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Color Organ Final Project

Introduction

The goal of this report was to construct an audio based circuit called a color organ. This is a circuit which was popular in dance clubs in the 60s and 70s. The idea of the circuit is to read in a song over a mic and flash different colored lights corresponding to different frequency ranges present in the song. Though here we are doing it for lights, similar circuits are used in speakers to separate a song into the low and high frequencies and put them in special speakers made to amplify them (called woofers and tweeters typically), so parts of this circuit have real applications outside of just a light show.

Design

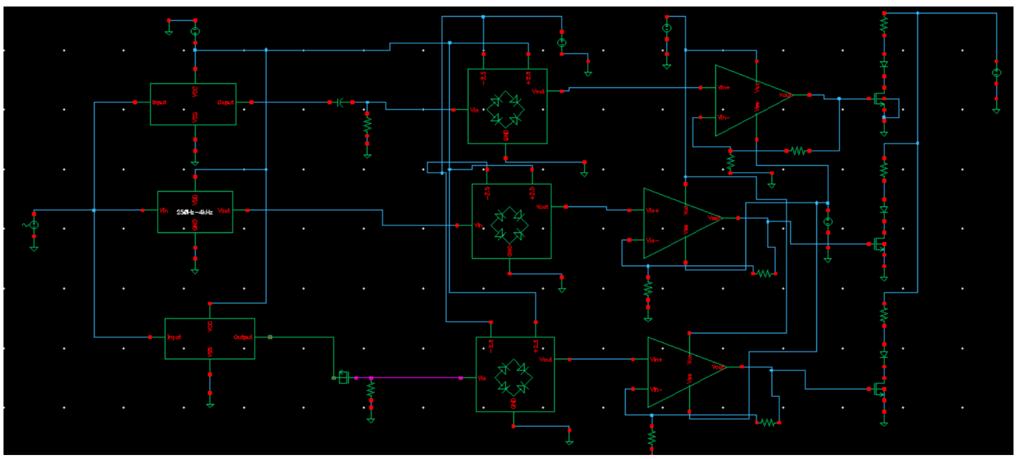

Figure 1. Final circuit

The original design that had been planned consisted of an initial amplifier that takes in the microphone signal to allow a larger signal at the frequency stage. This amplified signal would then be used as the input to three different filters that correspond to distinct frequency bands. These frequency filters would include op-amps in their schematics as well. Because all the op-amps used would take advantage of feedback in order to control the gain of the signal, the transistor-level configuration of those op-amps could be different with different intrinsic gain. Additionally, the intrinsic bandwidth of these op-amps used are much higher than the sound-wave frequencies being considered, so the transistor level of the op-amps do not need to match perfectly, and their individual specifications are overlooked.

The initial design specified the output signal from the bandpass filters directly driving a transistor to turn an LED on or off. However, further planning revealed that there should be a rectifier present to act as an AC to DC converter in order to keep an “on” signal constantly driving the transistor rather than oscillating. At high frequencies, this stage is rather unnecessary because visually, the human eye cannot catch the fast on-off switching of the LED and instead sees a constantly-on behavior. However, at low frequencies, the oscillation is slow enough that the on-off behavior could be seen. The decided design of the rectifier was a full wave rectifier using a diode bridge rectifier.

In implementing the circuits, one consideration for constructing the configuration of the op-amps and their feedbacks was the biasing at the inputs. From experience, most microphones contain a DC offset which can be set manually using certain components such as a coupling capacitor, so the op-amps were configured to operate with a 1.3V offset at the input (half of the supply voltage), a reasonable assumption for a voltage offset based on a typical microphone we found online (MAXIM).

