Music Light Show Using Low-Pass, High-Pass, and Band-Pass Filters

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Abstract:

The goal of this project was to create a light show that responds to a frequency input. This was accomplished through the use of four 6th order Butterworth equal termination filters to separate the frequency composition of the input. The separate frequency bands each control an independent LED array that light up depending on the intensity of the arrays respective input frequency.

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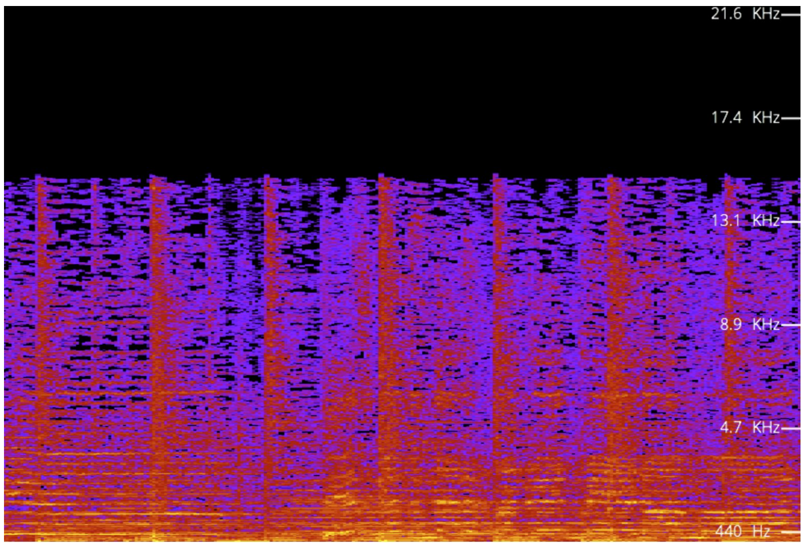
Introduction

The objective of the project was to create four arrays of LEDs that would each respond to a separate band of frequencies that fall within human range of hearing (typically 20-20000 Hz). To accomplish this we used four 6th order passive Butterworth filters, consisting of a low-pass, two band-passes, and a high pass, each with a singular gainstage at the end. The input into the system would be a 3.5mm auxiliary audio connection, where the speakers would receive a full stereo signal, and the filters would receive a mixed mono signal, to ensure that the LEDs fully reflected the frequency composition of both the left and right channels. The song that is used to demonstrate the function of this project is Africa by Toto. The spectrogram analysis[1] of this audio piece shows that the frequency ranges between 0 Hz - 10 kHz.



Spectrogram Analysis Fragment of Africa by Toto

Filter Design Summary:

There are four filters used in this circuit, one low-pass, one high pass, and two band-pass. All four filters are 6th order passive Butterworth equal termination filters. The low-pass filter has a set cutoff frequency of 200 Hz, the first band-pass filter has a set pass band between 250 Hz to 4 kHz, the second band-pass filter has a set pass band between 4.05 kHz to 9.95 kHz, and the high-pass filter has a set frequency cutoff of 10 kHz. After each filter is an operational amplifier with an adjustable gain using a potentiometer. At the end of each filter branch is a network of LEDs which are driven by an LM3915 (resistor and comparator network) which are used to indicate when a signal within the set filter frequencies passes through the branch; the LM3915 is used to indicate the intensity, or volume, of the signal.

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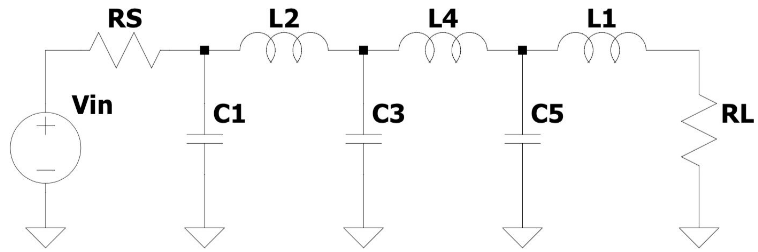
[1] See Reference 1: Spectrum Analyzer

Filter Calculations:

Low-Pass Component Calculations

The flow-pass filter in this circuit is a 6th order Butterworth equal termination filter. The cutoff frequency is 200 Hz. Given the Butterworth equal termination Low-Pass Prototype Element chart[2], and the following diagram,



Where[3], $RS = RL = 50\ \Omega$ and the following component values are calculated[4],

Ideal Component Values		Actual Component Values
C_1	$8.244\ \mu F$	$8.2\ \mu F$
L_2	$56.26\ mH$	$56\ mH$
C_3	$30.749\ \mu F$	$33\ \mu F$
L_4	$76.87\ mH$	$\frac{1}{\frac{1}{56\ mH}+\frac{1}{56\ mH}} + 56mH\ =\ 84\ mH$
C_5	$22.5\ \mu F$	$22\ \mu F$
L_6	$20.6\ mH$	$22\ mH$

Low-Pass Transfer Function

Given the Factors of Polynomials for 6th order filters[5], the following transfer function for the low-pass filter was calculated,

$H_{LP}(s) = \frac{G_0}{B_6(s)}$, where $G_0 = 1$, $B_6(s) = \frac{1}{(s^2+0.5176s+1)(s^2+1.4142s+1)(s^2+1.9319s+1)}$, and $\omega_c = 2\pi * 200 = 1256.6064\ rad/s$

$$H_{LP}(s) = \frac{G_0}{B_6(\frac{s}{\omega c})} = \frac{1}{((\frac{s}{\omega c})^2+0.5176(\frac{s}{\omega c})+1)((\frac{s}{\omega c})^2+1.4142(\frac{s}{\omega c})+1)((\frac{s}{\omega c})^2+1.9319(\frac{s}{\omega c})+1)}$$

$$H_{LP}(s) = \frac{1}{((\frac{s}{1256.6})^2+0.5176(\frac{s}{1256.6})+1)((\frac{s}{1256.6})^2+1.4142(\frac{s}{1256.6})+1)((\frac{s}{1256.6})^2+1.9319(\frac{s}{1256.6})+1)}$$

$$H_{LP}(s) = \frac{1}{2.53636*10^{-19}*s^6+1.23201*10^{-15}*s^5+2.99159*10^{-12}s^4+4.60529*10^{-9}s^3+4.72605*10^{-6}s^2+0.00307473*s+1}$$

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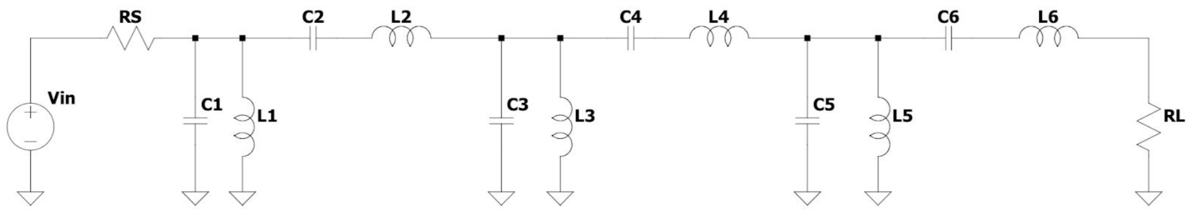
[2] See Appendix, Relevant Tables, Table 1: Low-Pass Prototype Element chart
[3] See Reference 2: RF Circuit Design
[4] See Appendix, Relevant Equations, 1: Low-Pass Prototype Value Equations
[5] See Appendix: Relevant Tables, Table 4: Factors of Butterworth Polynomials

Band-Pass 1 Component Calculations

The first band-pass filter in this circuit is a 6th order Butterworth equal termination filter. The band-pass frequency band is between 250 Hz - 4 kHz. Given the Butterworth equal termination Band-Pass Prototype Element chart[6], and the following diagram,



Where, $RS = RL = 50\ \Omega$, $f_c = \sqrt{250 * 4000} = 1000\ Hz$, and $\Delta = \frac{4000-250}{1000} = 3.75$ the following component values are calculated[7],

Ideal Component Values		Actual Component Values
L_1	$57.5956\ mH$	$56\ mH$
C_1	$440\ nF$	$470\ nF$
L_2	$3.000674\ mH$	$3.3\ mH$
C_2	$8.439\ \mu F$	$10\ \mu F$
L_3	$15.458301\ mH$	$15\ mH$
C_3	$1.64\ \mu F$	$1.5\ \mu F$
L_4	$4.099931\ mH$	$3.9\ mH$
C_4	$6.183\ \mu F$	$6.8\ \mu F$
L_5	$21.098492\ mH$	$22\ mH$
C_5	$1.2 \mu F$	$1.2\ \mu F$
L_6	$1.099257\ mH$	$1.2\ mH$
C_6	$23.062\ \mu F$	$24\ \mu F$

[6] See Appendix, Relevant Tables, Table 2: Band-Pass Prototype Element Chart
[7] See Appendix, Relevant Equations, 2: Band-Pass Prototype Value Equations

Band-Pass 1 Transfer Function

Given the Factors of Polynomials for 6th order filters[8], the following transfer function for the band-pass 1 filter was calculated[9],

$$H_{LP}(s) = \frac{G_0}{B_6(s)} \text{ , where } G_0 = 1$$

$$H_{LP}(s) = \frac{1}{(s^2+0.5176s+1)(s^2+1.4142s+1)(s^2+1.9319s+1)}$$

Next, the transfer function for the band-pass is calculated given the LPF-to-BPF transformation where the band-pass filter transfer function is $H(Q(\frac{s}{\omega_0} + \frac{\omega_0}{s}))$, the Q-factor is $Q = \frac{\omega_0}{\Delta\omega}$, the resonant frequency is $\omega_0 = \sqrt{\omega_1 \omega_2}$, the absolute bandwidth is $\Delta\omega = (\omega_2 - \omega_1)$, $\omega_1 = 250 * 2\pi = 1570.8\ rad/s$, and $\omega_2 = 4000 * 2\pi = 25132.74\ rad/s$. Such that,

$$\Delta\omega = (\omega_2 - \omega_1) = 25132.74 - 1570.8 = 23561.94\ rad/s$$

$$\omega_0 = \sqrt{\omega_1 \omega_2} = \sqrt{1570.8 * 25132.74} = 6283.19\ rad/s$$

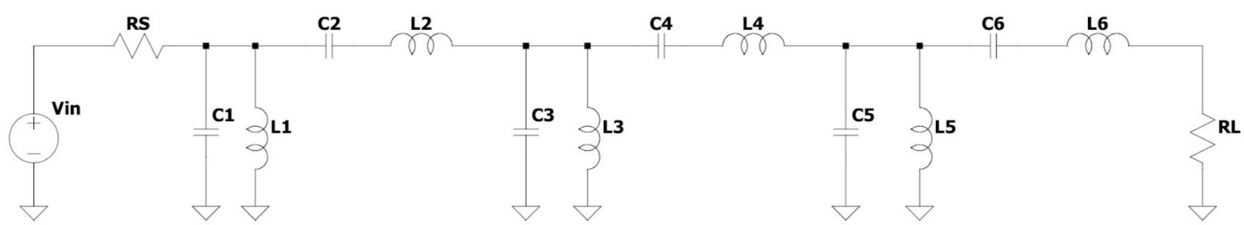
$$Q = \frac{\omega_0}{\Delta\omega} = \frac{23561.94}{6283.19} = 0.267$$

$$H_{BP1}(s) = \frac{1.526e34s^9}{8.987e07s^{15}+8.171e12s^{14}+3.928e17s^{13}+1.232e22s^{12}+2.665e26s^{11}+3.901e30s^{10}}$$

$$\overline{3.509e34s^9+1.54e38s^8+4.153e41s^7+7.58e44s^6+9.54e47s^5+7.836e50s^4+3.402e53s^3}$$

Band-Pass 2 Component Calculations

The second band-pass filter in this circuit is a 6th order Butterworth equal termination filter. The band-pass frequency band is between 4.05 kHz - 9.95 kHz. Given the Butterworth equal termination Band-Pass Prototype Element chart[10], and the following diagram,



Where, $RS = RL = 50\ \Omega$, $f_c = \sqrt{4050 * 9950} = 6348\ Hz$, and $\Delta = \frac{9950-4050}{6348} = 0.929426591$ the following component values are calculated[11],

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[8] See Appendix: Relevant Tables, Table 4: Factors of Butterworth Polynomials
[9] See Reference 3: Band-Pass Transfer Function Calculations
[10] See Appendix, Relevant Tables, Table 2: Band-Pass Prototype Element Chart
[11] See Appendix, Relevant Equations, 2: Band-Pass Prototype Value Equations

Ideal Component Values		Actual Component Values
L_1	2.248724 mH	2.2 mH
C_1	279 nF	270 nF
L_2	1.907208 mH	2.2 mH
C_2	330 nF	330 nF
L_3	603.544 μH	560 μH
C_3	1.042 μF	1 μF
L_4	2.605889 mH	2.7 mH
C_4	241 nF	220 nF
L_5	823.755 μH	820 μH
C_5	763 nF	680 nF
L_6	698.68 μH	680 μH
C_6	900 nF	1 μF

Band-Pass 2 Transfer Function

Given the Factors of Polynomials for 6th order filters[12], the following transfer function for band-pass 2 filter was calculated,

$H_{LP}(s) = \frac{G_0}{B_6(s)}$, where $G_0 = 1$

$H_{LP}(s) = \frac{1}{(s^2+0.5176s+1)(s^2+1.4142s+1)(s^2+1.9319s+1)}$

Next, the transfer function for the band-pass is calculated given the LPF-to-BPF transformation where the band-pass filter transfer function is $H(Q(\frac{s}{\omega_0} + \frac{\omega_0}{s}))$, the Q-factor is $Q = \frac{\omega_0}{\Delta\omega}$, the resonant frequency is $\omega_0 = \sqrt{\omega_1\omega_2}$, the absolute bandwidth is $\Delta\omega = (\omega_2 - \omega_1)$, $\omega_1 = 4050 * 2\pi = 25446.9\ rad/s$, and $\omega_2 = 9950 * 2\pi = 62517.69\ rad/s$. Such that,

$\Delta\omega = (\omega_2 - \omega_1) = 62517.69 - 25446.9 = 37070.79\ rad/s$

$\omega_0 = \sqrt{\omega_1\omega_2} = \sqrt{25446.9 * 62517.69} = 39885.9\ rad/s$

$Q = \frac{\omega_0}{\Delta\omega} = \frac{39885.9}{37070.79} = 1.0759$

$$H_{BP1}(s) = \frac{2.555e41s^9}{9.842e13s^{15}+1.41e19s^{14}+1.949e24s^{13}+1.58e29s^{12}+1.155e34s^{11}+6.022e38s^{10}}$$

$$\overline{2.793e43s^9+9.58e47s^8+2.923e52s^7+6.361e56s^6+1.248e61s^5+1.437e65s^4+1.596e69s^3}$$

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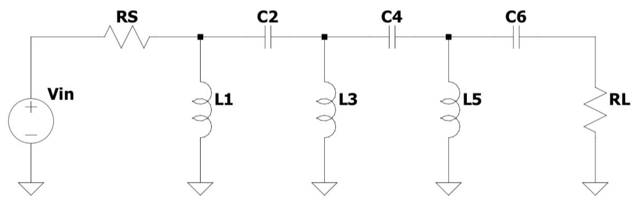
[12] See Appendix: Relevant Tables, Table 4: Factors of Butterworth Polynomials

High-Pass Component Calculations

The high-pass filter in this circuit is a 6th order Butterworth equal termination filter. The cutoff frequency is set to 10 kHz. Given the Butterworth equal termination High-Pass Prototype Element chart[13], and the following diagram,



Where, $RS = RL = 50\ \Omega$ and $f_c = 10000\ Hz$ the following component values are calculated[14],

Ideal Component Values		Real Component Values
L_1	$1.535883\ mH$	$1.8\ mH$
C_2	$225\ nF$	$220\ nF$
L_3	$412.221\ \mu H$	$220\ \mu H + 220\ \mu H = 440\ \mu H$
C_4	$165\ nF$	$150\ nF$
L_5	$562.626\ \mu H$	$470\ \mu\ H$
C_6	$614\ nF$	$680\ nF$

High-Pass Transfer Function

Given the Factors of Polynomials for 6th order filters[15], the following transfer function for high-pass filter was calculated,

$$H_{LP}(s) = \frac{G_0}{B_6(s)}\text{, where } G_0 = 1$$

$$H_{LP}(s) = \frac{1}{(s^2+0.5176s+1)(s^2+1.4142s+1)(s^2+1.9319s+1)}$$

Next, the transfer function for the high-pass is calculated given the LPF-to-HPF transformation where the band-pass filter transfer function is $H(\frac{\omega_c}{s})$ and $\omega_c = 10000 * 2\pi = 62831.85\ rad/s$. Such that,

$$\frac{\omega_c}{s} = \frac{62831.85}{s}$$

$$H_{HP}(s) = \frac{s^9}{s^9+2.428e05s^8+2.947e10s^7+2.268e15s^6+1.163e20s^5+3.784e24s^4+6.153e28s^3}$$

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[13] See Appendix, Relevant Tables, Table 3: High-Pass Prototype Element Chart
[14] See Appendix, Relevant Equations, 3: High-Pass Prototype Value Equations
[15] See Appendix: Relevant Tables, Table 4: Factors of Butterworth Polynomials

Simulation results:

The low-pass filter has a set cutoff frequency of 200 Hz, the first band-pass filter has a set pass band between 250 Hz to 4 kHz, the second band-pass filter has a set pass band between 4.05 kHz to 9.95 kHz, and the high-pass filter has a set frequency cutoff of 10 kHz.

