The Bandpass Butterworth Filter

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I Abstract

The objective of this project was to design a fourth order Butterworth Bandpass Filter that satisfies various specifications. The filter designed is specified to have a center frequency of 455kHz, a bandwidth of 100kHz and a passband gain of 10dB. The response of the passband must be as flat as possible with a steep transition from the passband to the stop band in order to maximize the filter's effectiveness. Furthermore, the filter designed should be capable of passing signals without any distortion in the pass band. The fourth order Butterworth filter was also compared to a second order filter in order to prove the effectiveness of the higher order filter.

II Discussion

To begin the project, a simple low pass filter, as seen in Figure 1, is utilized as a reference point in order to easily transform the circuit into a butterworth bandpass filter. The normalized values for the components of each element in the circuit were obtained from Table 1.

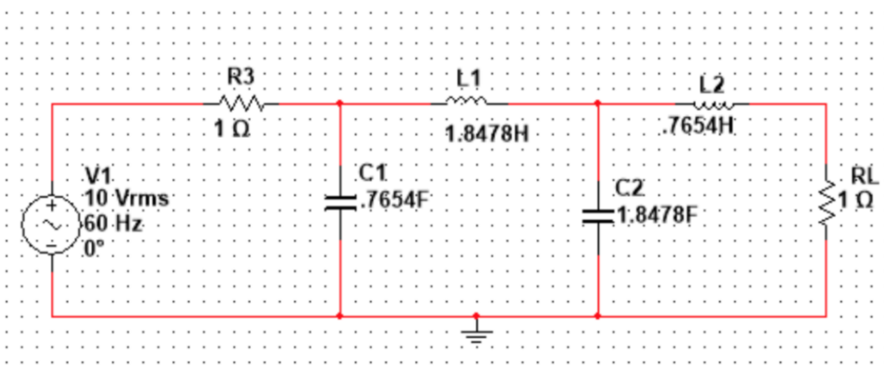


Figure 1: Lowpass Filter

Order	RS	C1	L1	C2	L2
1	1.0000	2.0000	-	-	-
2	1.0000	1.4142	1.4142	-	-
3	1.0000	1.0000	2.0000	1.0000	-
4	1.0000	0.7654	1.8478	1.8478	0.7654

Table 1: Normalized Values of lowpass filter

From these normalized values, the capacitors initial value, $C_{initial}$, is transformed into a new capacitance in parallel with an inductor. Similarly, an inductors initial value, $L_{initial}$, is transformed into a new valued inductance in series with a capacitor. These schematic transformations may be found below in Figure 2, and their mathematical equivalent models are seen below in equations 1 and 2.

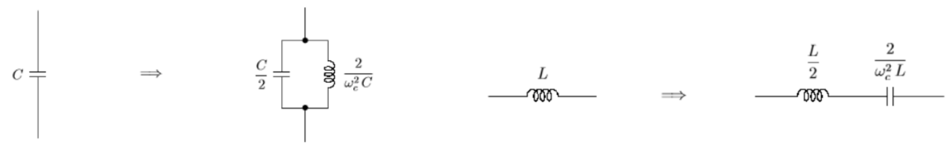


Figure 2: Component transformations

$$C_{initial} => C_{new} = \frac{C}{2} \qquad \& \qquad L_{new} = \frac{2}{\omega_c^2 C} \tag{1}$$

$$L_{initial} => L_{new} = \frac{L}{2} \qquad \& \qquad C_{new} = \frac{2}{\omega_c^2 L} \tag{2}$$

After having completed these transformations to meet the required bandwidth specifications of the design, a minor complication arose in regards to the amplification of the gain when implementing the operational amplifier. The common UA741 did not have a high enough performance in order to obtain the desired gain of 10dB at the filtered frequency. Therefore, high performance operational amplifiers such as the AD8067 and ADA4004 were implemented in order achieve the proper gain.

III Calculations

III.1 2nd Order Filter

To implement the specifications stated in the Discussion section, the second order low pass filter was transformed into a bandpass filter using the calculations shown in Figure 3. A Multisim schematic of the circuit is shown in Figure 4.