When constructing the op-amp configurations, one concern that influenced the design was a signal hitting the rail voltages of the op-amp and clipping for high gain, and cascading these op-amps could make this more likely. To mitigate this concern, the initial amplifier was removed and instead the input signal was put directly into filtering stages, and the filtering stages would pick up the gain that the initial amplifier was meant to provide. Another design consideration for the filters was the behavior at the cutoff frequencies. Because the filters used are unideal and do not drop off completely at the frequency cutoffs, it was decided for the cutoffs to contain a -40 dB/decade decrease in gain at the cutoffs so that the gain of the filters just outside of the wanted band decreases more quickly. Additionally, the design of each filtering stage has a different configuration to achieve the bandwidth requirement as decided by the individual designer.

The final design schematic for the low-pass filter with 250 Hz cut-off frequency and 20 dB AC gain is shown in figure 2. The DC bias of the input is provided by the input signal, which is about 1.3 V. The first stage inverter works as an amplifier, providing 20 dB AC gain. The second stage is a Sallen Key, working as a low pass filter with unity gain. We use the differential amplifier from lab 9 to build the Sallen Key.

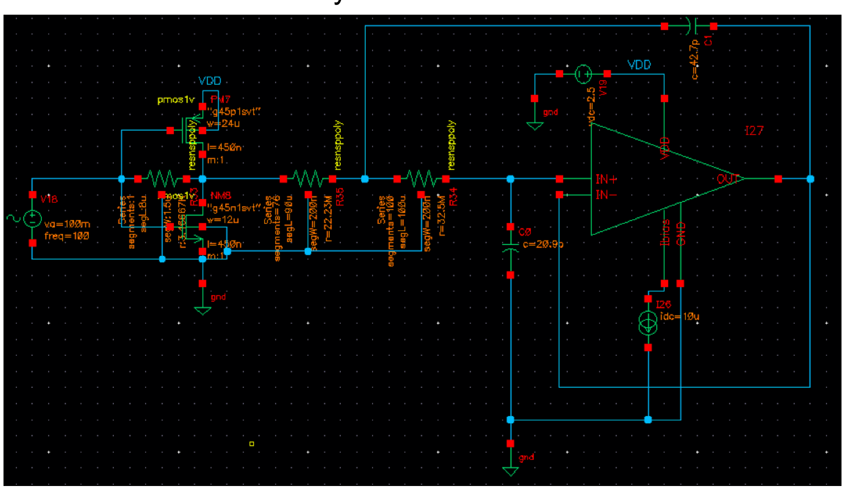

Figure 2. *0-250Hz Filter*. The filter used for this frequency range makes use of an inverter amplifier and a Sallen Key unity gain amplifier.

Figure 3 demonstrates the schematic for the 250Hz-4kHz filter. The high frequency cutoff is achieved using components at both the feedback path and the Vin+ input. The Vin+ input uses a low pass filter, and the impedance at the feedback loop also acts as a low pass for impedance. These two low-pass filters together allows the AC sweep to contain the -40 dB/dec cutoff that is desired. The low frequency cutoff achieves the +40 dB/dec slope using the components at the output and at the Vin- to VDD/GND path. The components at the Vin- to VDD/GND path cause a decrease in impedance as frequency increases, and thus the voltage at Vin- lowers at higher frequencies and allows gain to be greater than unity at higher frequencies. The output components act as a high-pass filter with the same cutoff frequency as the components described previously.