Summary of Simulation Results		
Low Pass	Set f_c Hz	200 Hz (1256.64 rad/s)
	Matlab f_c Hz	198.9 Hz (1.25 e03 rad/s)
	LTspice f_c Hz	187.214 Hz (1176.3 rad/s)
Band Pass 1	Set f_c Hz	250 Hz - 4000 Hz (1571 - 25132.7 rad/s)
	Matlab f_c Hz	249.9 - 3995 Hz (1.57e03 - 2.51e04 rad/s)
	LTspice f_c Hz	238.7 - 4204.8 Hz (1499.8 - 26420 rad/s)
Band Pass 2	Set f_c Hz	4050 - 9950 Hz (25447 - 62517.7 rad/s)
	Matlab f_c Hz	4058 - 9947 Hz (2.55e04 - 6.25e04 rad/s)
	LTspice f_c Hz	4287 - 10104 Hz (26936 - 63485 rad/s)
High Pass	Set f_c Hz	10000 Hz (62831.85 rad/s)
	Matlab f_c Hz	10027 Hz (6.3e04 rad/s)
	LTspice f_c Hz	10578.48 Hz (66466.6 rad/s)

These four circuits have less than a 0.6% difference from the original set cutoff frequencies and Matlab simulations,

Percent Difference Between Set f_c & Matlab f_c Simulation							
Low Pass		Band-Pass 1		Band-Pass 2		High-Pass	
Set f_c & Matlab f_c	0.55%	Set f_c & Matlab f_c	0.04% & 0.125%	Set f_c & Matlab f_c	0.197% & 0.03%	Set f_c & Matlab f_c	0.27%

And less than a 7% difference from the set cutoff frequencies and the LTspice simulations,

Percent Difference Between Set f_c & LTspice f_c Simulation							
Low Pass		Band-Pass 1		Band-Pass 2		High-Pass	
Set f_c & LTspice f_c	6.6%	Set f_c & LTspice f_c	4.6% & 4.99%	Set f_c & LTspice f_c	5.69% & 1.54%	Set f_c & LTspice f_c	5.6%

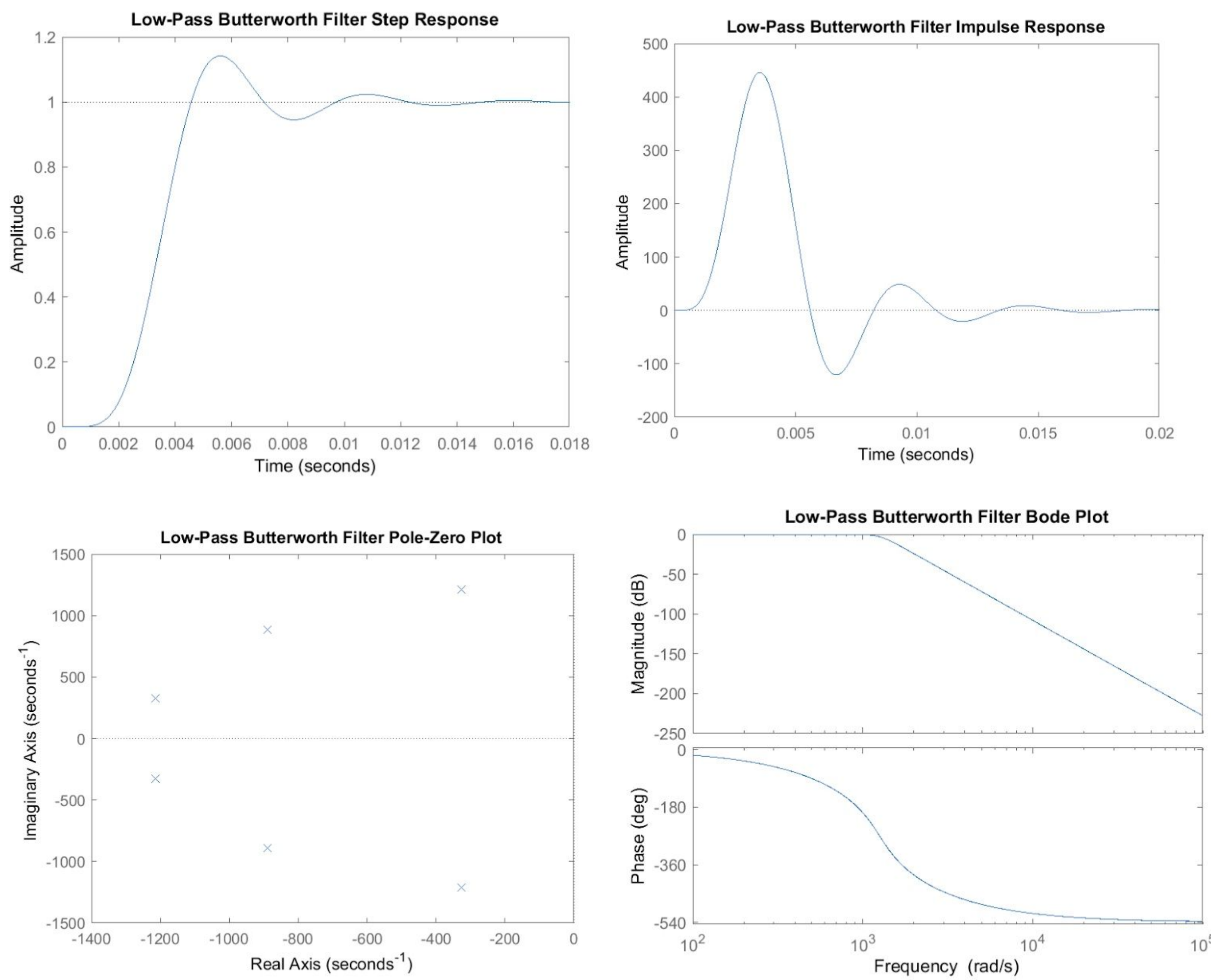
MATLAB Results[16]:

Low-Pass Filter:

Using the transfer function calculated earlier,

$$H_{LP}(s) = \frac{1}{2.53636*10^{-19}*s^6+1.23201*10^{-15}*s^5+2.99159*10^{-12}s^4+4.60529*10^{-9}s^3+4.72605*10^{-6}s^2+0.00307473*s+1}$$

Linear System Analysis LP



[16] See Appendix, MATLAB Code

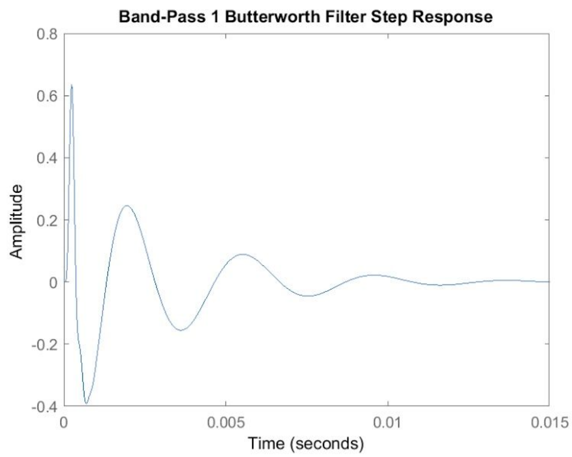
Band-Pass Filter 1:

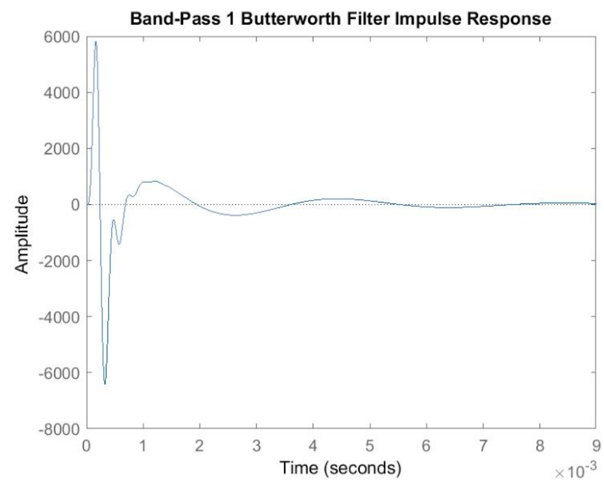
Using the transfer function calculated earlier,

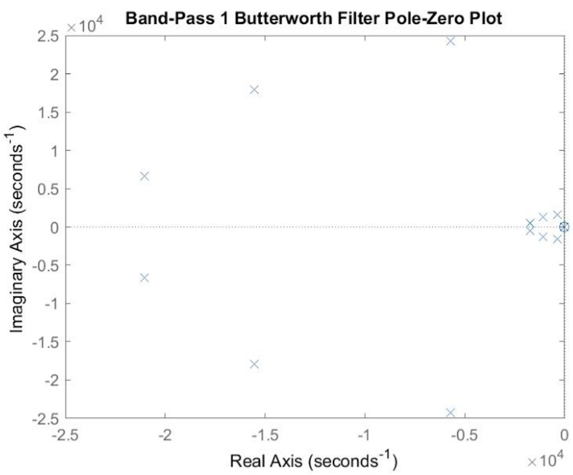
$$H_{BP1}(s) = \frac{1.526e34s^9}{8.987e07s^{15}+8.171e12s^{14}+3.928e17s^{13}+1.232e22s^{12}+2.665e26s^{11}+3.901e30s^{10}}$$

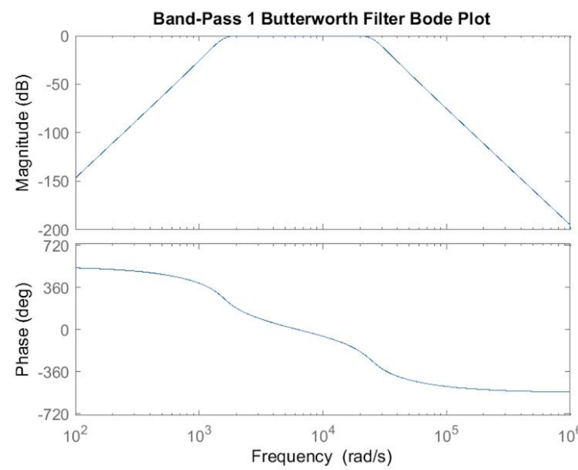
$$\overline{3.509e34s^9+1.54e38s^8+4.153e41s^7+7.58e44s^6+9.54e47s^5+7.836e50s^4+3.402e53s^3}$$

Linear System Analysis BP1









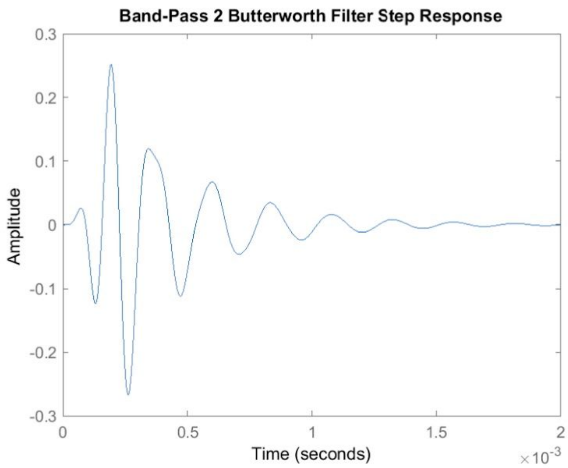
Band-Pass Filter 2:

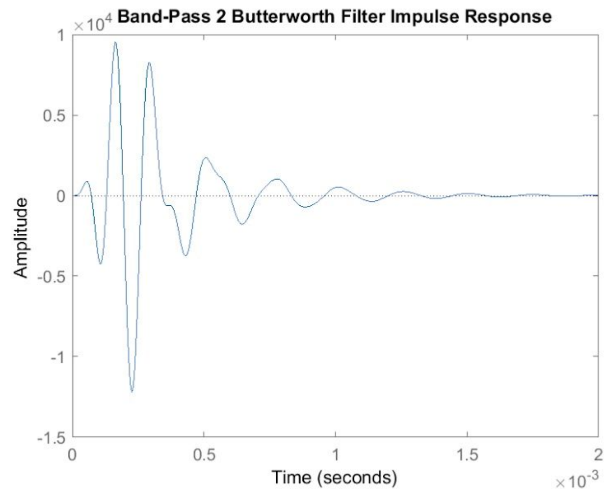
Using the transfer function calculated earlier,

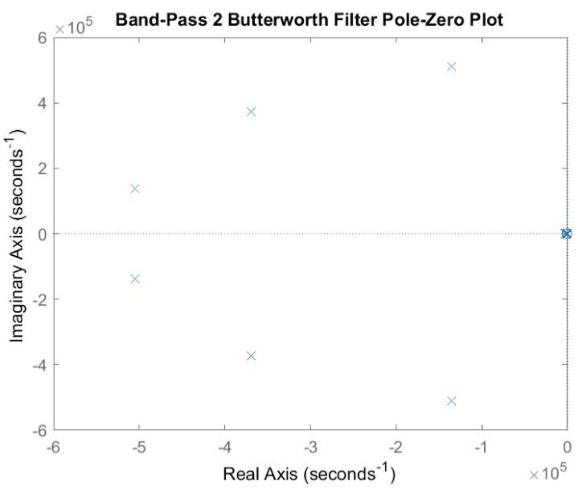
$$H_{BP1}(s) = \frac{2.555e41s^9}{9.842e13s^{15}+1.41e19s^{14}+1.949e24s^{13}+1.58e29s^{12}+1.155e34s^{11}+6.022e38s^{10}}$$

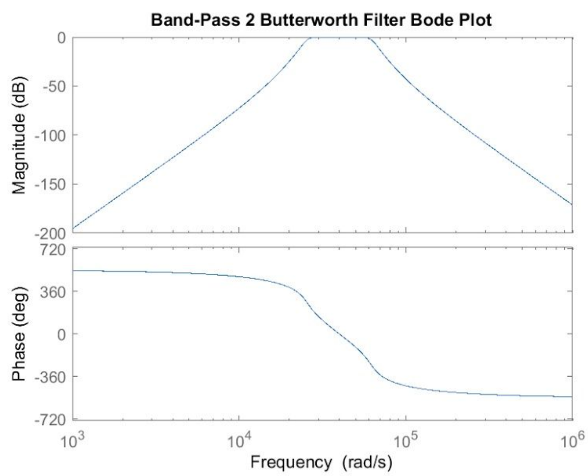
$$\overline{2.793e43s^9+9.58e47s^8+2.923e52s^7+6.361e56s^6+1.248e61s^5+1.437e65s^4+1.596e69s^3}$$

