Optical Uplink

Multiple Feedback Bandpass Filter Module

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Abstract

The design, simulation, and construction of a multiple feedback bandpass filter are described. An LF347 wide bandwidth quad JFET input operational amplifier integrated circuit, MFBP filter, with rail voltages of ±12V, was used to amplify the output signal from a transimpedance amplifier. This is used as a module for an optical uplink circuit. The filter is required to have a center frequency of 20kHz, a 3dB bandwidth between 1.5kHz and 5kHz, a gain of greater than 60dB, and rail supplies of ±12V. A sinusoidal waveform with an amplitude of 100mV and frequency of 20kHz was used for the input to the MFBP filter. The output voltage operated with a gain of 71.4dB, with a bandwidth at 3dB of 2.11kHz and a center frequency of 20.2kHz.

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Images/barcode.png

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1 Introduction

This report describes the design, implementation and test of an active multifeedback bandpass (MFBP) filter. The MFBP filter consists of a wide bandwidth quad JFET input operational amplifier integrated circuit with negative and positive rail voltages, and a voltage divider at the input. The MFBP filter takes a small input and converts it to a greater output voltage. This circuit uses a sinusoidal input waveform generated by the Digilent Analog Discovery 2 (DAD2) which is fed into the voltage divider at the input of the circuit. A unity gain buffer is located at the output of the MFBP filter to lower the impedance generated by the operational amplifier IC. Figure 1 below demonstrates where in the optical link relay design the MFBP filter falls.

Introduction/Block_Diagram_MFBP.png

Figure 1: Block diagram for optical uplink[1]

The output from the previous module, the photodetector TZA seen in 1, will be in the μV range, which is too small for the purposes of the optical link project. The noise output from the TZA also needs to be filtered by using an active bandpass filter, similar to the one in Figure 2.

Introduction/MFBF_generic.png

Figure 2: General schematic of the MFBP[1]

Figure 2 is the generic schematic for a multiple feedback bandpass filter. By passing the signal through this active bandpass filter, the noise is reduced and the signal will be amplified.

Section 2 of this report describes the design of the MFBP filter. Simulations are discussed in section 3 and experimental results are in section 4. A discussion of the results, sources of error, and areas of possible improvement are outlined in section 5. Section 6 concludes this report.

2 Circuit Development

This section covers the design choices associated with the MFBP filter module. The LF347 quad operational amplifier was provided for this lab with the intention of providing options regarding the amount of of cascading operational amplifiers that would be used to reach the desired specifications. Figure 3 is the schematic design of the MFBP filter for this lab.

`CircuitDevelopment/MFBPbasic.png`

Figure 3: Basic schematic for three stage MFBP filter with unity gain buffer

In Figure 3, a three stage MFBP filter is shown. Each successful stage has will have a gain that is approximately 100 times smaller than the gain specification for this lab of 1000 $\frac{V}{V}$. By doing this, we will not need a single MFBP filter with high gain and a high quality factor. After each stage, the gain is increased and the 3dB bandwidth decreases.

The choice of using three stages for the MFBP filter is due to the lab requirement that the bandwidth between 1.5 kHz and 5 kHz. The gain and quality factor can not be set independently[2] By using three cascading LF347 operational amplifiers, the bandwidth can be kept narrow by setting the gain of an individual op amp to be relatively small. Instead of attempting to have the full gain with a single stage, which would result in a wide bandwidth, the op amps are cascaded together. This relation can be seen with Equation 1[2],

$$Q = \frac{f_c}{\Delta f} \tag{1}$$

where f_c is the center frequency and Δf is the bandwidth. This method allows sufficient gain while still maintaining a narrow bandwidth.

There are considerations that need to be taken in regarding the range of values that are usable for the capacitors. For the purposes and design of this three stage MFBP filter, the capacitor values need to be less than 1nF because the effect on the value of the resistors would be minimal and unrealistic to use in this circuit. The other reasoning is the capacitors need to be large enough to filter the noise, as this is an active bandpass filter.

There are two approached to consider for choosing component values with regard to the capacitors and resistors. The first approach is to initially choose realistic capacitor values, each being equivalent to each other. The second approach is to choose a value for the resistor value for R_1, then derive the remaining components.