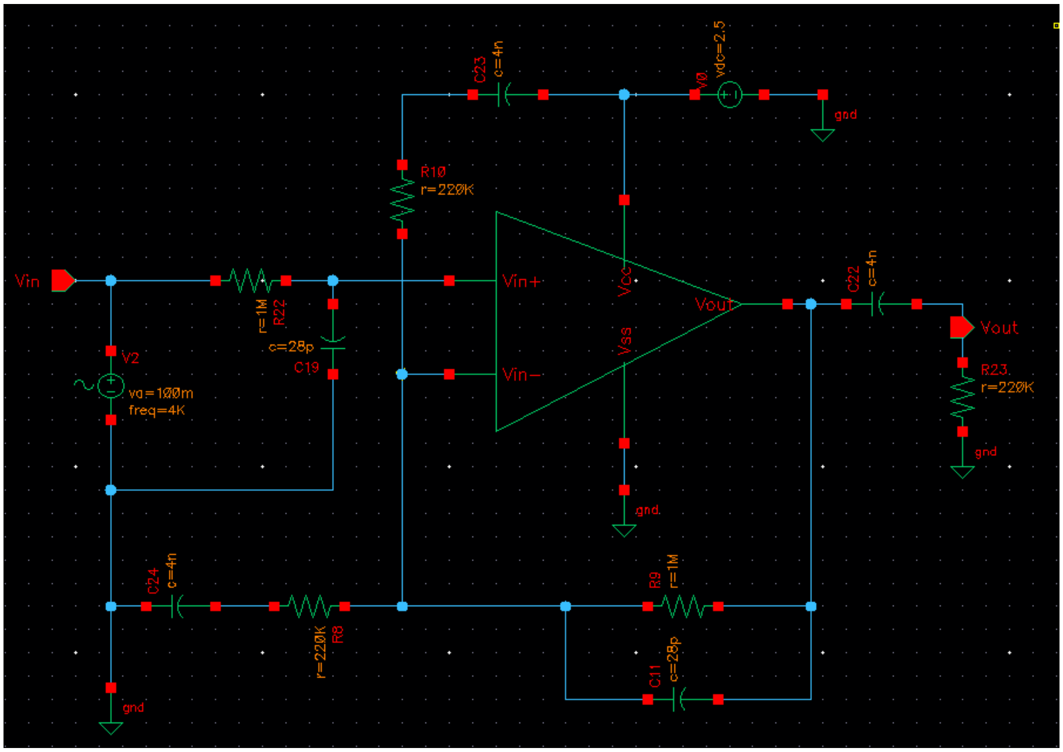

Figure 3. *250Hz-4kHz Filter*: The filter used for this frequency range makes use of one op-amp with four RC sections to achieve the bandwidth desired.

Due to some difficulties in repeating the above design for the high range frequencies, for the 4k-6k range signals a Sallen-Key filter was used as shown in figure 4 below. We began by researching the different forms of the Sallen-Key filters to see which would work best for use. To test things out we attempted to do both a single op amp band pass Sallen-Key and a double amp band pass Sallen-Key (one high pass and one low pass as shown above). Due to transistor saturation issues we found that we were unable to get the single op amp design to work and so we went with the double (even if it is more components).

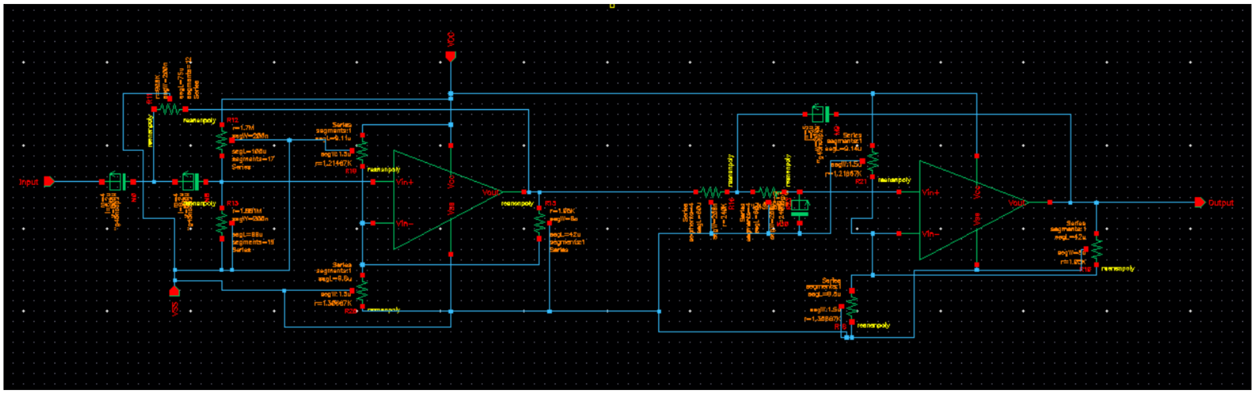

Figure 4. *4k-6kHz Filter*: The filter used for this frequency range makes use of two Sallen-Key filters to accomplish the goal.