Linear System Analysis BP2







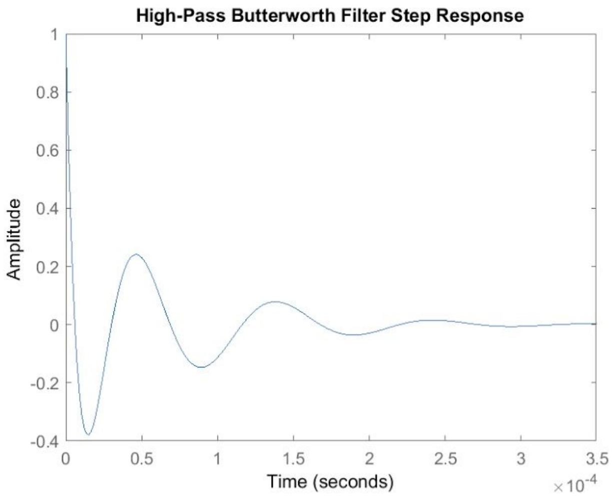


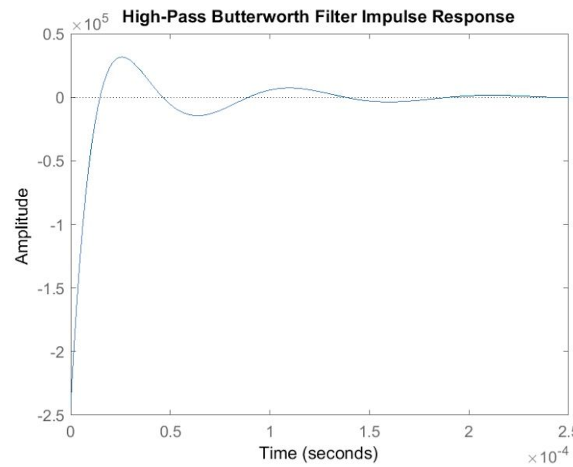
High-Pass Filter:

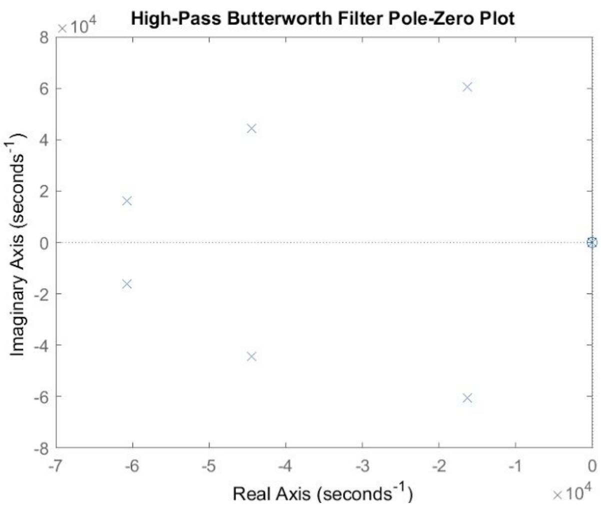
Using the transfer function calculated earlier,

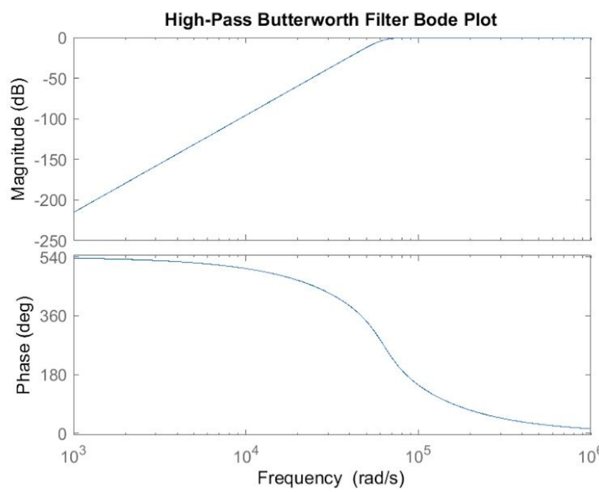
$$H_{HP}(s) = \frac{s^9}{s^9{+}2.428e05s^8{+}2.947e10s^7{+}2.268e15s^6{+}1.163e20s^5{+}3.784e24s^4{+}6.153e28s^3}$$

Linear System Analysis HP





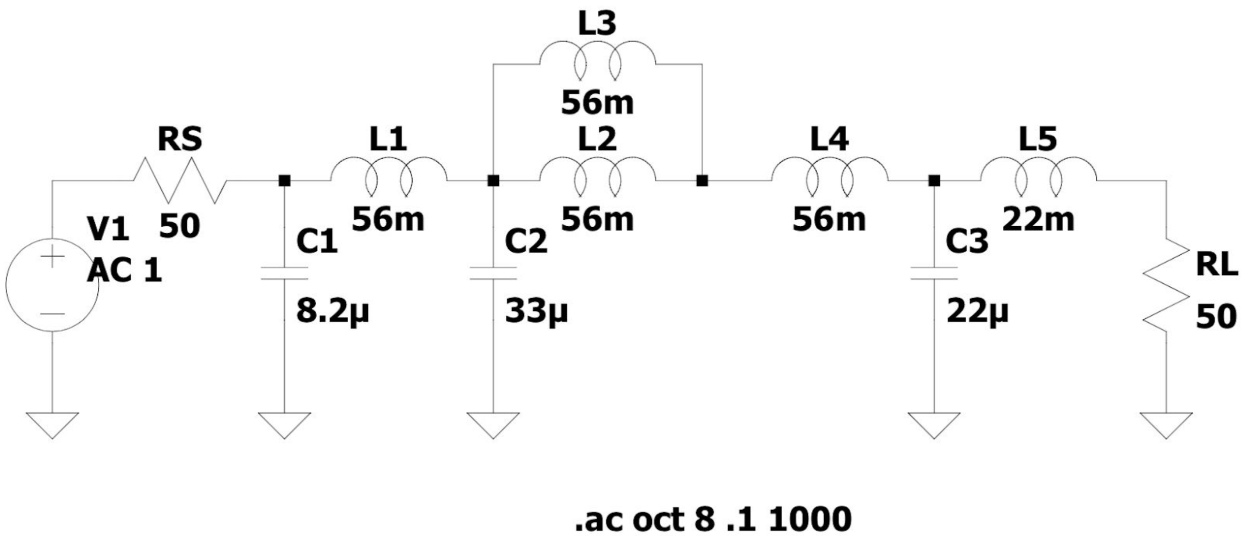




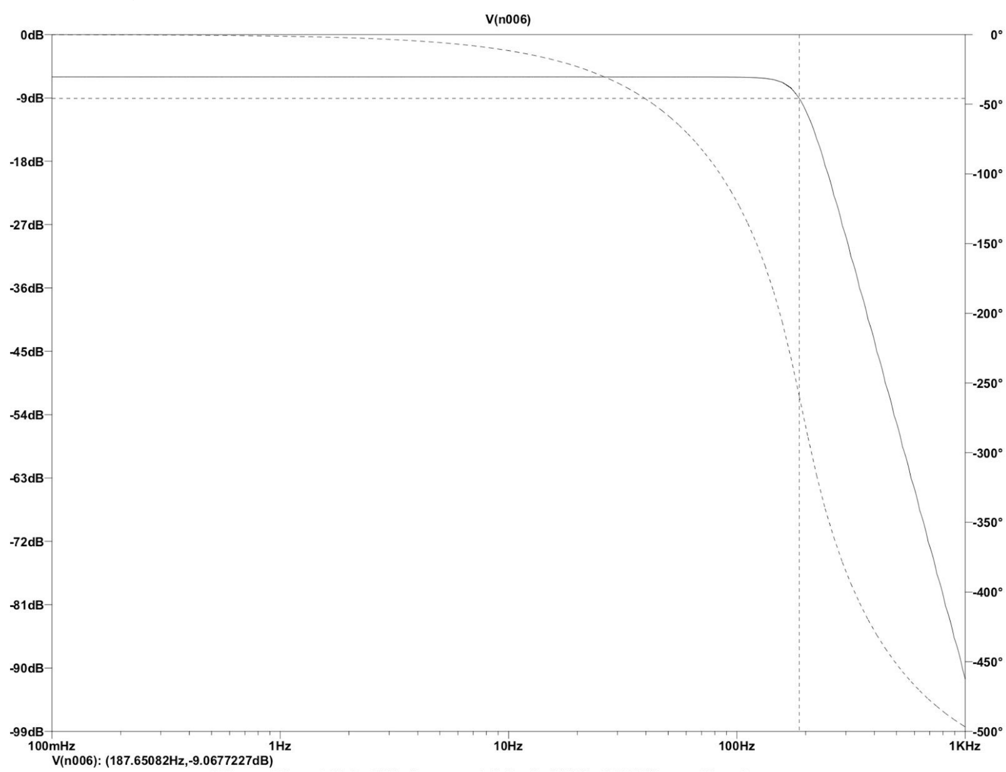
LTSpice Results:

Low-Pass Filter

Using the following real component values from the filter calculations the following low-pass filter was simulated in LTspice,

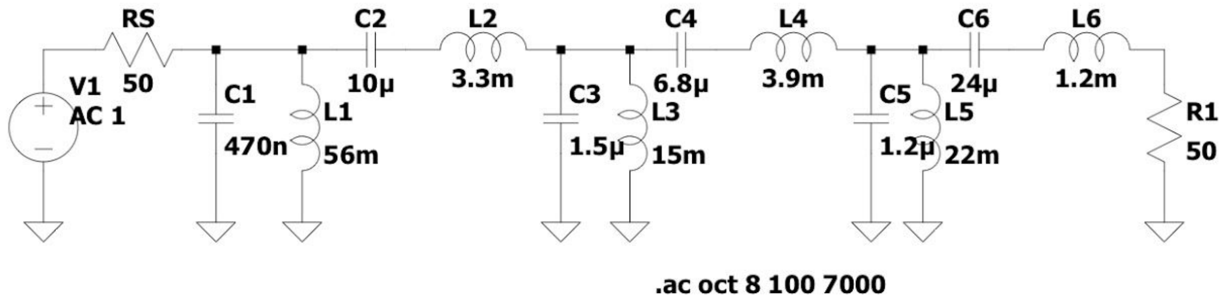


The filter produced the following Bode Plot with a -3dB, half power point, at 187.2 Hz which has a 6.6% difference to the original set cutoff frequency of 200 Hz. The frequency response plot can be seen below,

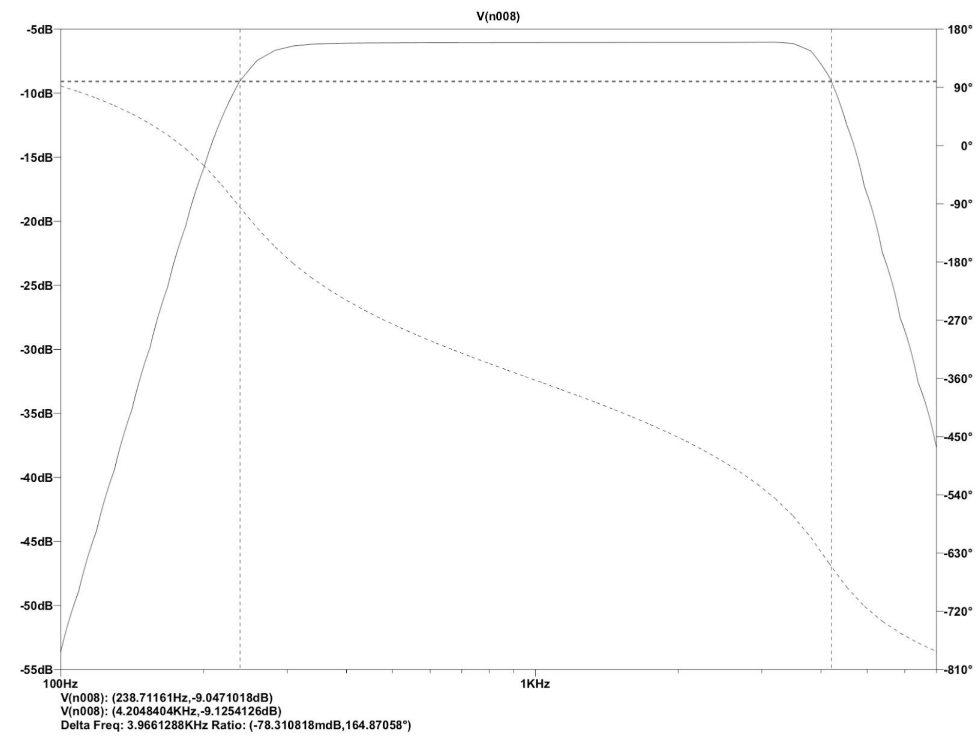


Band-Pass 1 Filter

Using the following real component values from the filter calculations, the following band-pass filter was simulated in LTspice,

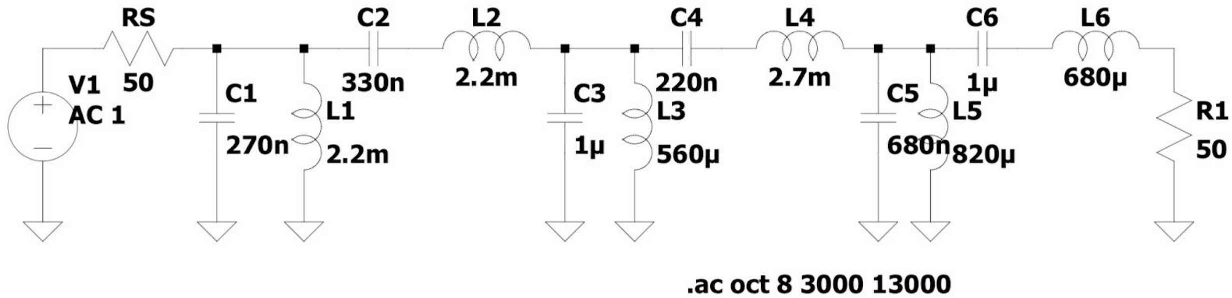


The filter produced the following Bode Plot with two -3dB, half power points, at 238.7 - 4204.8 Hz, which has a 4.63% and 4.99% difference respectively to the original set pass band of 250 - 4000 Hz. The frequency response plot can be seen below,

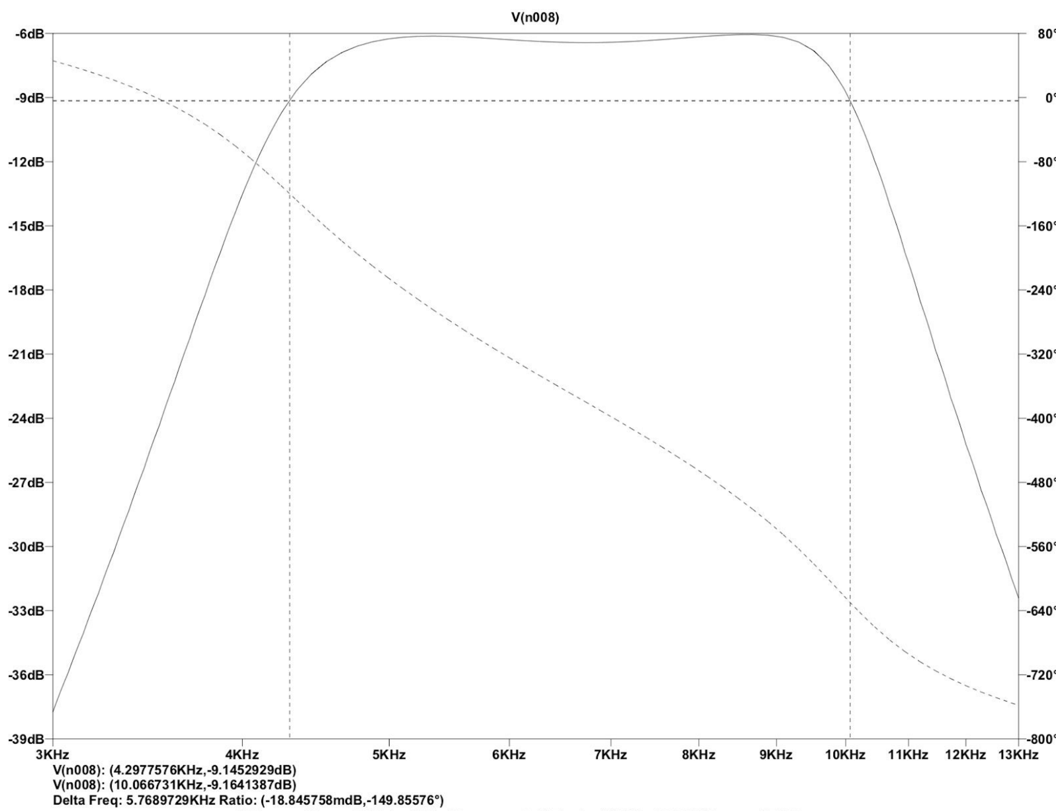


Band-Pass 2 Filter

Using the following real component values from the filter calculations, the following band-pass filter was simulated in LTspice,