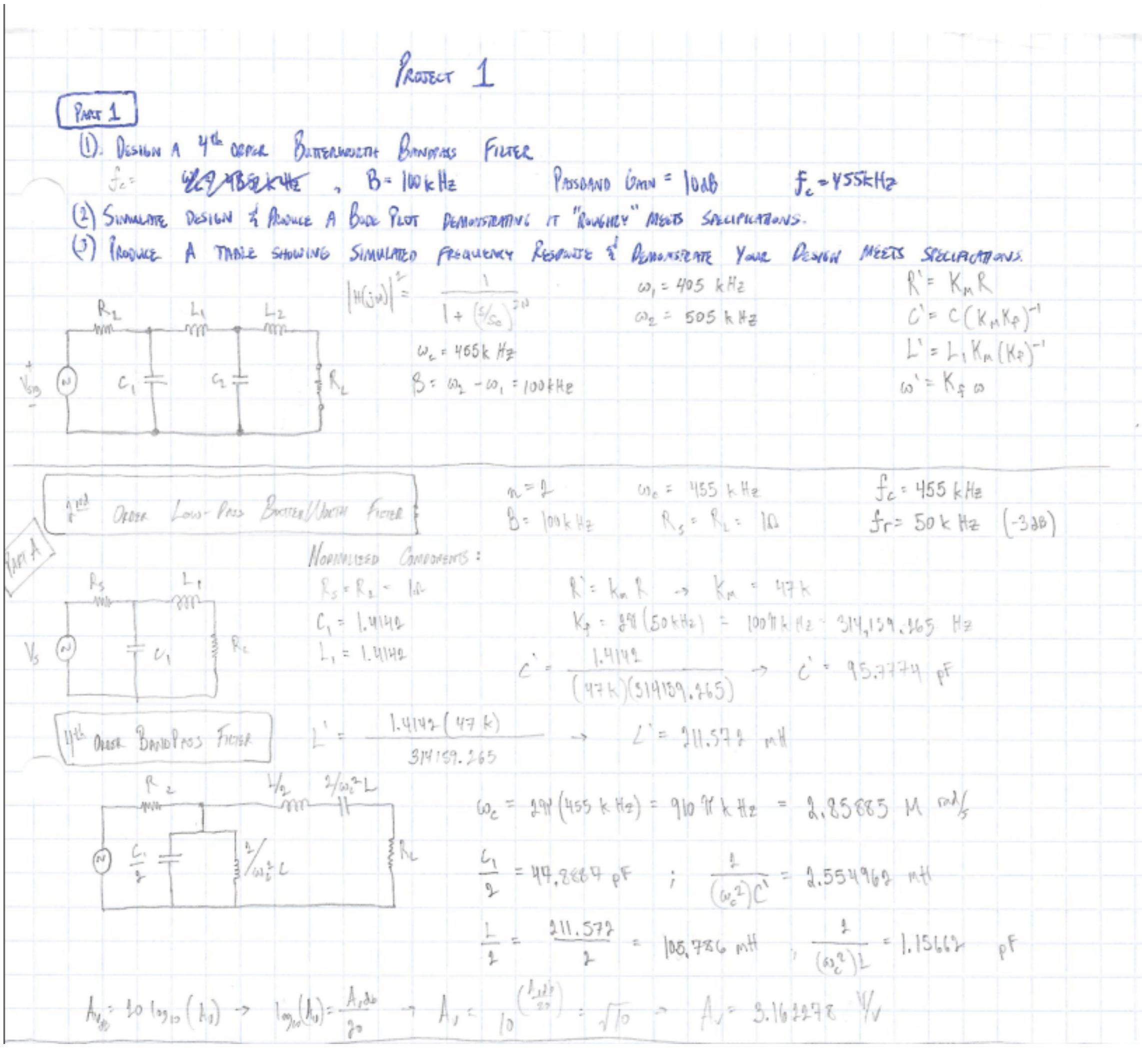


Figure 3: Bandpass 2nd order filter calculations

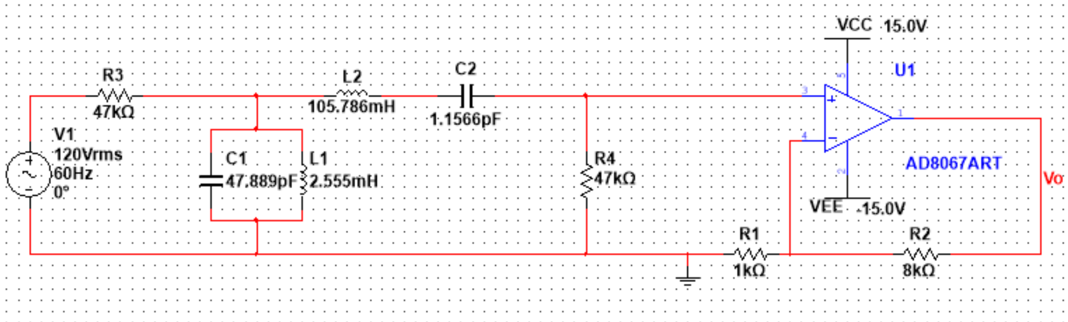


Figure 4: Bandpass 2th order filter Multisim schematic

III.2 4th Order Filter

The same procedure was used for the 4th order filter. Figure 5 and 6 shows the Multisim schematic and calculations, respectively.