Early into the design of the filters one major issue we recognised early on was whether our filter was amplifying the AC or the DC of the input signal. A normal op amp amplification topology (like a simple inverting amplifier) amplifies the total voltage of the input signal. For this application, that was not really acceptable as if DC was amplified it would cause clipping in the signal for the positive peaks of the audio signal. In order to accomplish this we needed the inverting and non-inverting terminals of the op amp to have a constant DC bias in order to only amplify the AC coming in, as shown in figure 5 below. These keep a 1.3 voltage bias in the circuit. The AC is amplified to bounce around this DC bias. This biasing was done for the mid-range filter as well.

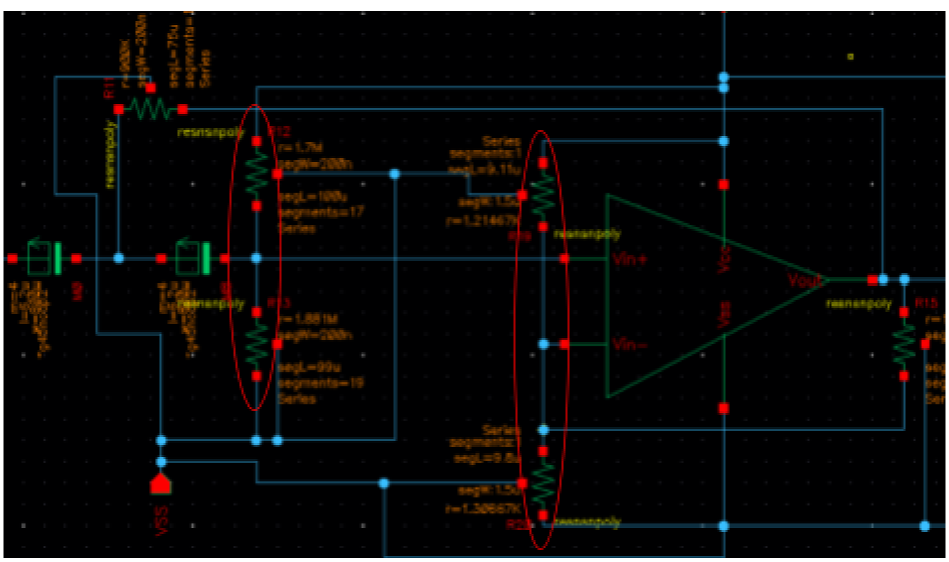

Figure 5. *4k-6kHz Filter*: Voltage divider used to maintain DC bias on terminals.

Another factor taken into consideration with the design was the voltage requirements for the diode rectifying bridge. Each diode used has a specified turn-on voltage, and the cascading diodes in the bridge-rectifier require that turn-on voltage to function. As a result, the voltage input to the rectifier needs to be above those turn-on voltages such that the diodes in the bridge can turn on, and the output voltage ripple is not large enough to turn off the transistor that the rectifier output drives.

In order to keep the LEDs from staying on all the time, it was very important to take the output of each filter and remove the DC bias and have them oscillate around 0 V. Otherwise the rectifier would be pointless as the signal would always be positive. In order to accomplish this, we decided on using some simple decoupling capacitors to kill the DC signal. The RC break point of this block was set to extremes by making the resistance values huge (several mega ohms for some). The results of this edit are shown below in Figure 6 and 7.