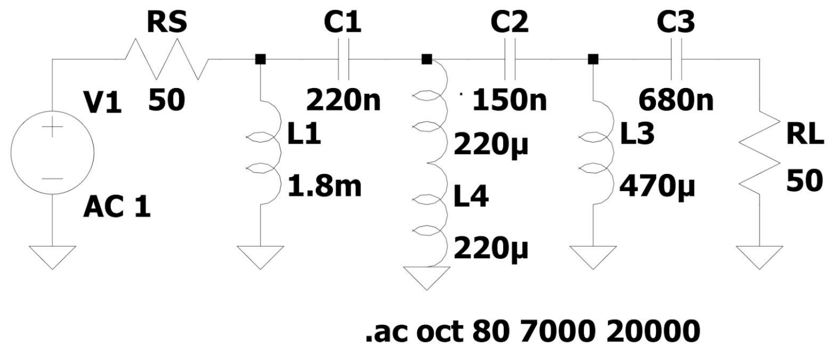


The filter produced the following Bode Plot with two -3dB, half power points, at 4287 - 10104 Hz, which has a 5.69% and 1.54% difference respectively to the original set pass band of 4050 - 9950 Hz. The frequency response plot can be seen below,

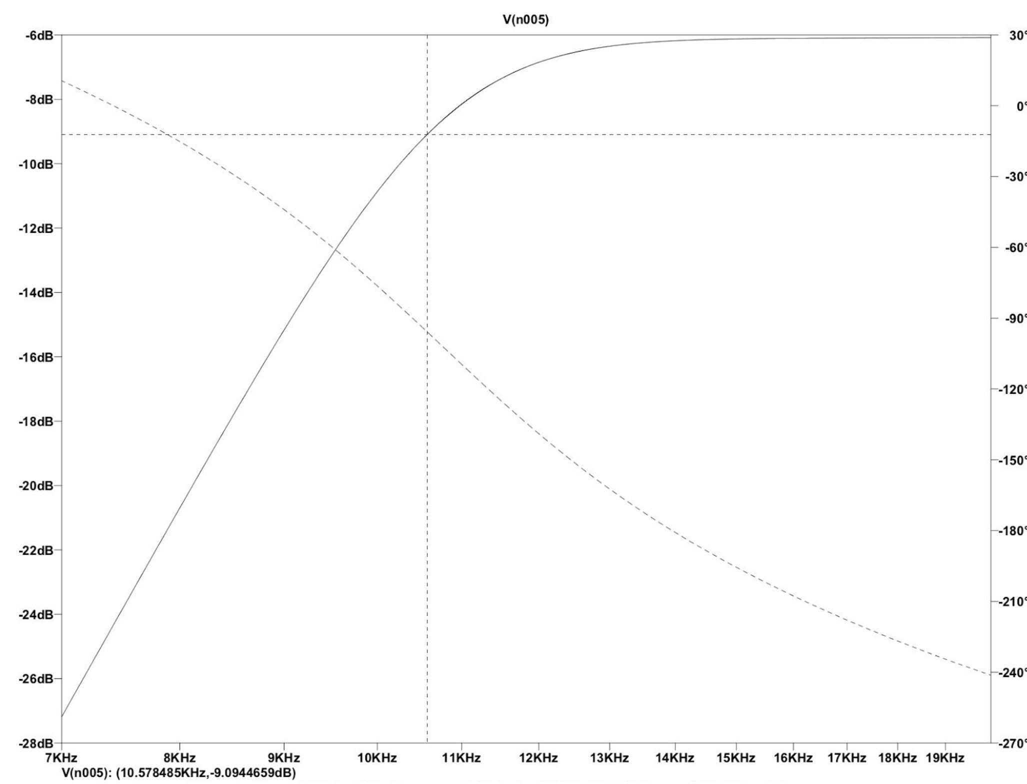


High-Pass Filter

Using the following real component values from the filter calculations, the following high-pass filter was simulated in LTspice,

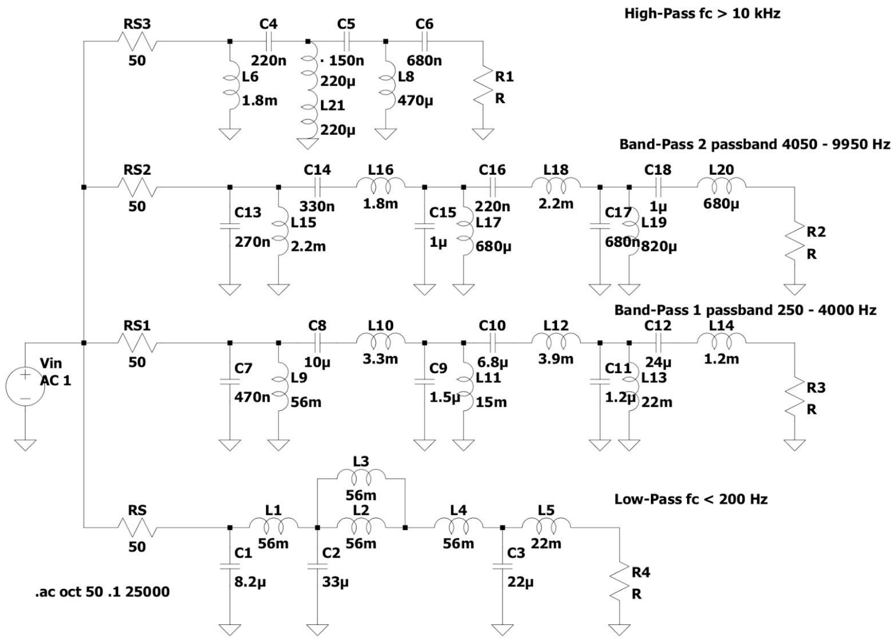


The filter produced the following Bode Plot with a -3dB, half power point, at 10578.48 Hz, which has a 5.6% difference to the original set cutoff frequency of 10000 Hz. The frequency response plot can be seen below,

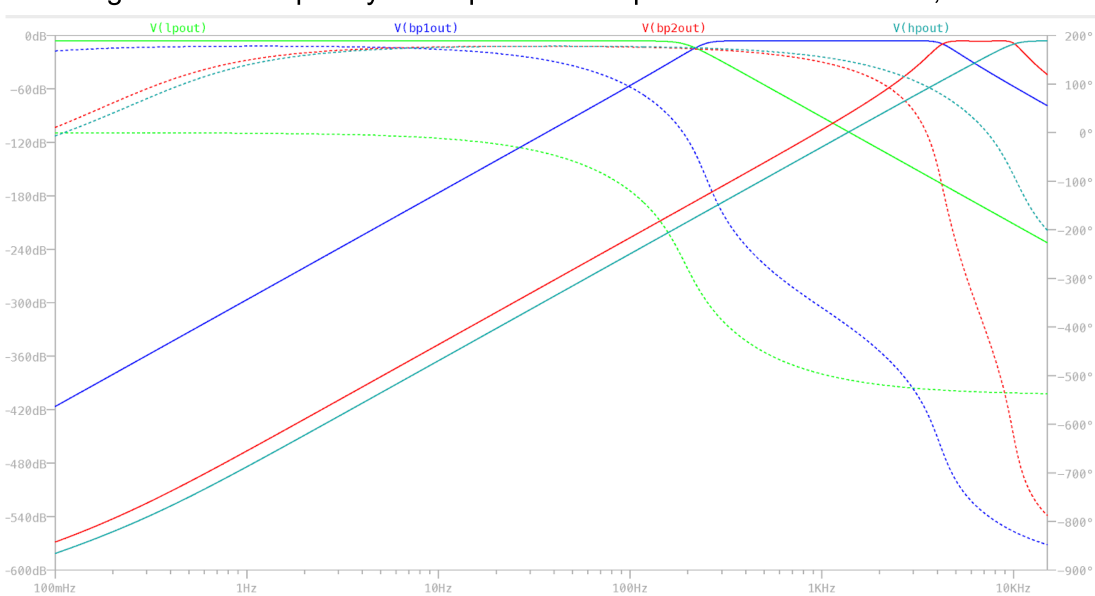


All Filter Branches with Amplification

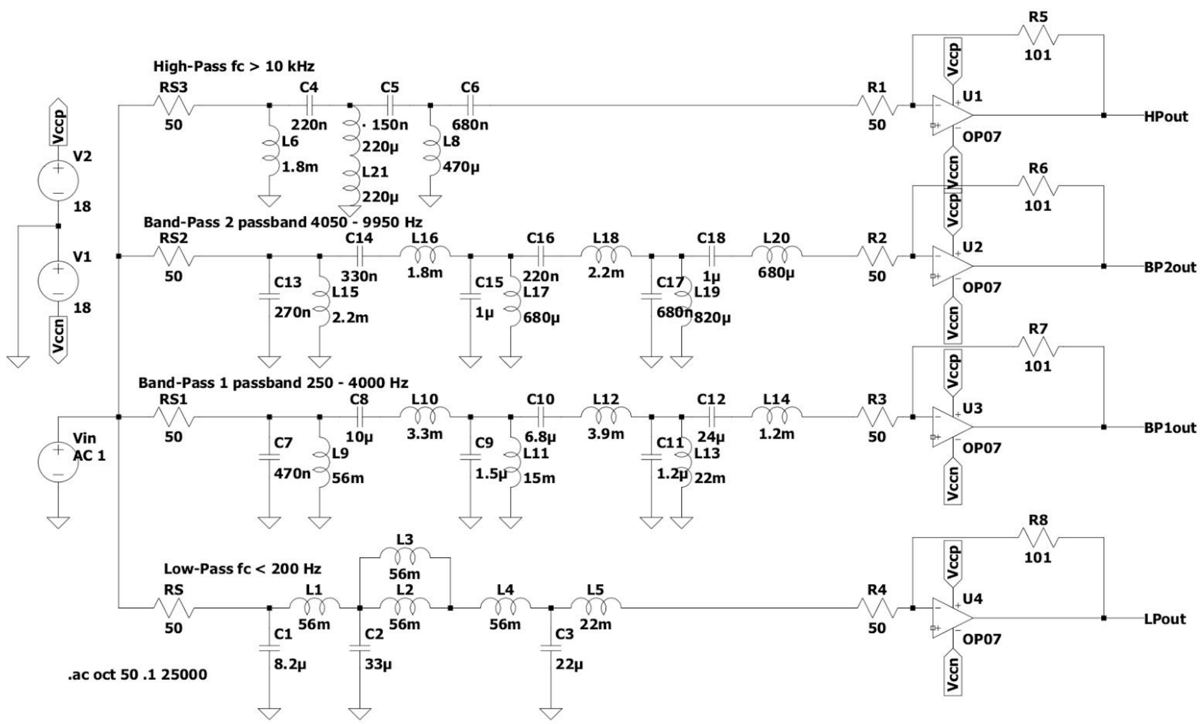
Using each of the filter designs and real component values, the full filter branch design is seen below,

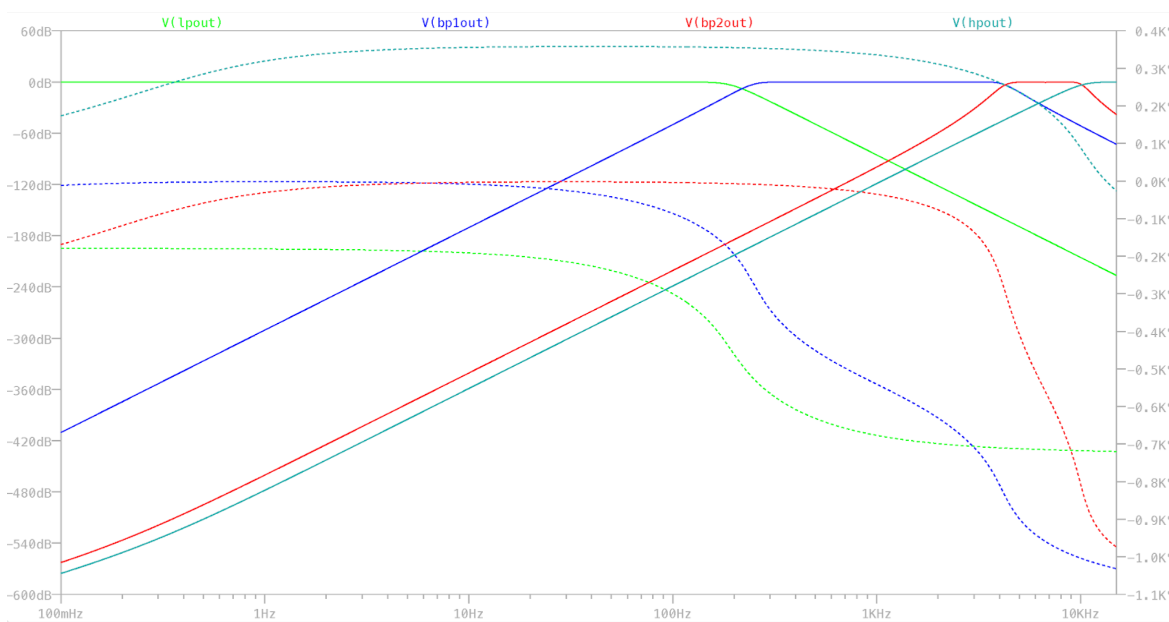


The bode plot of each voltage output qualitatively and numerically covers the full range of human hearing with little frequency overlap. The bode plot can be seen below,



All four filter branches peak around -6.02dB without gain. To mitigate this, the op amps following each filter branch must have a minimum gain of 2 to bring the peaks to around 0dB. Adding in some basic op amps into the simulation with a gain of 2 raises the peaks of each filter branch as seen in the diagram and frequency response plot as follows,





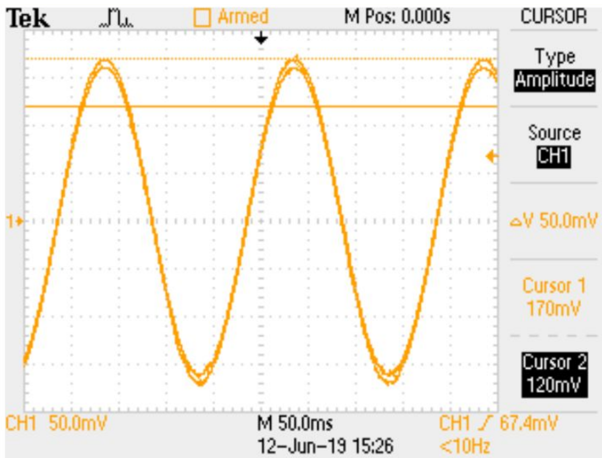
With a gain of at least two, the filter outputs will be about 0dB, the gain on the op amps will be controlled by using a potentiometer as the feedback resistor. However, given that the op amps will send the filtered signal to an LM3915, which has a range of 0 - 90 dB, there must be a maximum gain. One benefit of using the op amps with the LM3915 is that the op amp will never output a signal greater than 60 dB since the op amp will have a maximum gain of 200.

Test results:

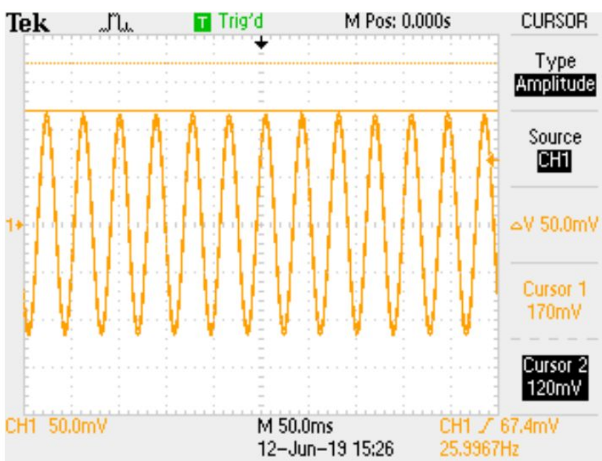
The frequency response of each filter will be between 0 Hz to 20 KHz, across the range of average human hearing. The filter PCB output is tested using the standard setup with a Function Generator and an Oscilloscope. The function generator is set to the unity frequency with an amplitude of 1V.

Low-Pass Filter Results

The low-pass filter unity was found at 10 Hz with an amplitude of 170mV. The half-power point was found to be at $170\ mV * \frac{1}{\sqrt{2}} = 120.21\ mV$. The low-pass filter has a cutoff frequency of 26.0 Hz. Which is 153.98% different from the set cutoff frequency of 200 Hz.