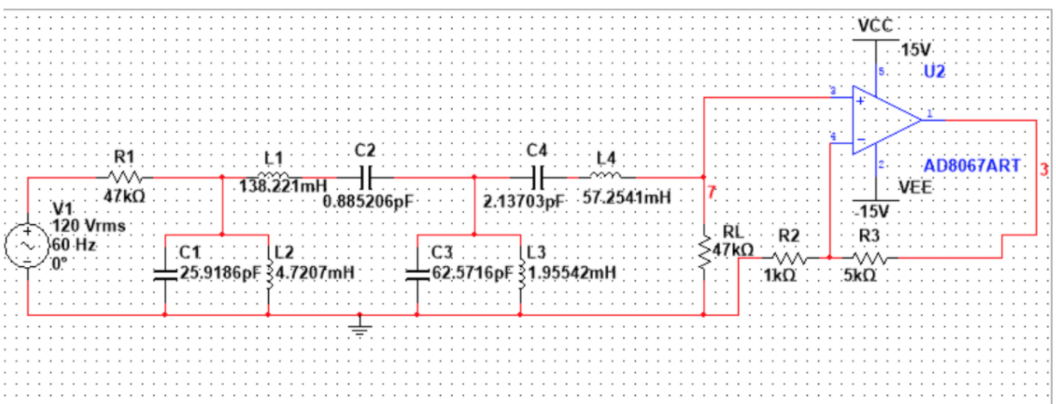


Figure 5: Bandpass 4th order filter

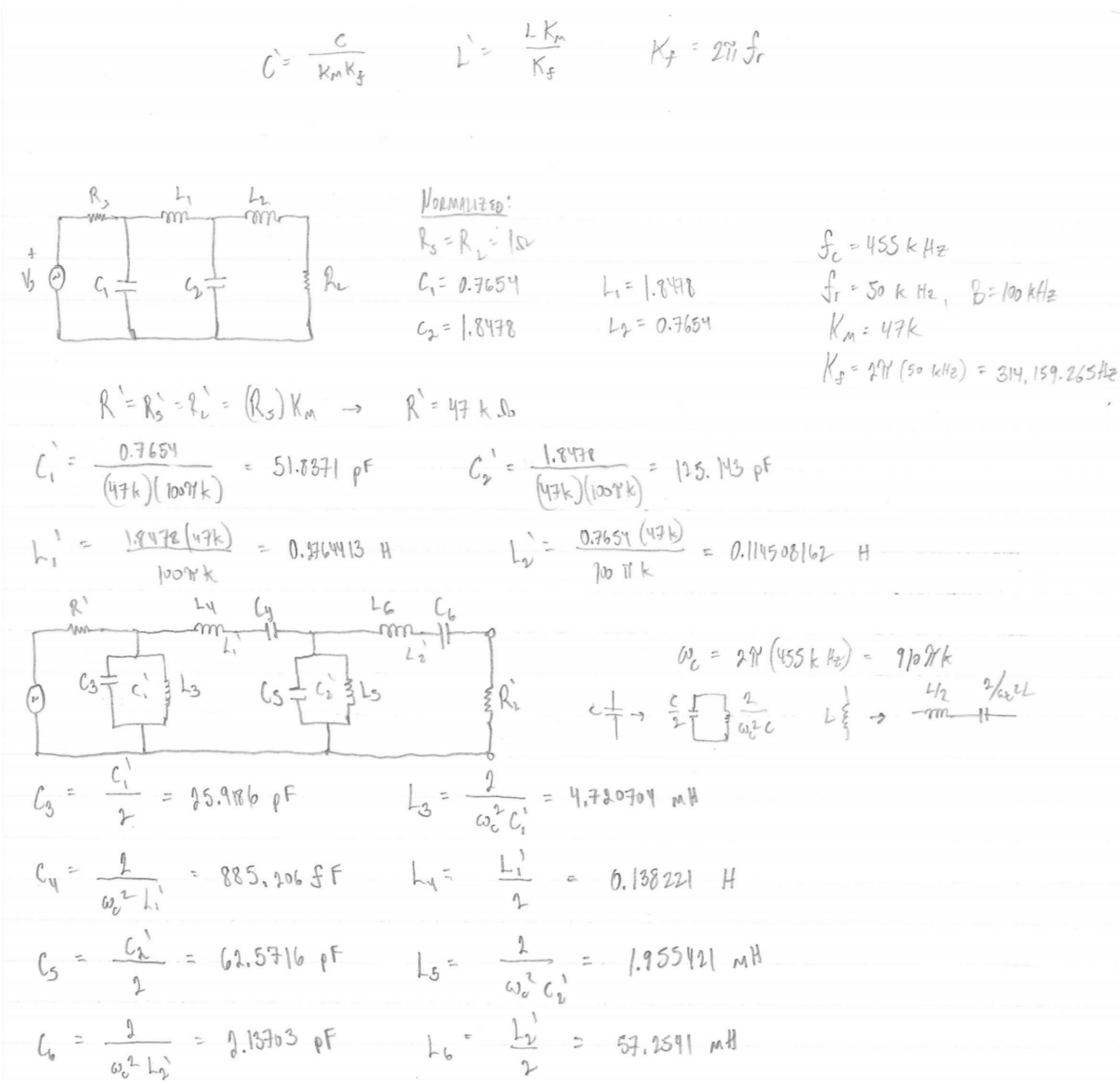


Figure 6: 4th order filter calculations

IV Results

The above designs were ran through SPICE simulations and the below figures/graphs show successful Butterworth Bandpass filters. Figure 7 shows the 2nd order filter with center frequency at 455kHz and Figure 8 shows the 4th order filter with the same center frequency. Figure 9 represents the 4th order filter with the application of the AD8067 high performance operational amplifier to the load in order to reach the desired 10dB.