In choosing the values for each of these components, the output specifications of the active filter must be used. These can be seen in Table 1.

Table 1: MFBP filter specifications

Filter Topology	MFBP Filter Specification Requirements
Center Frequency (f_c)	20 kHz
$3dB$ Bandwidth	Between 1.5 kHz and 5 kHz
Gain	Greater than 1000 $\frac{V}{V}$
Rail Supplies	± 12 V

Table 1 summarizes the specifications of the lab. The approach chosen for the purpose of this lab is the first, to choose capacitor values to derive the values of the resistors needed to match specifications. The values of C_1 and C_2 were chosen to be 470pF as they are in the middle of the desired range of values and readily available. Larger capacitor values result in smaller resistor values. In order to minimize the loading effects on the stages of the MFBP, the input resistance should be kept greater than 1kΩ.

In order to determine the values, the transfer function is needed to derive the equations needed for each component base on the chosen capacitor, quality, gain and center frequency values. The transfer function for the MFBP filter is shown in Equation 2

$$H(s) = \frac{\frac{-1}{R_1 R_2 C_1 C_2}}{s^2 + s\frac{1}{C_1}(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}) + \frac{1}{R_2 R_3 C_1 C_2}} \tag{2}$$

The values of the capacitors were chosen to be 470pF. The quality factor needs to have a realistic value as well. The higher the Q, the narrower the bandwidth. The desired bandwidth range at 3_{dB} is between 1.5kHz and 5kHz. The quality factor will initially be chosen at 5. the value of the quality factor, Q, reflects the ratio of the center-frequency to the 3dB bandwidth.

The center frequency, f_o has already been determined to be 20 kHz. Based on the required specifications of the active filter, a gain of more than $1000\frac{V}{V}$ is needed, so G must be more than 10. Real world factors will affect the circuit so the the gain was set to 12 to account for losses during experimentation. The capacitor values C_1 and C_2 were chosen to be 470pF. Equation 3 will be used to calculate the needed values for the first resistor, R_1.

$$R_1 = \frac{Q}{G * 2\pi f_o C_1} \tag{3}$$

Equation 3 demonstrates the solution for R_1. R_2 can be found by Equation 4,

$$R_2 = \frac{Q}{(2 * Q^2 - G)2\pi f_o C_1} \tag{4}$$

where, notably, the Q factor begins to dominate the denominator in Equation 4. R_3 can be found by Equation 5.

$$R_3 = \frac{Q}{\pi f_o C} \tag{5}$$

Equation 5, is no longer dependent on gain or Q in the denominator. Based on the relationships between the components of this active filter, the center frequency, in Equation 6, can be found.

$$f_o = \frac{1}{2\pi C}\sqrt{\frac{R_1 + R_2}{R_1 R_2 R_3}} \tag{6}$$

The role resistors play in changing center frequency can be seen with Equation 6. The gain can be found similarly in Equation 7.

$$G = \frac{1}{2\frac{R_1}{R_3}} \tag{7}$$

The gain, from Equation 7, can be seen to depend only on R_1 and R_3. All values that were calculated based on the specifications can be seen in Table 2.

Table 2: Calculated

Component	Value
R_1	7kΩ
R_2	2.2kΩ
R_3	170kΩ
$C_1 = C_2$	470pF
V_{CC}	12V
V_{EE}	-12V

Table 2 demonstrates that the calculated values fall within the lab specifications. Based on these calculations, simulations will be conducted in Section 3.

3 Simulations

This section describes the simulation of the MFBP using NGSpice integrated with Matlab.The frequency response, including center frequency, bandwidth, and gain were simulated.

The final circuit that was simulated is shown in Figure 4.

`Simulations/Lab_2_simulated.png`

Figure 4: Simulated circuit of MFBP

Figure 4 uses the same design structure as Figure 2 seen in Section 2. All of the simulated circuit values are summarized in Table 3.

Table 3: Simulated values

Component	Value
R_1	7kΩ
R_2	2.2kΩ
R_3	170kΩ
$C_1 = C_2$	470pF
V_{CC}	12V
V_{EE}	-12V

Table 3 was simulated using the same values that were calculated in Section 2. These simulations were close to the required specifications.