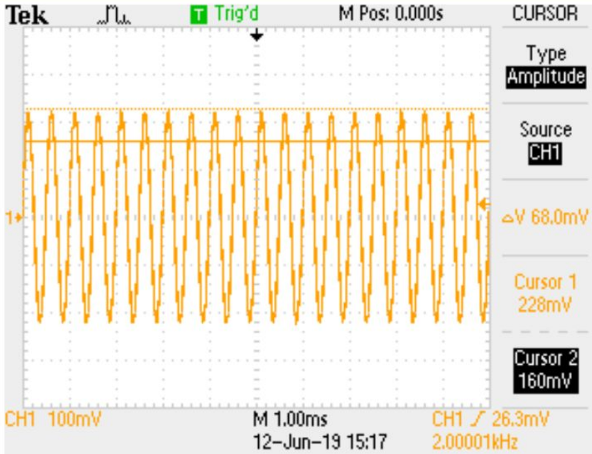
Low-Pass Filter Output Frequency Response, Unity



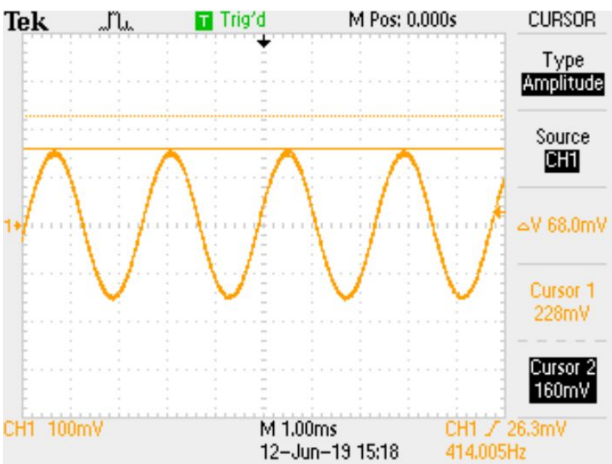
Low-Pass Filter Output Frequency Response, Cutoff

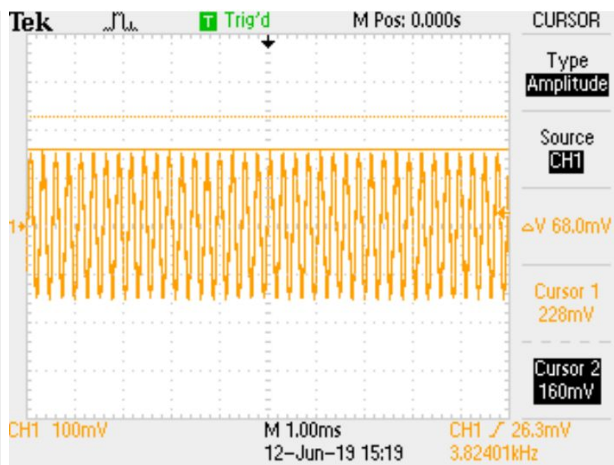
Band-Pass 1 Filter Results

The band-pass 1 filter unity was found at 2 kHz with an amplitude of 228 mV. The half-power point was found to be at $228\ mV * \frac{1}{\sqrt{2}} = 161.22\ mV$. The first band-pass filter was found to have a cutoff frequency of 414 Hz - 3.824 kHz. Which is 69.71% and 4.499% different from the set cutoff frequency of 250 - 4000 Hz.



Band-Pass 2 Filter Frequency Response, Unity

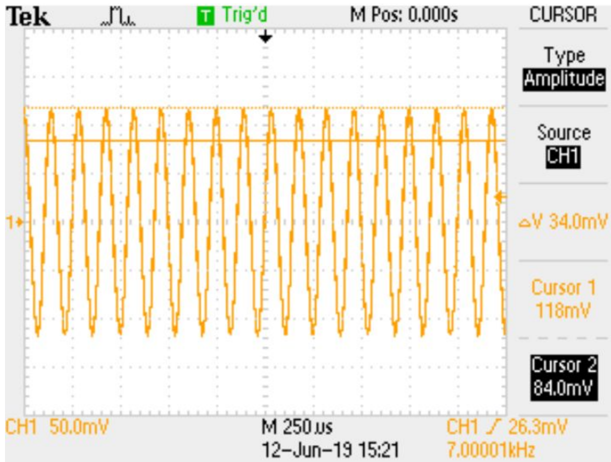




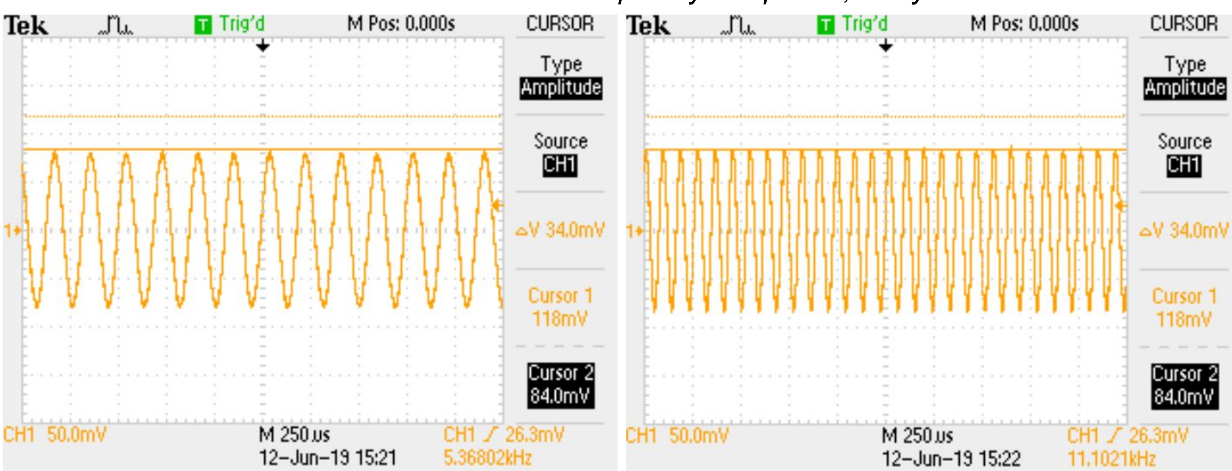
Band-Pass 1 Filter Output Frequency Response, Low Cutoff (Left) and High Cutoff (Right)

Band-Pass 2 Filter Results

The band-pass 2 filter unity was found at 7 kHz with an amplitude of 118 mV. The half-power point was found to be at $118\ mV * \frac{1}{\sqrt{2}} = 83.44\ mV$. The second band-pass filter was found to have a cutoff frequency of 5.368 - 11.102 kHz. Which is 27.99% and 10.94% different from the set cutoff frequency of 4050 - 9950 Hz.



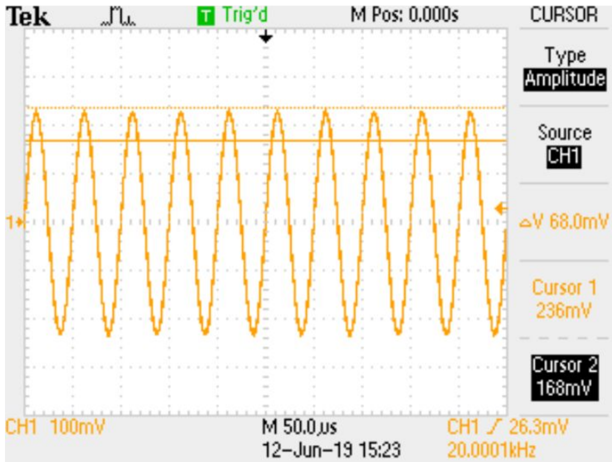
Band-Pass 2 Filter Frequency Response, Unity



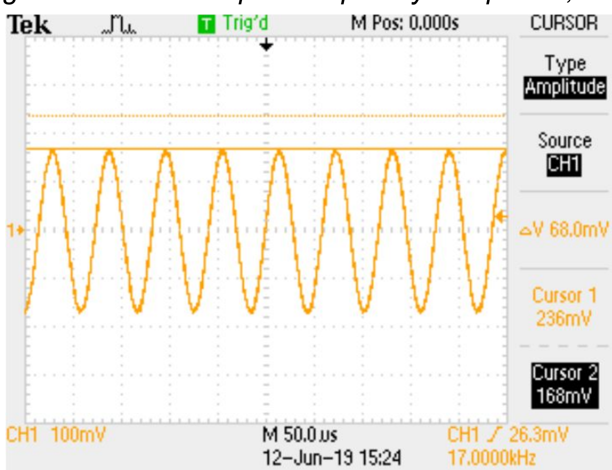
Band-Pass 2 Filter Frequency Response, Low Cutoff (Left) and High Cutoff (Right)

High-Pass Filter Results

The high-pass filter unity was found at 20 kHz with an amplitude of 236 mV. The half-power point was found to be at $236\,mV * \frac{1}{\sqrt{2}} = 166.88\,mV$. The high-pass filter was found to have a cutoff frequency of 17 kHz. Which is 51.85% different from the set cutoff frequency of 10000 Hz.



High-Pass Filter Output Frequency Response, Unity

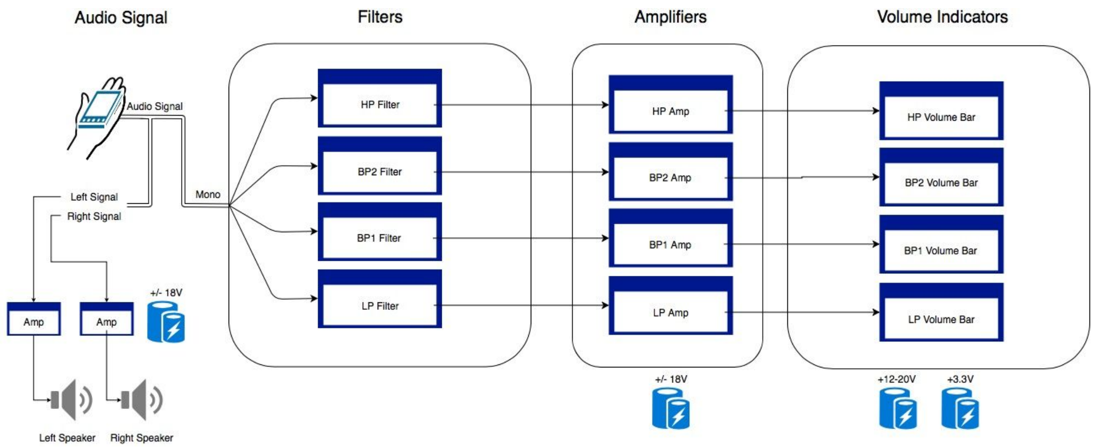


High-Pass Filter Output Frequency Response, Cutoff

Circuit Design & Layout:

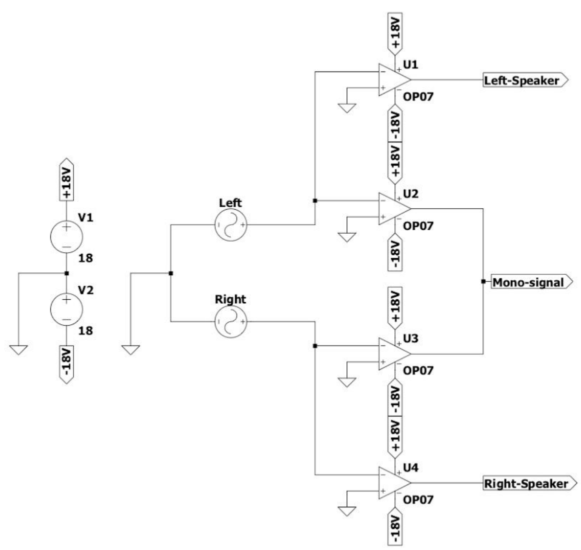
Circuit Diagram

The function of this circuit is to filter an audio signal and indicate, by light, the filtered frequency presence. The audio signal is filtered through four branches, each filter branch has its own adjustable volume/LED indicator which is activated when a signal passes through the filter branch. Below is the block diagram[17] for the circuit design,



Audio Design Summary

The audio is split into a stereo (binaural) and a mono (mixed) branch. The audio system design ensures that the music played over the speakers is kept separate as left and right audio channels and the filtered signal contains all the audio data. The audio data splits are made using NE5532 op amps used as buffers.

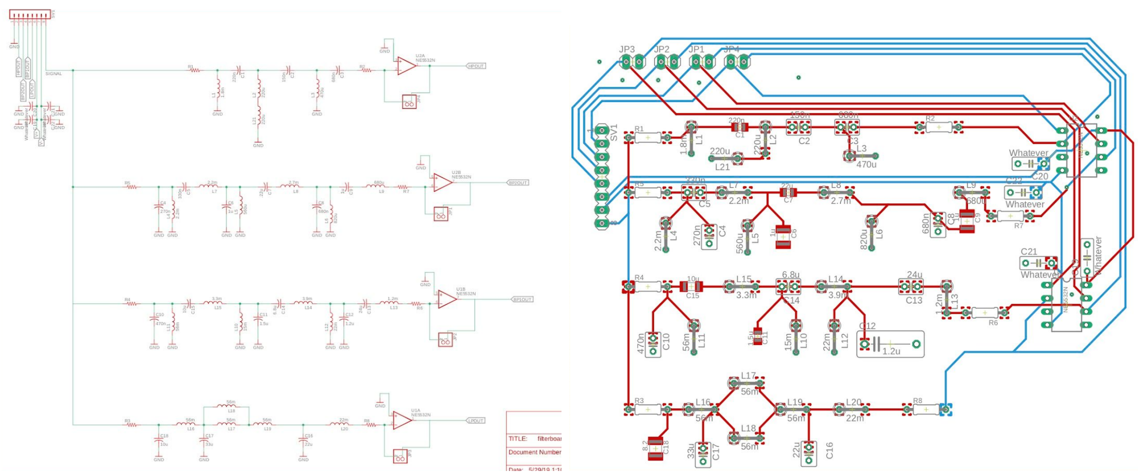


Audio System Diagram

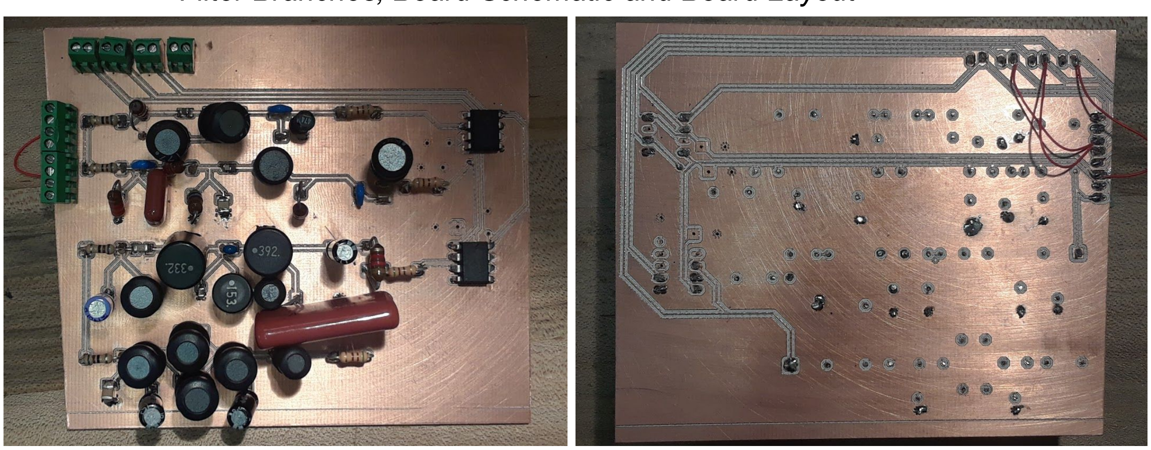
[17] See Reference 4: Flowchart Maker

Filter Design Summary

There are four filters used in this circuit, one low-pass, one high pass, and two band-pass. All four filters are 6th order passive Butterworth equal termination filters. The low-pass filter has a set cutoff frequency of 200 Hz, the first band-pass filter has a set pass band between 250 Hz to 4 kHz, the second band-pass filter has a set pass band between 4.05 kHz to 9.95 kHz, and the high-pass filter has a set frequency cutoff of 10 kHz. At the output of each filter there is an operational amplifier with an adjustable gain (using a potentiometer). Per the LTspice simulations, the gain for this op amp should indicate no filter signal output to a maximum gain of 200. With the real component values, all four filter branches have less than a 7% difference from the set cutoff frequencies. These circuits were routed and assembled on a PCB[18].