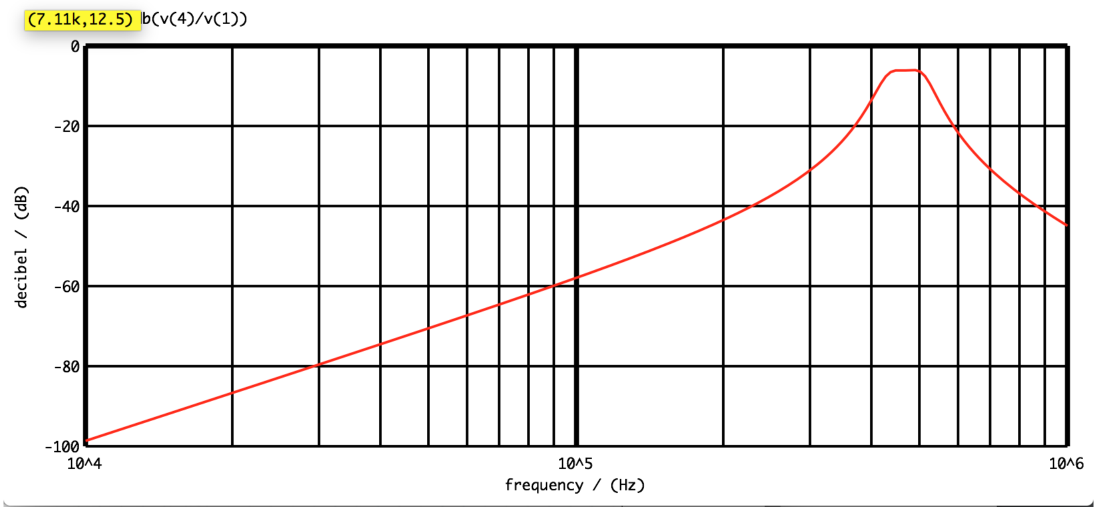


Figure 7: 2nd Order Bandpass filter

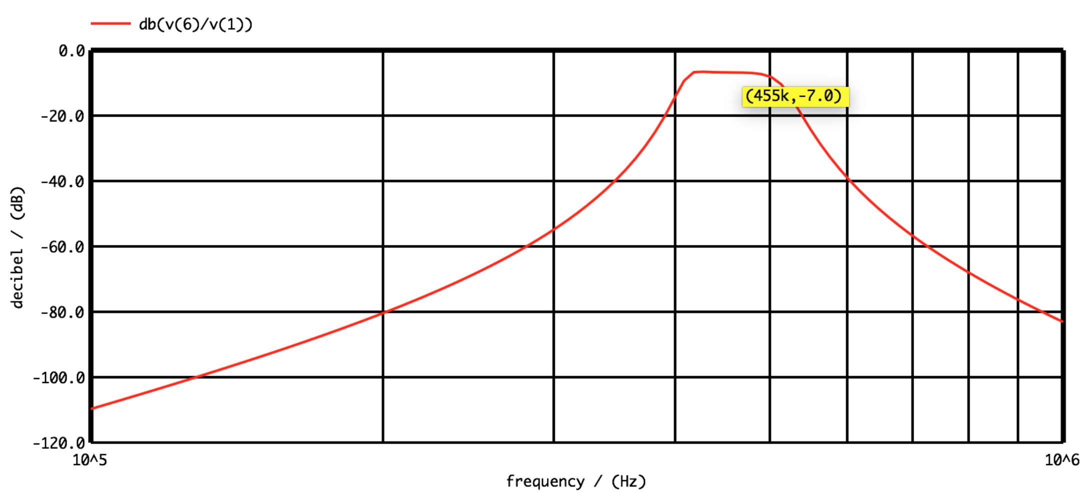


Figure 8: 4th Order Bandpass filter before applying gain

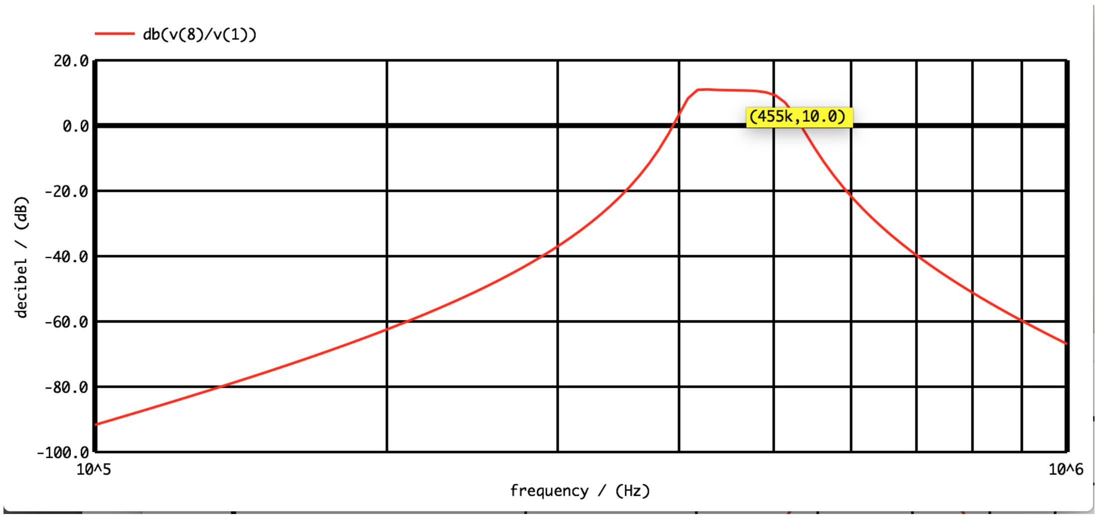


Figure 9: Bandpass filter after applying gain

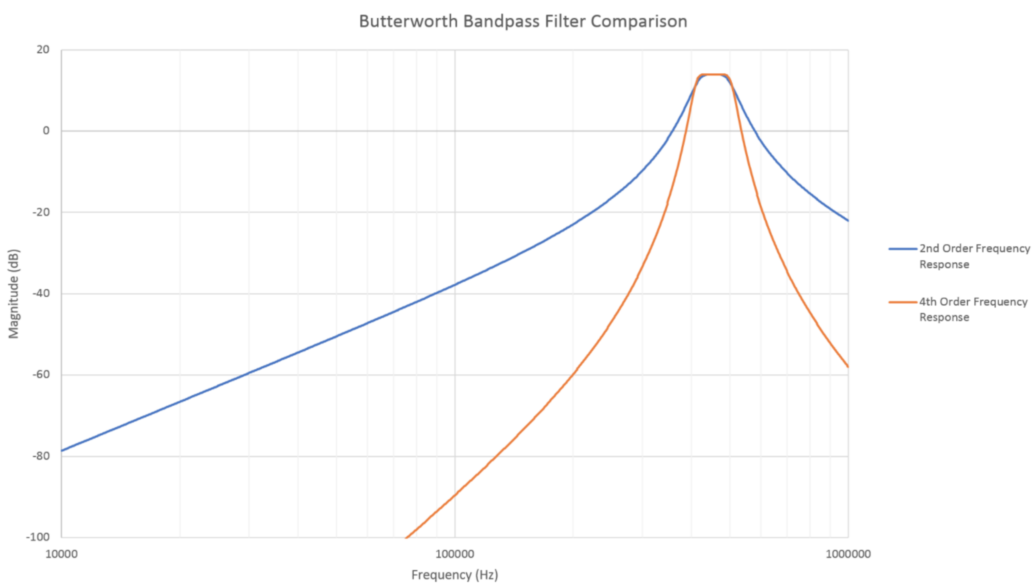


Figure 10: 4th order vs 2nd order butterworth bandpass filter

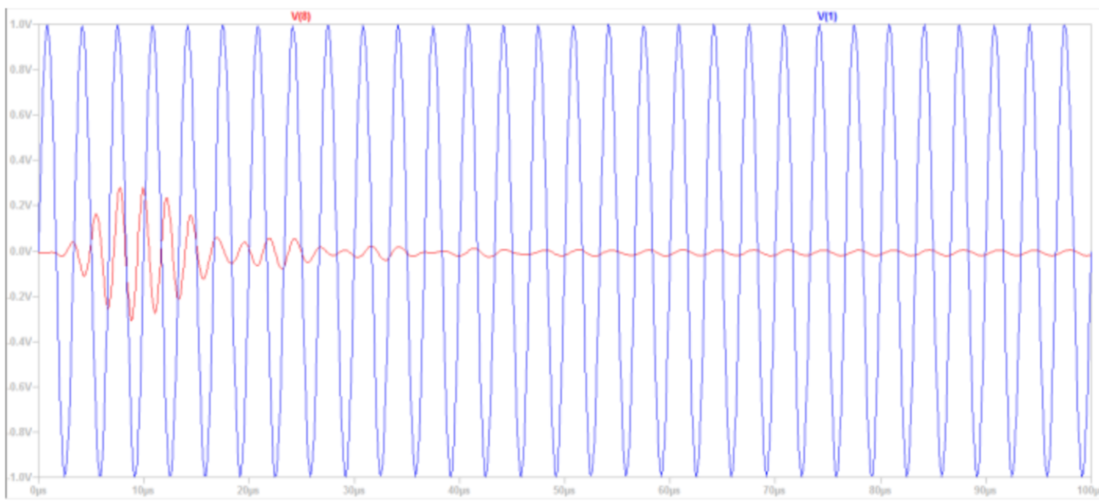
When comparing the 2nd and 4th order filters, as seen in figure 10, it is easy to notice the higher performance of the 4th order filter compared to the 2nd order filter. The stopband frequencies of the 4th order are much steeper, representing a much more reliable filter. For a more detailed comparison of the two filters, a portion of the specific frequencies and decibels of each filter can be seen in table 2.