The frequency response was simulated using an AC sweep in NGSpice. Figure 5 below shows the frequency response. The simulation was performed from 100Hz to 1MHz.

`Simulations/sim_frequency_gain_with_legend.jpg`

Figure 5: Simulated AC analysis of MFBP

The center frequency in Figure 5 was found to be a little less than the required 20kHz. However, upon taking into account the frequency bandwidth, the MFBP is within specifications. The resistors available for design have a ±5% tolerance about their nominal value. The available capacitor values have a±10% value about their nominal value. The effect of these tolerances on the performance is summarized in Figure 6. The simulation was performed in 10 iterations using Matlab random number generator to choose values that fell within the respective component tolerances[3].

Simulations/resp_two_sigma_variation.jpg

Figure 6: Two-sigma variation

As Figure 6 the tolerances could lower the center frequency quite significantly. Care should be taken when constructing the circuit to choose components that fall close to their nominal values. Table 4 summarizes the simulated results of the circuit.

Table 4: Simulated results

Value	Simulated
Center Frequency	19.45 kHz
Gain	65.1 dB
Bandwidth	1.89 kHz

The simulated results in Table 4 fell within an acceptable margin of error for this simulation.

4 Experimental Implementation

The LF347 is a model featuring four on board op amps. Only three were required by the final design, the fourth was instead used as a unity gain buffer one the output. The final circuit is shown in Figure 7 below.

ExperimentalImplementation/Lab_2.png

Figure 7: Experimental circuit schematic

The experimental design required several changes, as seen in Figure 7, compared to the simulated model. Notably, the simulated design failed to meet the 60dB specification with a peak gain of 54dB. The MFBP was subsequently redesigned due to failing to meet the specified values in a real world scenario. The final component values are summarized in Table 5.

Table 5: Experimental values

Component	Value
R_1	2.7kΩ
R_2	4.3kΩ
R_3	160kΩ
$C_1 = C_2$	470pF
V_{CC}	12V
V_{EE}	-12V

The final values that are expressed in Table 5 are different than the simulated due to real world parasitic capacitance and limitations of the breadboard at higher frequencies. The experimental results are as follows: the output voltage, which did not saturate; the frequency response, with a center frequency of 20.2kHz; and the bench test, where the specifications were met.

4.1 Output Voltage

The measured voltage output is found below in Figure 8. The time domain signal was measured using the Digilent Discovery and Waveforms software. The time domain was measured on a 50μs/div scale with a voltage range of 2V/div.

ExperimentalImplementation/voltage_out_exp.jpg

Figure 8: Voltage output of MFBP

The output signal, as seen in Figure 8, did not saturate the op amp and had no discernible noise. Notably, the signal was still well within rail voltages so the risk of saturation is small. Finally, the frequency response was measured.

4.2 Frequency Response

The measured frequency response is found below in Figure 9. A frequency sweep was done using the Digilent Discovery 2's network analyzer. The frequency sweep was performed from 1kHz to 500kHz. The wave generator was attached to the input of the voltage divider. The channel one scope was used as a reference channel and was tied to the input of the circuit. Channel 2 was used to measured the output of the MFBP filter.

ExperimentalImplementation/peak_db_exp.jpg

Figure 9: Experimental AC analysis

As seen in Figure 9, the center frequency was found to be 20.2 kHz with a gain of 71.4 dB. Notably there was another pole located at 70kHz; this is addressed in the Discussion section. The bandwidth is shown in Figure 10.

ExperimentalImplementation/3db_lab2.jpg

Figure 10: Experimental bandwidth

The bandwidth was found to be, in Figure 10, 2.11kHz, which is within the specifications of the lab.

4.3 Bench Test

The final circuit operated mostly as expected under testing conditions. The DC output while the input tied to ground was found to be 5mV. While greater than ±2mV outlined, it was still within allowable tolerances. The AC output was found to be ±50mV, which falls within the allowable range of around 0V.. The circuit also returned to the ±50mV noise upon the removal of an input waveform. The professor, Dr. Kotecki, noted that the differences between the results and that of the benchmark were minor and fell within allowable ranges.