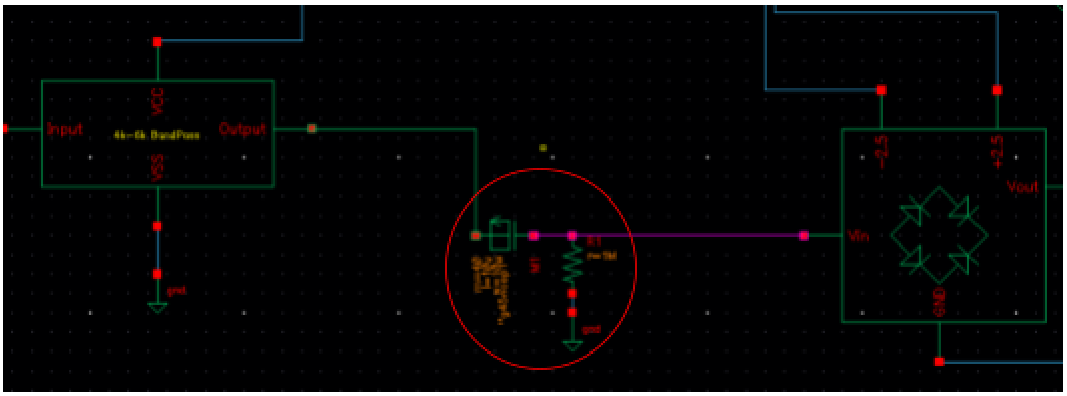

Figure 6. Decoupling stage after filter circled above

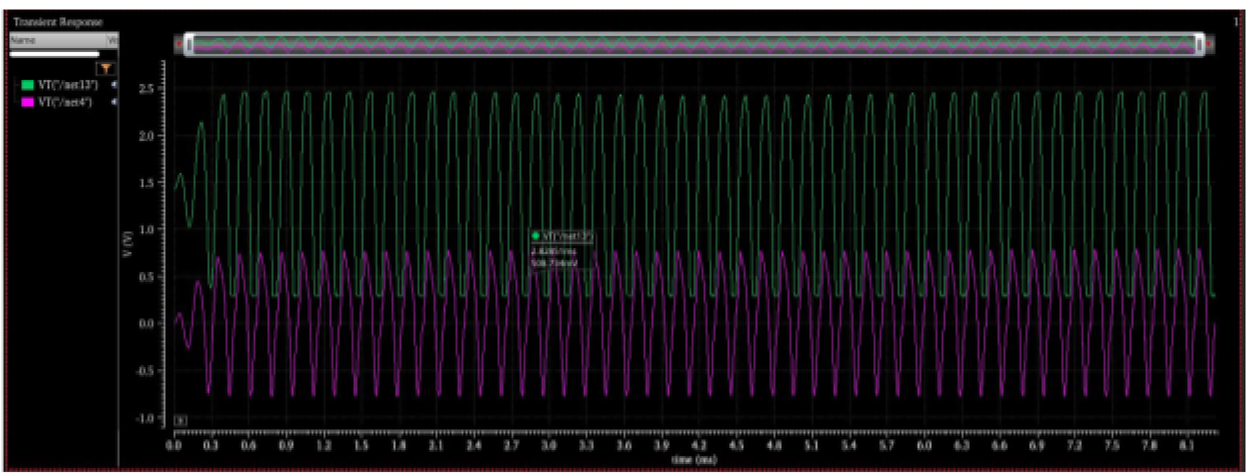

Figure 7. Output of filter shown in green, decoupled signal shown in purple

One more aspect that was taken into consideration when using the rectifier was blocking out low-amplitude signals such that out-of-band signals that come out of the filters are not strong enough to pass through the rectifier. This, in turn, requires that the output of the filters is biased about 0V as stated before so that low amplitude signals still do not pass through the rectifier. Initially, we tried amplifying the signal out of the filter (after decoupling) first and then ran it through the rectifier to be sent to the LED stage. We did this because of inherent attenuation after the rectifying stage. This ended up causing unwanted amplification of out of band signals causing the LED to turn on when it should not. To fix this we changed the order, first rectifying then amplifying later. This is shown in the rectifier schematic shown in Figure 8.

Figure 8 shown below is the leftover amplifier from our initial amplification attempt and is not actually connected to the output of the rectifier component. This way, only wanted signals that had a high enough voltage to turn on the base of the transistor. With the aforementioned amplification displayed in Figure 9, we were able to get out a final signal which turned on the base transistor exactly when we wanted.