Frequency	2nd Order dB	4th Order dB
4.07E+05	6.36E+00	6.59E+00
4.17E+05	8.30E+00	8.34E+00
4.27E+05	9.54E+00	9.52E+00
4.37E+05	1.00E+01	1.01E+01
4.47E+05	1.00E+01	1.02E+01
4.57E+05	1.00E+01	1.02E+01
4.68E+05	1.00E+01	1.02E+01
4.79E+05	9.95E+00	1.01E+01
4.90E+05	9.35E+00	9.74E+00
5.01E+05	7.96E+00	8.75E+00
5.13E+05	4.99E+00	7.11E+00

Table 2: Frequencies in Hz and dBs of 2nd & 4th order filters

IV.1 Transient Analysis

To prove that the 4th order Butterworth bandpass filter operates as desired, a transient analysis was applied and tested. The analysis involved feeding various signals through the filter to determine successful operation. Signals for each stopband and passband were fed through the filter and the results can be seen in the figures below.



Red: Output Blue: Input

Figure 11: transient analysis of a 300kHz signal through the 4th order filter

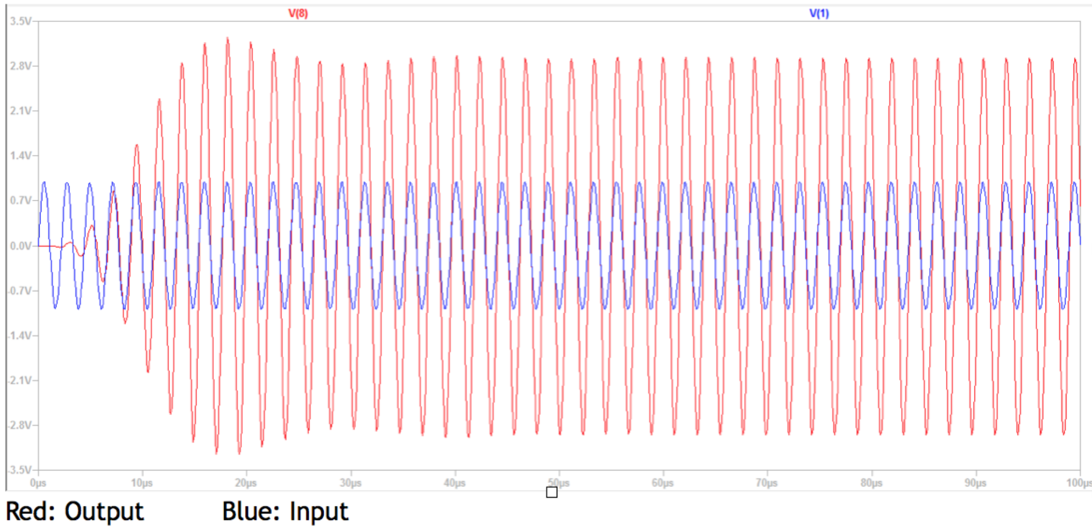


Figure 12: transient analysis of a 455kHz signal through the 4th order filter

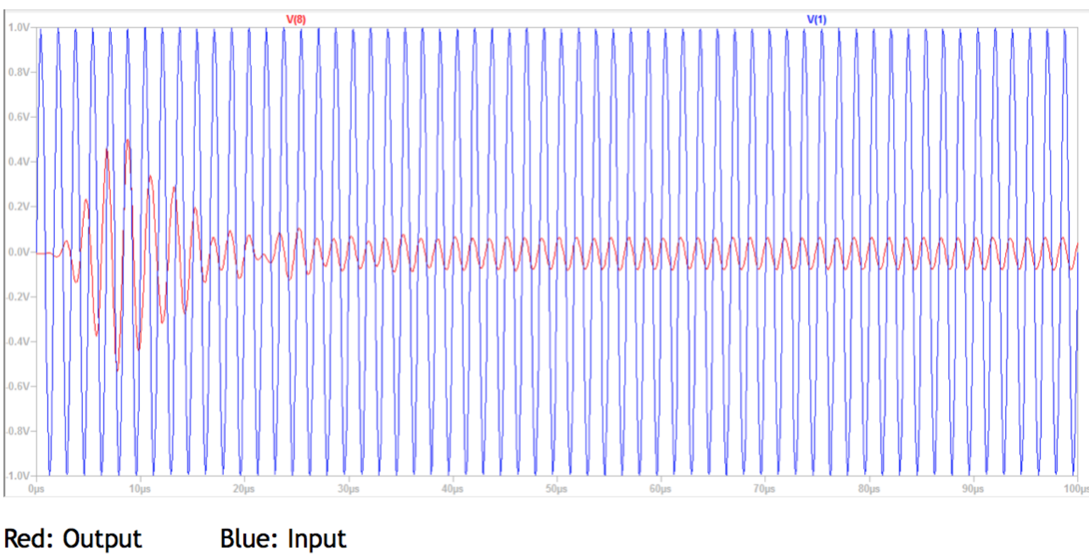


Figure 13: transient analysis of a 600kHz signal through the 4th order filter

As seen in the above figures, the 4th order Butterworth bandpass filter operates as expected and intended. The filter rejects the 300kHz and 600kHz stopband signals and allows the passband signal of 455kHz to flow through.

V Conclusion

For this project, two bandpass filters were to be designed. Each with a center frequency of 455Khz, a bandwidth of 100Khz, and a passband gain of 10dB. Second and fourth-order Butterworth filters were chosen for this design. First, a simple low-pass filter with a break frequency of half bandwidth was developed. Then, this filter was transformed to a bandpass filter