Filter Branches, Board Schematic and Board Layout[19]

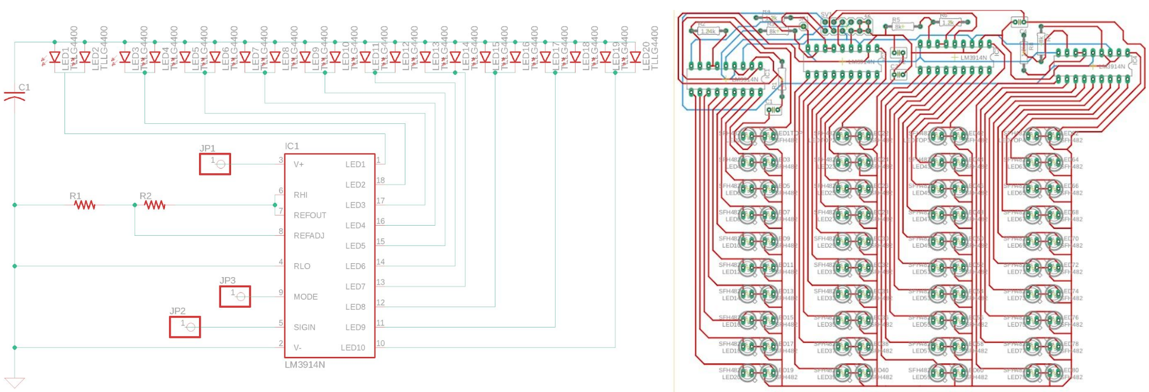


Filter Branches PBC, Front and Back

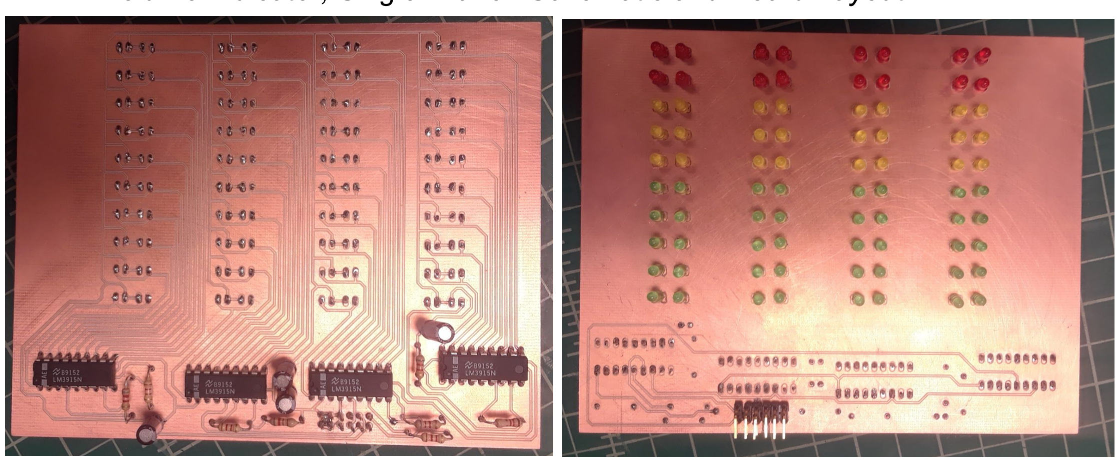
[18] Using EAGLE 9.3.2 and A406
[19] See Appendix, Figures 1 and 2 for Full Images

Volume Meter Design

At the end of each filter branch is a LED volume indicator circuit. These circuits contain a series of LEDs and an LM3915[20] (resistor and comparator network). This circuit is used to indicate when an audio signal satisfies the filter frequencies and passes through that branch; the LM3915 is used to indicate the intensity (i.e. volume) of the signal. These circuits will have the display of two rows of 5 green, 3 yellow, and 2 red LEDs, totalling 20 LEDs per branch. There are four volume indicators, each receiving an amplified signal from a filter. The intensity of each volume indicator is controllable via a potentiometer controlling the gainstage on its respective filter. These circuits were routed and mounted on a custom designed PCB.



Volume Indicator, Single Branch Schematic and Board Layout[21]



Volume Indicator PCB, Back and Front

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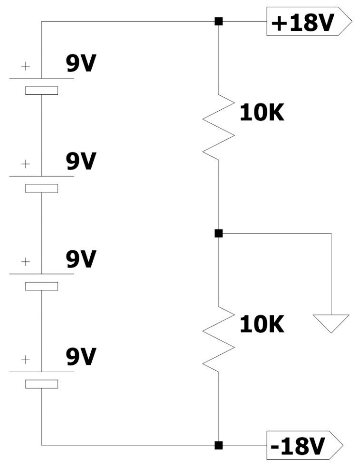
[20] See Reference 5: LM3915 Datasheet

[21] See Appendix, Figures 3 and 4 for Full Images

Power System Design

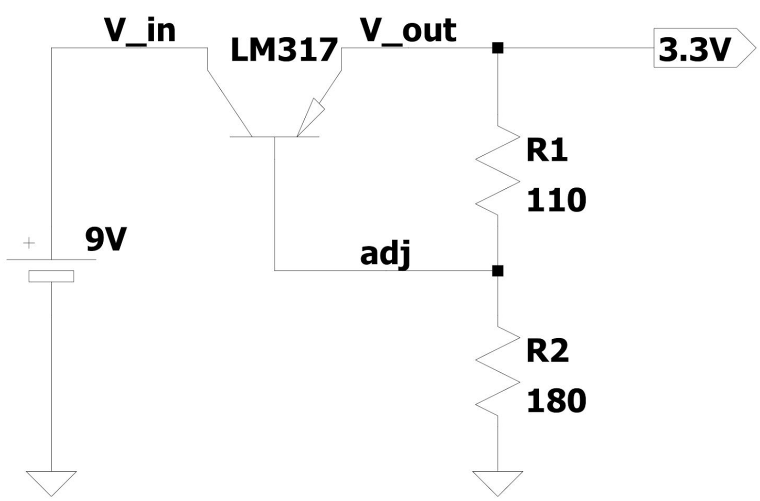
This project has several NE5532 op amps that need +18V and -18V, four LM3915s that need 12-20V, and four LED circuits which need 3-5V. To satisfy the power requirements the project uses a total of seven 9V batteries. These seven batteries are split between three battery packs with a common ground.

The first battery pack powers all the op amp rails, it is four 9V batteries in series with a voltage divider to define a common ground and supply the +18V and -18V, see below.



36V Voltage Divider Circuit

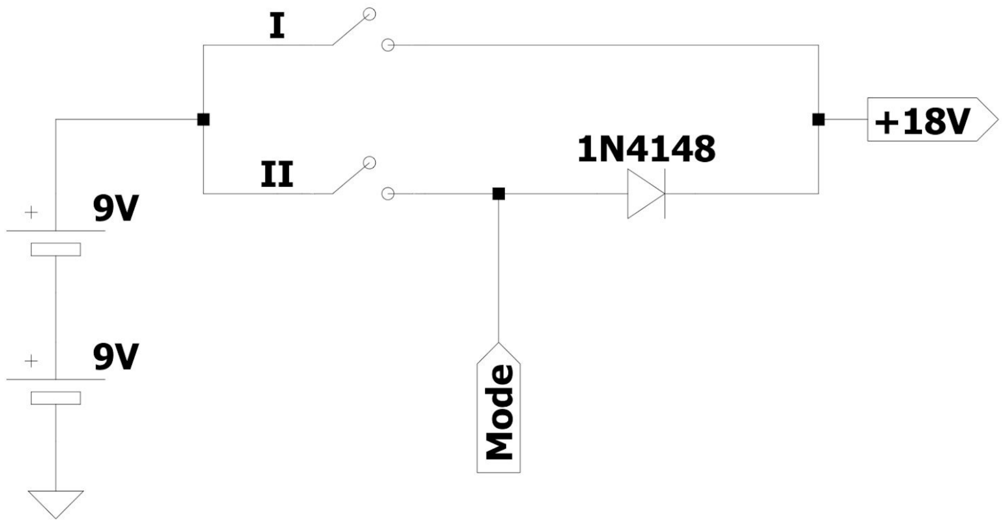
The third battery pack powers the LEDs in the volume indicator circuit by using a single 9V and an LM317 voltage regulator to supply 3.3V. The equation[22] used to calculate the V_{out} value of the LM317 is $V_{out} = 1.25 * (1 + \frac{R_2}{R_1})$. The resistor values were calculated using the prior equation where $R_1 = 110\Omega$ and $R_2 = 180\Omega$.



3.3V Voltage Regulator Circuit

[22] See Reference 6: LM317 Datasheet

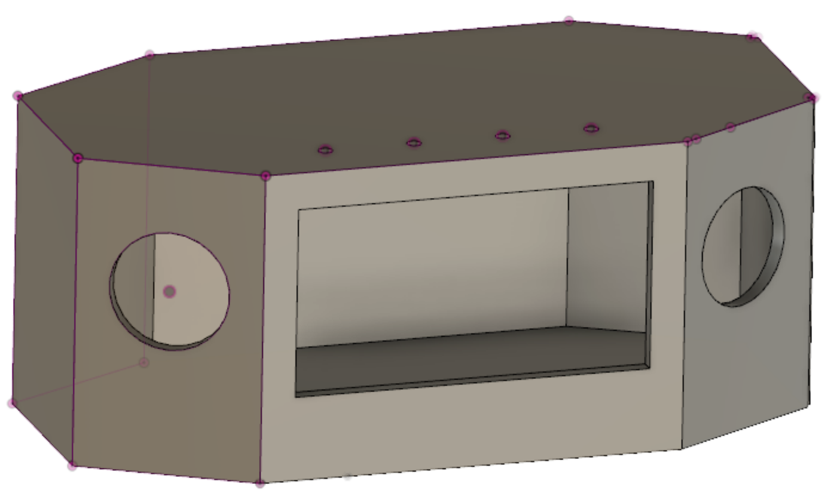
The second battery pack powers the volume indicator circuit main power and contains two 9V batteries in series to supply +18V. There is also a power switch mounted to the housing that is placed within this circuit. The power switch has three states, I, Off, and II. There is a diode, 1N4148, which prevents the mode from being triggered when I is selected and allows the mode to be changed when selecting II, see below.



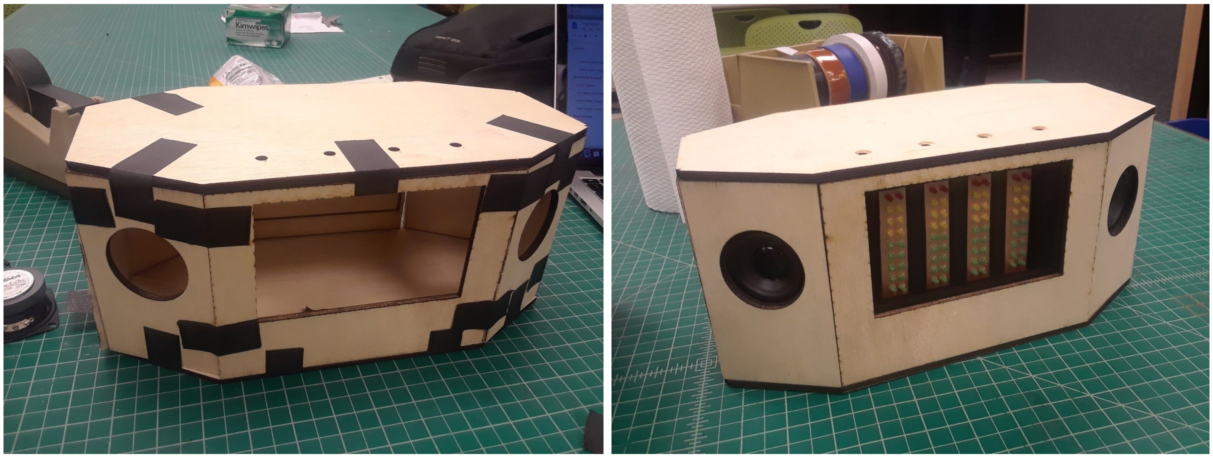
18V Power Switch Circuit

Housing Design

This project is housed within a pressed wood frame. The housing was designed using AutoDesk Fusion360 where each side was exported to .dxf file type. These files were then imported to RDWorks and then cut using a QD-1390 laser cutter. The 45° chamfers were then cut using a scroll saw.



CAD Housing Model



Project Housing, Progressing Stages

The housing joint corners are bonded together with wood glue while components, speaker, PCBs, potentiometers, etc. are mounted with screws. There is a power switch on the back which allows the system to be turned on and shut off safely and allows the user to change the volume indicator display between bar and dot mode. The aux cable is fed through a hole in the back of the housing with a cable mount for convenience. There is a hinged door on the back of the housing which allows the project systems to be easily accessed by the user for maintenance and/or troubleshooting. The pressed wood is sanded, stained, and the joints are patched with wood filler for a smooth finish.

Discussion

Adjusting the simulator for real component values rather than ideal calculated values. Comparing theoretical transfer function (matlab) to simulated circuit (LTspice) with real component values, and finally physical circuit results; variance/standard deviation/real transfer functions.

Summary of Simulation Results		
Low Pass	Set f_c Hz	200 Hz (1256.64 rad/s)
	Matlab f_c Hz	198.9 Hz (1.25 e03 rad/s)
	LTspice f_c Hz	187.214 Hz (1176.3 rad/s)
	Test f_c Hz	26 Hz (169.6 rad/s)
BP1	Set f_c Hz	250 Hz - 4000 Hz (1571 - 25132.7 rad/s)
	Matlab f_c Hz	249.9 - 3995 Hz (1.57e03 - 2.51e04 rad/s)
	LTspice f_c Hz	238.7 - 4204.8 Hz (1499.8 - 26420 rad/s)
	Test f_c Hz	414 - 3824 Hz (2601 - 24027 rad/s)
BP2	Set f_c Hz	4050 - 9950 Hz (25447 - 62517.7 rad/s)
	Matlab f_c Hz	4058 - 9947 Hz (2.55e04 - 6.25e04 rad/s)
	LTspice f_c Hz	4287 - 10104 Hz (26936 - 63485 rad/s)
	Test f_c Hz	5368 - 11102 Hz (33728 - 69756 rad/s)
HP	Set f_c Hz	10000 Hz (62831.85 rad/s)
	Matlab f_c Hz	10027 Hz (6.3e04 rad/s)
	LTspice f_c Hz	10578.48 Hz (66466.6 rad/s)
	Test f_c Hz	17000 Hz (106814 rad/s)

These four circuits have between a 4% - 153.98% difference from the original set cutoff frequencies and the test cutoff frequencies,

Percent Difference Between Set f_c & Test f_c							
Low Pass		Band-Pass 1		Band-Pass 2		High-Pass	
Set f_c & Test f_c	153.98 %	Set f_c & Test f_c	69.71 & 4.5 %	Set f_c & Test f_c	27.99 & 10.94 %	Set f_c & Test f_c	51.85%

And between 9 - 152% difference from the LTspice simulations and the test cutoff frequencies,

Percent Difference Between LTspice f_c & Test f_c							
Low Pass		Band-Pass 1		Band-Pass 2		High-Pass	
LTspice f_c & Test	151.2%	LTspice f_c & Test	53.7 & 9.49%	LTspice f_c & Test	22.39 & 9.41%	LTspice f_c & Test	46.57%

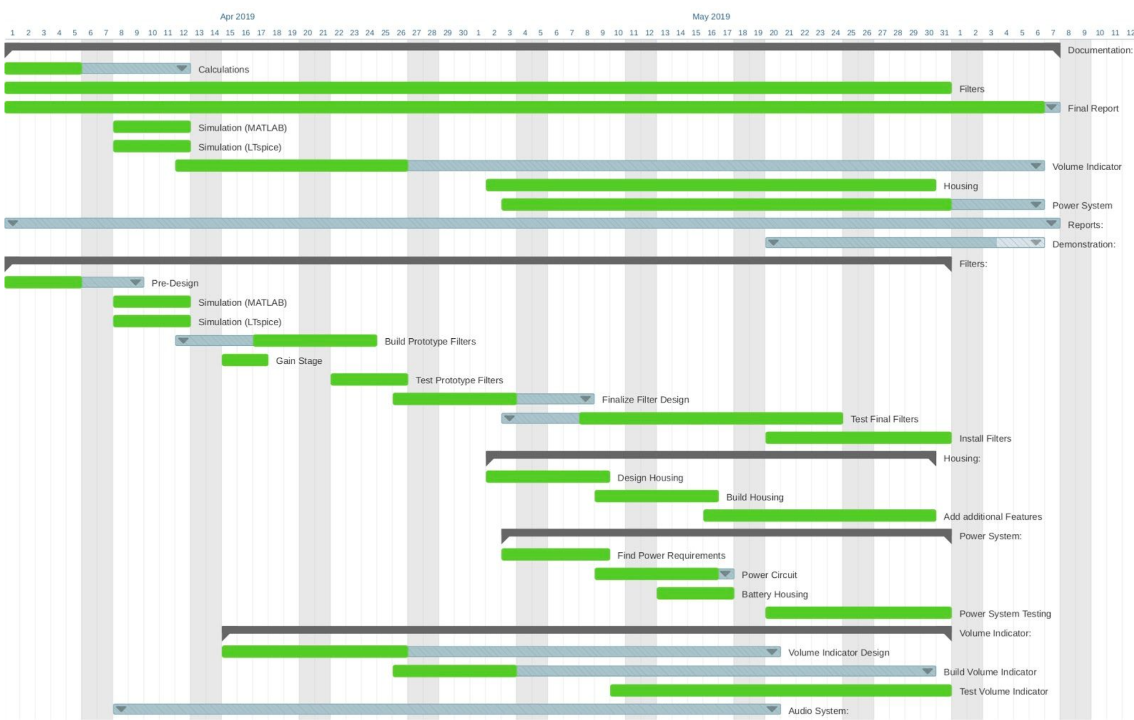
f_c		f_c		f_c		f_c	

The low pass filter was the least accurate of all four filters. The band-pass and high-pass filters were fairly accurate. In a redesign of the project, the low-pass filter would be made to a higher order than the other filter branches to improve the accuracy.