The final experimental results are summarized in Table 6.

Table 6: Experimental results

Value	Experimental
Center Frequency	20.2 kHz
Gain	71.4 dB
Bandwidth	2.11 kHz

As seen in Table 6, the experimental results fall within the lab specifications outlined.

5 Discussion

The simulated circuit failed to meet lab specifications after construction. This can be accounted for by analysis of Figure 6. The simulated values were not available in the parts store and had to be created using several resistors in series. With each additional resistor the chance of tolerances affecting the circuit increases. Component tolerances can quite significantly change the center frequency. This would explain why the built circuit failed to meet specifications. If the center frequency was on the low on end of 17kHz, then the input 20kHz signal would not see the max gain, and thus fail to meet specifications. The Table 7 outlines the specifications for this lab.

Table 7: MFBP filter specifications

Filter Topology	MFBP Filter Specification Requirements
Center Frequency (f_c)	20 kHz
$3dB$ Bandwidth	Between 1.5 kHz and 5 kHz
Gain	Greater than 1000 $\frac{V}{V}$
Rail Supplies	± 12 V

Table 7 summarizes the specifications that were required by this lab. Another consideration for this design was the role center frequency and gain played. If the gain of the circuit was designed to be too high (¿100dB) then upon applying rail voltages the op amp would be pushed into oscillation. The circuit would also be pushed into saturation. The op amps would then no longer be operating in their linear regions and the circuit would essentially be behaving as an multivibrator. This is a key difference between ideal and non ideal op amps. From mathematical background, it would make sense to try and design the filter to generate as high a gain as possible. The real circuit, however, is in fact bound by rail and feedback limitations. Attempting to build this circuit with too high of a gain will result in a nonfunctional circuit. Table 8 summarizes the simulated and experimental results of this report.

Table 8: Results summary

Values	Simulated	Experimental
R_1	7kΩ	2.7kΩ
R_2	2.2kΩ	4.3kΩ
R_3	170kΩ	160kΩ
C	470pF	470pF
Gain	65.1dB	71.4dB
Center Frequency	19.45kHz	20.2kHz
Bandwidth	1.89kHz	2.11kHz

Table 8 provides an overview of the major results from this lab.

The circuit was then redesigned using parts that were readily available in the parts store. the gain was also increased to ensure that the 60dB threshold was reached. The final circuit performed within lab specifications. The final circuit did, however, "fail" some of the bench tests. Notably the DC noise was 5mV, which is greater than that stated on the bench test. This, however, was said to be still to be in an allowable range by the Professor. The AC noise was ±50mV, which was said to be within the allowable range. To help eliminate some of the noise bypass capacitors were added to the positive and negative rail voltages. A parallel plate capacitor was added in parallel with a electrolytic capacitor. The parallel plate capacitor filters our high frequency noise, while the electrolytic filters out low frequency noise.

Section 6 that follows concludes this report.

6 Conclusion

The design, simulation, and implementation of the multi-feedback bandpass filter have been explained. Lab specification required that the MFBP have a center frequency of approximately 20kHz, a bandwidth of between 1.5k and 5kHz, and a gain of at least 60dB. The MFBP takes an input voltage and filters out frequency outside of the bandwidth around the center frequency as well as generates a gain. The MFBP circuit was constructed using the following parts: a 2.7kΩ, a 4.3kΩ, and a 160kΩ resistors; a 470pF capacitor; and finally an LF347 operational amplifier with $\pm$12V rail voltages. An 100:1 voltage divider was used at the output of the wave generator in order to create an appropriately small input to the MFBP filter. The gain was 71.4 dB, with a bandwidth of 2.11kHz centered at 20.2kHz. An important lesson about the behavior of non-ideal op amps was displayed by the tendency of an op amp to be pushed into oscillation when the gain is set too high.

References

[1] D.E. Kotecki Lab.(2017) Lab #2 Active Bandpass Filters [Online]. Available: http://web.eece.maine.edu/ kotecki/ECE342/labs/ECE342_2017_Lab2.pdf

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