using equations (1) and (2), resulting in a bandpass filter of the correct bandwidth. An amplifier stage was added at the output to get the correct passband gain. These designs were then simulated using tools such as MacSpice, MultiSim, LTSpice, and Excel in order to produce and prove the success of the Butterworth bandpass filter .

VI References

References

[1] P. Mathys, Wireless Electronics for Communication, March 3, 2012.

[2] P. Horowitz and W. Hill, “Butterworth Filters” The Art of Electronics 3rd ed. Cambridge University Press, 2015.

VII Appendix

VII.1 Second Order Butterworth Filter Spice netlist

```
*2nd order bandpass netlist

.include AD8067.cir
x1 4 5 7 8 6 AD8067
Vs 1 0 AC 1
R1 1 2 47k
C1 2 0 47.887pF
L1 2 0 2.555mH
C2 2 3 1.157pF
L2 3 4 105.786mH
RL 4 0 47k
R3 5 0 1k
R2 5 6 5.5k
VCC 7 0 15
VEE 8 0 -15
.AC dec 100 100k 1meg
.end
```

VII.2 Fourth Order Butterworth Filter Spice netlist

```
*4th order bandpass netlist

.include AD8067.cir
x1 6 7 9 10 8 AD8067
Vs 1 0 AC 1
R1 1 2 47k
C1 2 0 25.9186pF
L1 2 0 4.7207mH
L2 2 3 138.221mH
C2 3 4 .885206pF
```

```
C3 4 0 62.5716pF
L3 4 0 1.95542mH
C4 4 5 2.13703pF
L4 5 6 57.2541mH
RL 6 0 47k
R2 7 0 1k
R3 7 8 5k
VCC 9 0 15
VEE 10 0 -15
.AC dec 100 10k 1meg
.end
```

VII.3 Fourth order filter Transient Function Test @ 300kHz,400kHz & 600kHz frequencies

```
*netlist

.include AD8067.cir
Vs 1 0 sin(0 1 300k)
*Vs 1 0 sin(0 1 455k)
*Vs 1 0 sin(0 1 600k)
x1 6 7 9 10 8 AD8067
*Vs 1 0 AC 1
R1 1 2 47k
C1 2 0 25.9186pF
L1 2 0 4.7207mH
L2 2 3 138.221mH
C2 3 4 .885206pF
C3 4 0 62.5716pF
L3 4 0 1.95542mH
C4 4 5 2.13703pF
L4 5 6 57.2541mH
RL 6 0 47k
R2 7 0 1k
R3 7 8 5k
```

```
VCC 9 0 15
VEE 10 0 -15
.tran 100u
*.AC dec 100 10k 1meg
.end
```