This design requires several components; not including prototyping costs, the manufacturing and production cost of one system is $100.09. The total cost of this project, including components, tool fees, prototypes, and the shipping was $202.08[23]. The final product is aesthetically pleasing and robust. Each circuit board is mounted securely to the housing to ensure safe transport and little to no maintenance. Once future improvements are made to the project, the design can be streamlined and made more consumer friendly. With the growing market in DIY electrical build kits[24], this project has the potential to be marketed as such with as much as a 2x mark-up in price with coherent instructions made available to the consumer.

Teamwork

The team attempted to split the work as evenly as possible. David performed the LTSpice simulations, parts sourcing, and filter board design. Jennifer performed the Matlab simulations, transfer function calculations, LED board design, and housing design/construction. Both team members performed power system design, audio system design, testing, and assembled the PCBs. See appendix for a full gantt chart breakdown[25].



23 See Appendix Management 1: Budget
24 See Reference 7: Forbes Article
25 See Appendix Management 2: Full Gantt Chart

Project Gantt Chart, Main Tasks[26]

Conclusion

When first designing the filter branches, the team was unaware that the 6th order butterworth filters would produce an average 37% accuracy (excluding the low-pass filter). With more time, the team would redesign the project with several additional filter branches containing more bands within the 300 - 4 kHz frequency range. These additional filters would demonstrate the wider range of frequencies present in most music. The team would also pay more attention to the low-pass filter by designing it at a higher order to improve the accuracy. The design of the filters could also be changed to all surface mount devices instead of the current design which contains both through-hole and surface mount. Using a full SMD design, the size and assembly time of the filter board would be greatly reduced

The power system was originally using a single pack of four 9V batteries. During testing we found that these four batteries were not able to supply enough current. The revised design added two additional batteries in parallel with the +18 V rail, to increase the current capacity. Despite this being a more elegant solution, the team decided that simply separating the power systems for the LEDs, and the filter board was the safer option, as there was no time to order replacements parts if any part of the project was overloaded. With additional time, the team would redesign the power system to run of lithium polymer batteries, because of their greater current density, greater discharge rate, and rechargeability

Overall this project, cemented the ideas of filter design for both team members, as well as reinforcing the importance of proper planning in an ambitious project. There was minimal hardware troubleshooting upon system integration, which is the opposite of team member's past experiences. The team attributes this to our in-depth simulations and calculations before we began constructing the hardware. The team also did multiple prototype iterations before final integrations. The project was rewarding for each team member as it was a way to get the hands-on experience necessary to fully gain a conceptual understanding of the material.

[26] See Reference 7: Instagantt/Asana

Appendix:

Relevant Tables:

Table 1:

Butterworth equal termination Low-Pass Prototype Element chart					
C_1	L_2	C_3	L_4	C_5	L_6
0.518	1.414	1.932	1.932	1.414	0.518

Table 2:

Butterworth equal termination Band-Pass Prototype Element chart											
L_1	C_1	L_2	C_2	L_3	C_3	L_4	C_4	L_5	C_5	L_6	C_6
1.93	0.518	1.414	0.707	0.518	1.932	1.932	0.518	0.707	1.414	0.518	1.932

Table 3:

Butterworth equal termination High-Pass Prototype Element chart					
L_1	C_2	L_3	C_4	L_5	C_6
1.93	0.707	0.518	0.518	0.707	1.93

Table 4:[27]

n	Factors of Butterworth Polynomial $B_n(s)$
1	$(s+1)$
2	$(s^2+1.414s+1)$
3	$(s+1)(s^2+s+1)$
4	$(s^2+0.765s+1)(s^2+1.848s+1)$
5	$(s+1)(s^2+0.618s+1)(s^2+1.618s+1)$
6	$(s^2+0.518s+1)(s^2+1.414s+1)(s^2+1.932s+1)$
7	$(s+1)(s^2+0.445s+1)(s^2+1.247s+1)(s^2+1.802s+1)$

[27] See Reference 9: Electric Circuits

8	$(s^2+0.390s+1)(s^2+1.111s+1)(s^2+1.6663s+1)(s^2+1.962s+1)$

Relevant Equations:

1. Butterworth equal termination Low-Pass filter Prototype Values
   a. Inductor values: $L = \frac{R_L L_n}{f_c 2\pi}$ (H)
   b. Capacitor values: $C = \frac{C_n}{f_c 2\pi R_L}$ (F)
2. Butterworth equal termination Band-Pass Prototype Values
   a. $\omega_0 = \sqrt{\omega_1 \omega_2}$; where ω_2 is the high cutoff and ω_1 is the low cutoff
   b. $\Delta = \frac{\omega_2 - \omega_1}{\omega_0}$
   c. $\omega_0 = f_c 2\pi$
   d. Inductor values when $n = odd$: $L = \frac{L_{n,odd} \Delta R_L}{f_c 2\pi}$ (H)
   e. Inductor values when $n = even$: $L = \frac{L_{n,even} R_L}{\Delta f_c 2\pi}$ (H)
   f. Capacitor values when $n = odd$: $C = \frac{C_{n,odd}}{R_L \Delta f_c 2\pi}$ (F)
   g. Capacitor values when $n = even$: $C = \frac{C_{n,even} \Delta}{f_c 2\pi R_L}$ (F)
3. Butterworth equal termination High-Pass filter Prototype Values
   a. Inductor values: $C = \frac{C_n}{f_c 2\pi R_L}$ (F)
   b. Capacitor values: $L = \frac{R_L L_n}{f_c 2\pi}$ (H)
4. Butterworth Low-Pass to High-Pass Transfer Function $s \rightarrow (\frac{\omega_c}{s})$
5. Butterworth Low-Pass to Band-Pass Transfer Function $s \rightarrow Q(\frac{s}{\omega_0} + \frac{\omega_0}{s})$

MATLAB Code (Analysis & Simulation Results):

```
%Transfer Function Analysis for Low-Pass 6th Order Butterworth Filter
%ECE223 Sp19, Jennifer Jordan & David Lay
s = tf('s');
H = 1/
(2.53636*10^-19*s^6+1.23201*10^-15*s^5+2.99159*10^-12*s^4+4.60529*10^-9*s^3+4.7260
+1)
%Figures:
figure(1);
bode(H);
title('Low-Pass Butterworth Filter Bode Plot');
figure(2);
impulse(H);
title('Low-Pass Butterworth Filter Impulse Response');
figure(3);
step(H);
title('Low-Pass Butterworth Filter Step Response');
figure(4);
pzplot(H);
title('Low-Pass Butterworth Filter Pole-Zero Plot');
H=
1
```

```
---------------------------------------------------------------------
 2.536e-19 s^6 + 1.232e-15 s^5 + 2.992e-12 s^4 + 4.605e-09 s^3
+ 4.726e-06 s^2 + 0.003075 s + 1
```

```
%Transfer Function Analysis for Band-Pass 1 6th Order Butterworth
 Filter
%ECE223 Sp19, Jennifer Jordan & David Lay

s = tf('s');
x = (.267*((s/6283.19)+(6283.19/s))); %LP to HP transformation

condition
H = 1/((x^2+.5176*x+1)*(x^2+1.4142*x+1)*(x^2+1.9319*x+1))

%Figures:
figure(1);
bode(H);
title('Band-Pass 1 Butterworth Filter Bode Plot');
figure(2);
impulse(H);
title('Band-Pass 1 Butterworth Filter Impulse Response');
figure(3);
step(H);
title('Band-Pass 1 Butterworth Filter Step Response');
figure(4);
pzplot(H);
title('Band-Pass 1 Butterworth Filter Pole-Zero Plot');

H=
1.526e34 s^9
---------------------------------------------------------------------

 8.987e07 s^15 + 8.171e12 s^14 + 3.928e17 s^13 + 1.232e22 s^12

+ 2.665e26 s^11 + 3.901e30 s^10 + 3.509e34 s^9 + 1.54e38 s^8

+ 4.153e41 s^7 + 7.58e44 s^6 + 9.54e47 s^5 + 7.836e50 s^4

+ 3.402e53s^3

Continuous-time transfer function.
```

```
%Transfer Function Analysis for Band-Pass 2 6th Order Butterworth
 Filter
%ECE223 Sp19, Jennifer Jordan & David Lay

s = tf('s');
x = (1.0759*((s/39885.9)+(39885.9/s))); %LP to BP transformation

condition
H = 1/((x^2+.5176*x+1)*(x^2+1.4142*x+1)*(x^2+1.9319*x+1))

%Figures:
figure(1);
bode(H);
title('Band-Pass 2 Butterworth Filter Bode Plot');
figure(2);
impulse(H);
title('Band-Pass 2 Butterworth Filter Impulse Response');
figure(3);
step(H);
title('Band-Pass 2 Butterworth Filter Step Response');
figure(4);
pzplot(H);
title('Band-Pass 2 Butterworth Filter Pole-Zero Plot');

H=
2.555e41 s^9
---------------------------------------------------------------------------

 9.842e13 s^15 + 1.41e19 s^14 + 1.949e24 s^13 + 1.58e29 s^12 +
 1.155e34 s^11

s^3
+ 6.022e38 s^10 + 2.793e43 s^9 + 9.58e47 s^8 + 2.923e52 s^7

   + 6.361e56 s^6 + 1.248e61 s^5 + 1.437e65 s^4 + 1.596e69

Continuous-time transfer function.
```

```
%Transfer Function Analysis for High-Pass 6th Order Butterworth Filter
%ECE223 Sp19, Jennifer Jordan & David Lay

s = tf('s');
x = (62831.85/s); %LP to HP transformation condition
H = 1/((x^2+.5176*x+1)*(x^2+1.4142*x+1)*(x^2+1.9319*x+1))
%Figures:
figure(1);
bode(H);
title('High-Pass Butterworth Filter Bode Plot');
figure(2);
impulse(H);
title('High-Pass Butterworth Filter Impulse Response');
figure(3);
step(H);
title('High-Pass Butterworth Filter Step Response');
figure(4);
pzplot(H);
title('High-Pass Butterworth Filter Pole-Zero Plot');

H=
s^9
---------------------------------------------------------------------

 s^9 + 2.428e05 s^8 + 2.947e10 s^7 + 2.268e15 s^6 + 1.163e20 s^5

s^3+ 3.784e24 s^4 + 6.153e28

Continuous-time transfer function.
```

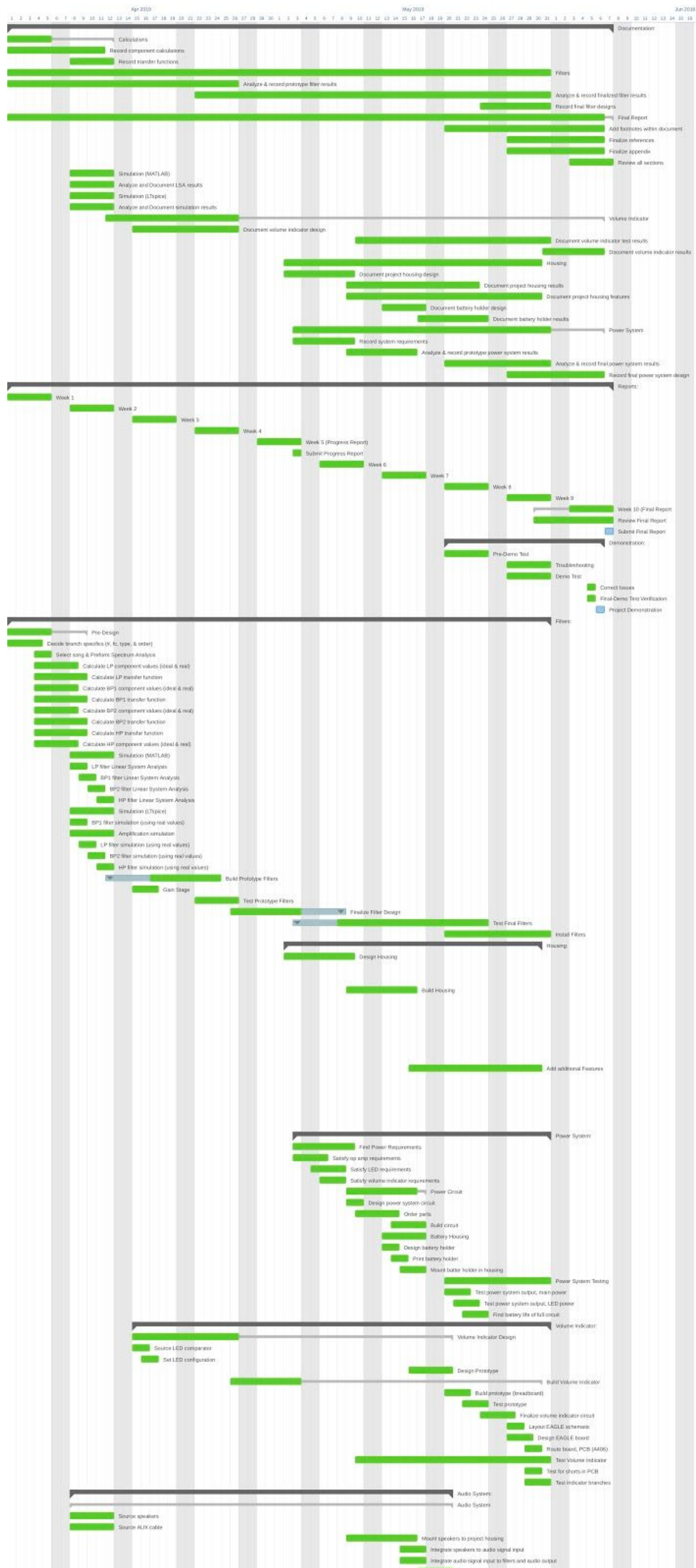
Management:

1. Full budget including prototyping costs,

Part	Quantity	Cost Each	Shipping Cost	Total Component Cost
Speakers, 4ohm 5w, two speakers	1	11.89	0	11.89
Fixed Ind 56mH 20mA 135 ohm TH	4	0.93	4.99	8.71
Fixed Ind 22mH 70mA 48 ohm th	1	0.59	0	0.59
Dual Sided Copper	1	10	-	10
Soldering Fee	2	1	-	2
A406 routing fee	1	5	-	5
Wire	1	0.25	-	0.25
Capacitors (misc)	2	0.25	-	0.5
Resistors (misc)	4	0.1	-	0.4
LM3915	2	3	-	6
M-F connectors	4	0.1	-	0.4
750qty 3mm LEDs	1	12.99	0	12.99
CAP ALUM 24UF 20% 400V T/H	2	0.92	0	1.84
FIXED IND 56MH 18MA 200 OHM TH	2	0.49	0	0.98
FIXED IND 3.3MH 220MA 6.56 OHM	2	0.56	0	1.12
FIXED IND 15MH 82MA 15 OHM TH	2	0.57	0	1.14
IND 3.9MH 270MA 9.9 OHM TH	2	0.72	0	1.44
FIXED IND 22MH 25MA 92 OHM TH	2	0.36	0	0.72
FIXED IND 1.2MH 115MA 17.5 OHM	2	0.41	0	0.82
IND 2.2MH 100MA 19 OHM TH	3	0.52	0	1.56
IND 560UH 160MA 8.8 OHM TH	2	0.41	0	0.82
INDUCTOR 2700UH 10% 90MA	2	0.53	0	1.06
INDUCTOR 820UH 10% 170MA	2	0.46	0	0.92
IND 680UH 68MA 25.3 OHM TH	2	0.27	0	0.54
FIXED IND 1.8MH 95MA 26 OHM TH	3	0.41	0	1.23
FIXED IND 220UH 155MA 5 OHM TH	6	0.31	4.99	6.85
9 Volt Batteries (8x pack)	1	9.99	0	9.99
9 Volts T type connectors (10x pack)	1	4.96	0	4.96
Voltage Regulators	1	12	-	12
EPL Charges	1	10	0	10
EPL Charges	1	14.25	0	14.25
EPL Charges	1	6	0	6
Digikey order (Inductors)	1	10.12	18.99	29.11

