H_{HP}(s) = \frac{s^2 R_1 R_2 C_1 C_2}{1 + s(C_1 + C_2)R_2 + s^2 R_1 R_2 C_1 C_2} \tag{10}$$

Using the exact same method to determine component values as with the low-pass stage we get the required behaviour (i.e. $f_0 = 60\text{Hz}$) using $R_1 = 1991\Omega$, $R_2 = 1\text{k}\Omega$ and $C_1 = C_2 = 7,04\mu\text{F}$.

Final Construction

In order to give the amplifier an input impedance of 15 kΩ the easiest solution is to use a resistor to ground in conjunction with a voltage follower. This is obviously not the most economical solution, requiring an extra op amp circuit, but it reduces the design complexity while allowing independent design of the following high-pass filter stage (and it may also be argued that it is advantageous to use an even number of op-amps as most packages contain multiples of two).

The complete design can be seen in the circuit diagram in figure 3. The frequency response of the the signal amplifier is shown below in figure 2 where it is clear that the amplifier meets the gain and bandwidth specifications to within a small margin of error.

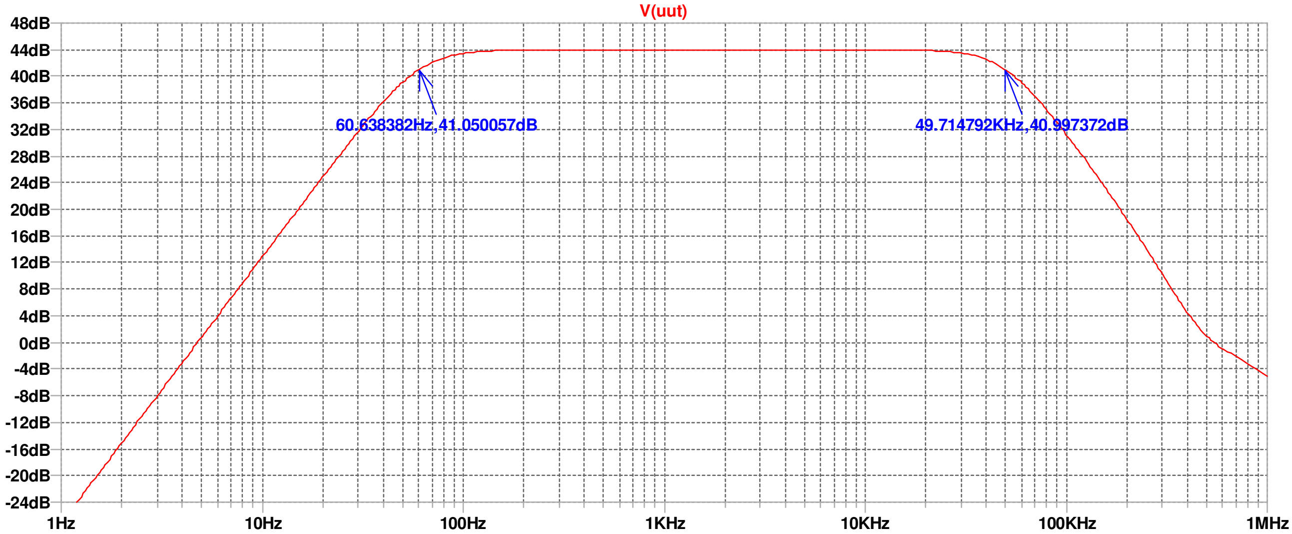

Figure 2: *The frequency response of the amplifier. The cutoff frequencies are marked in blue.*

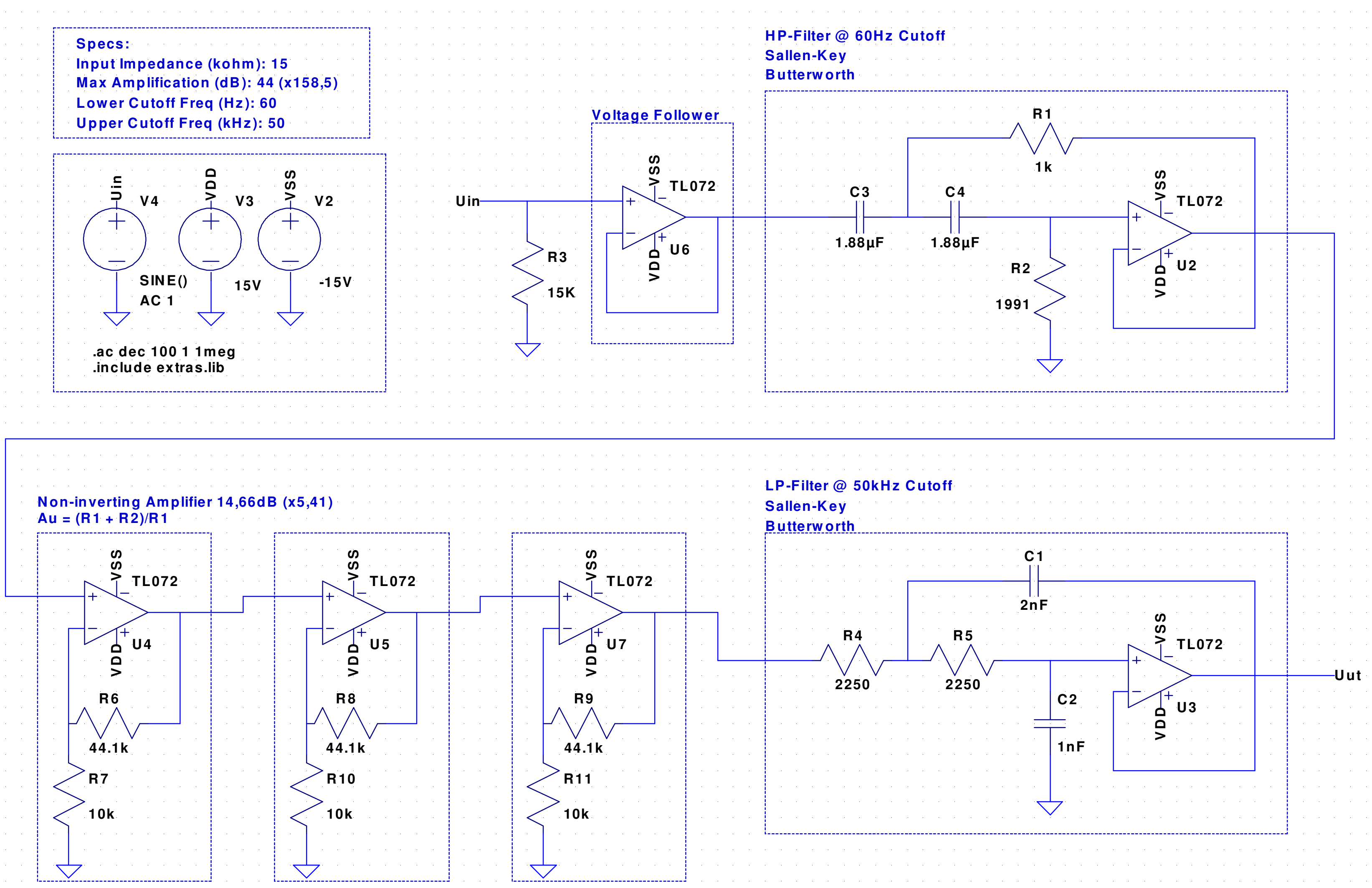

Figure 3: *Circuit Diagram in SPICE*