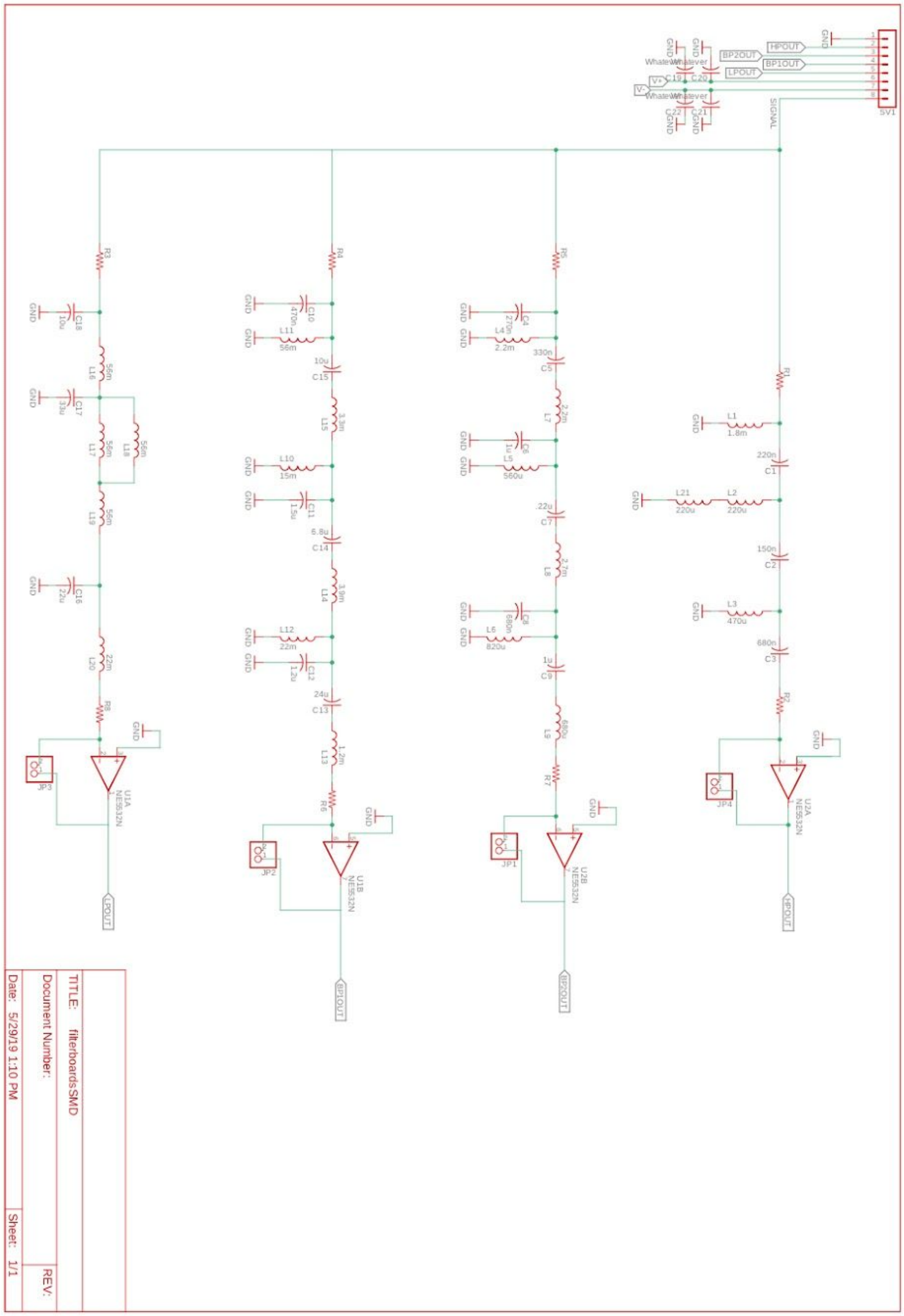
EPL Charges	1	36	0	36

2. Full Gantt Chart,

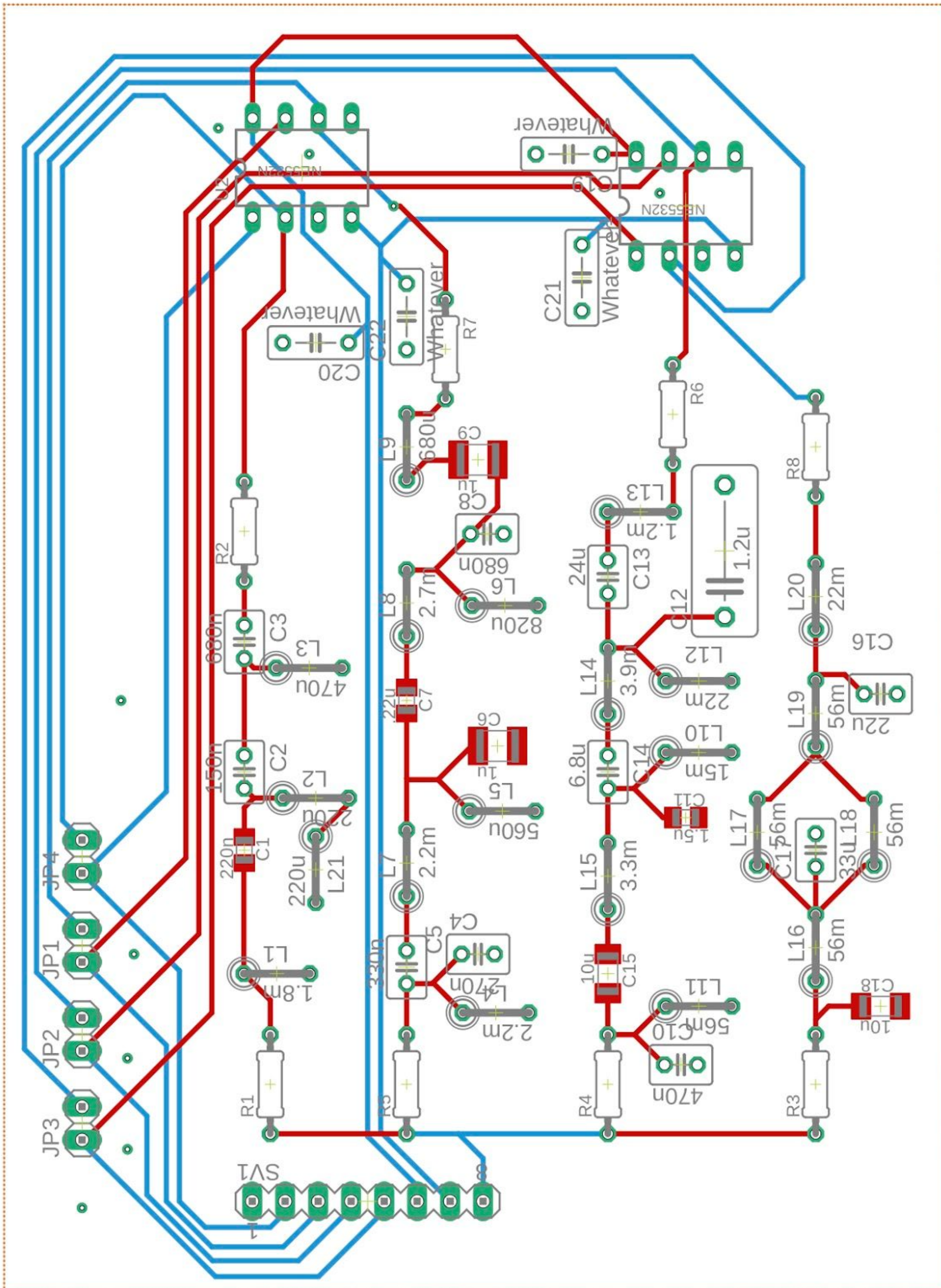


Figures:

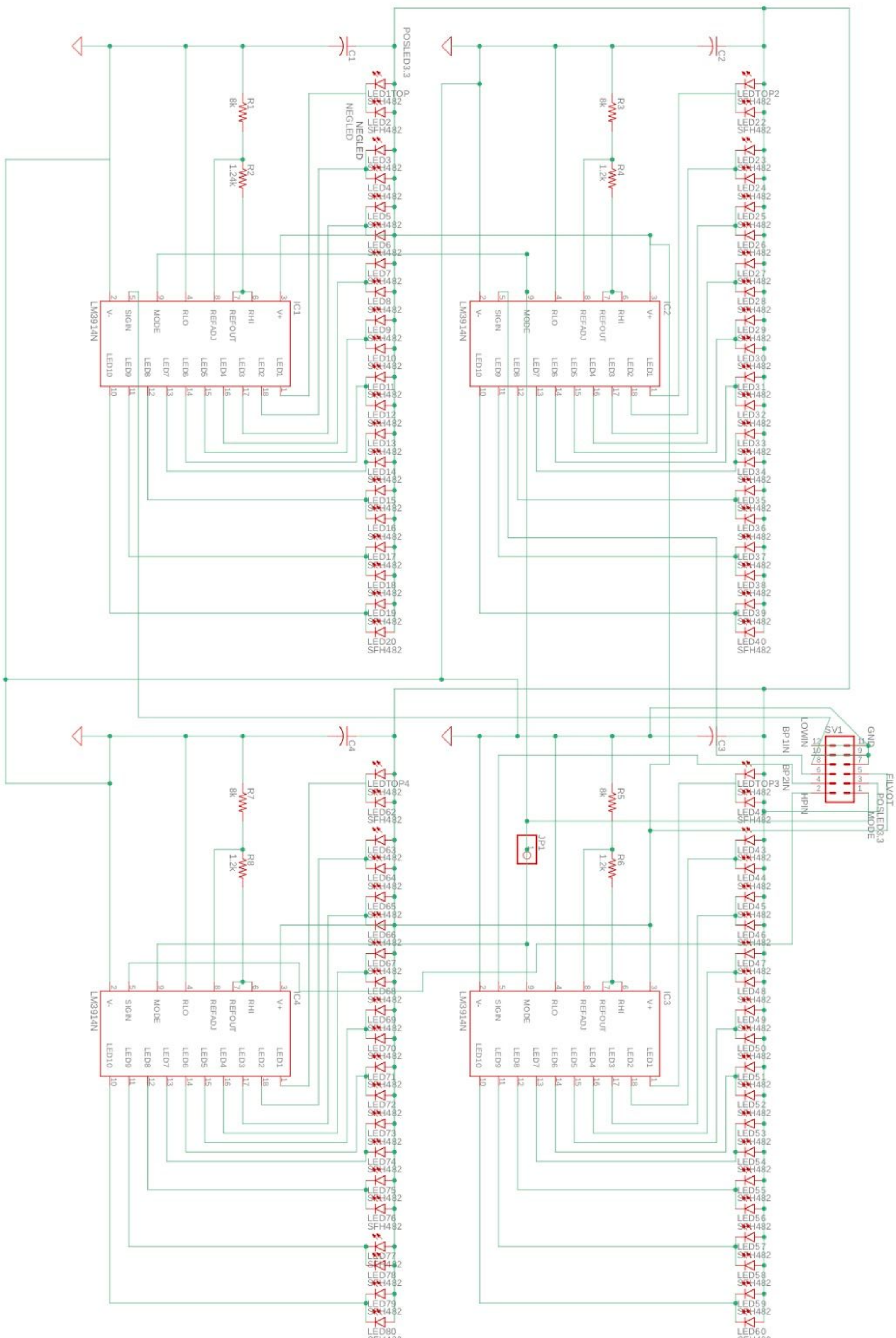
1. Filter PCB schematic full size,



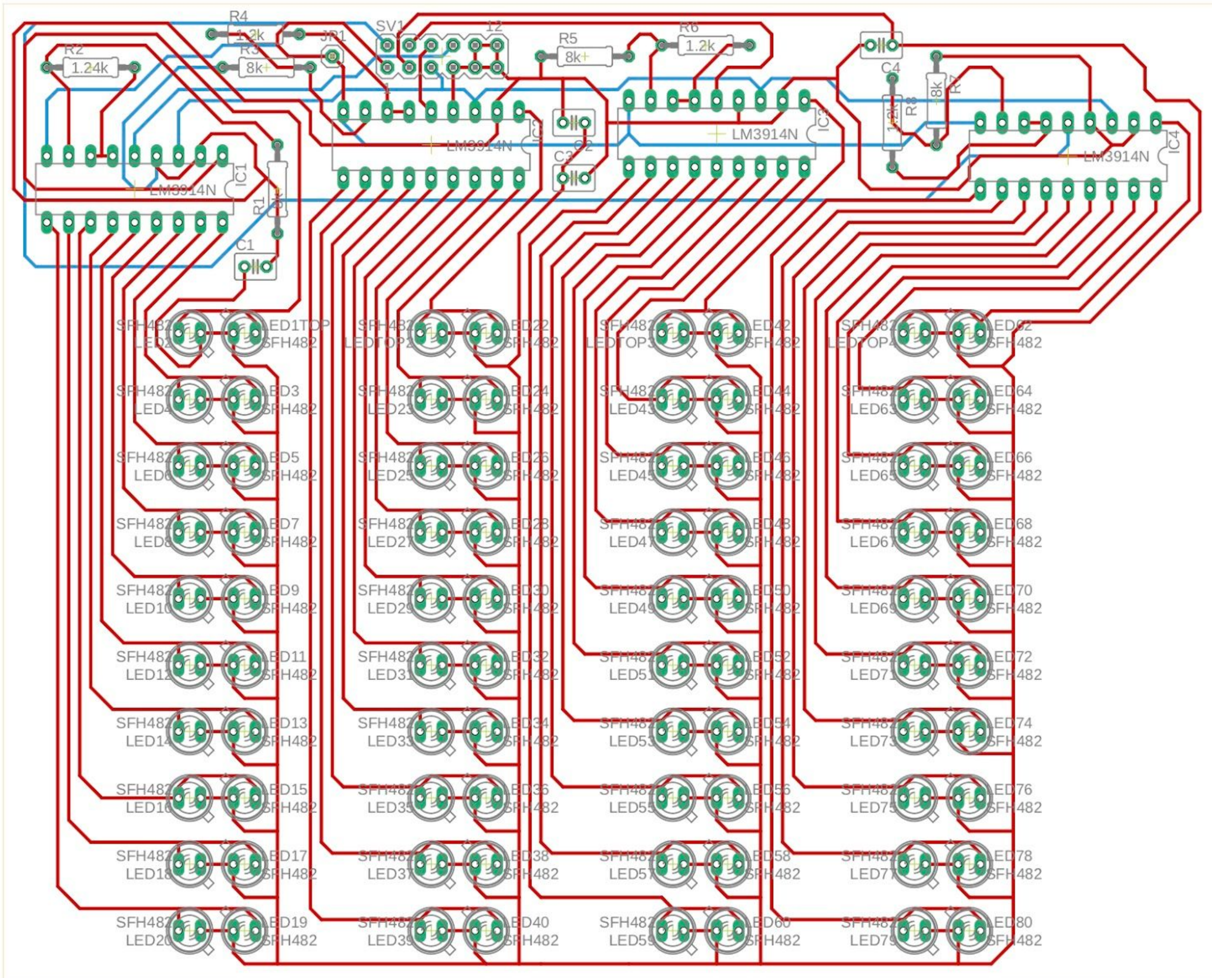
2. Filter PCB board full size,



3. Volume indicator PCB schematic full size,



4. Volume indicator PCB board full size,



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