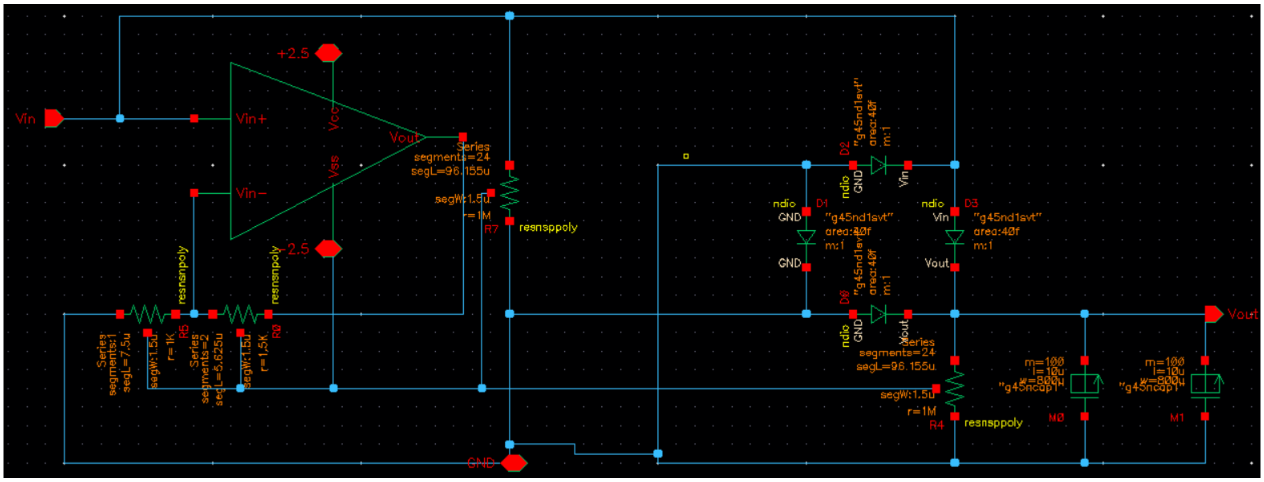

Figure 8. Rectifier circuit diagram

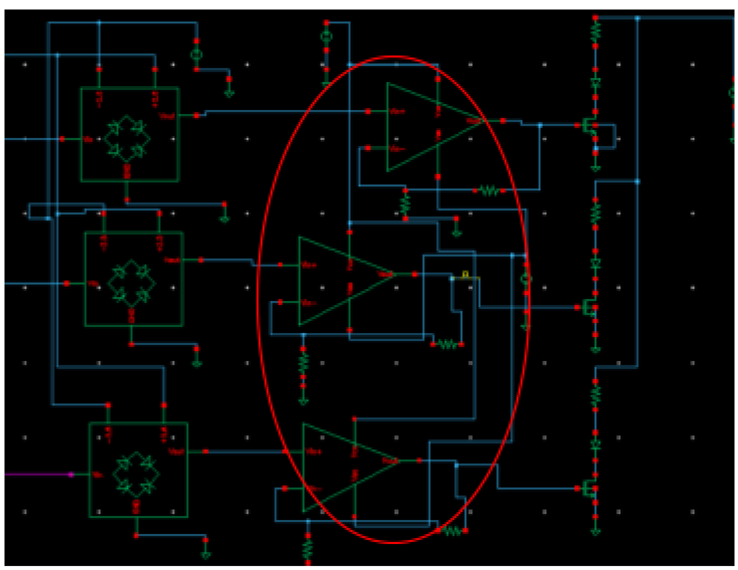

Figure 9. Amplification following rectification circled in red

Simulating LEDs was done with simple diodes as real LEDs are diodes. This is not a perfect simulation but is a step in the right direction. Current limiting resistors were placed in series with the diodes as real LEDs have current limits.

Discussion

Simulation Results

The end result of the filtering for each filter band is shown below in figure 10. The high band looks more like a peak due to how thin the band is.

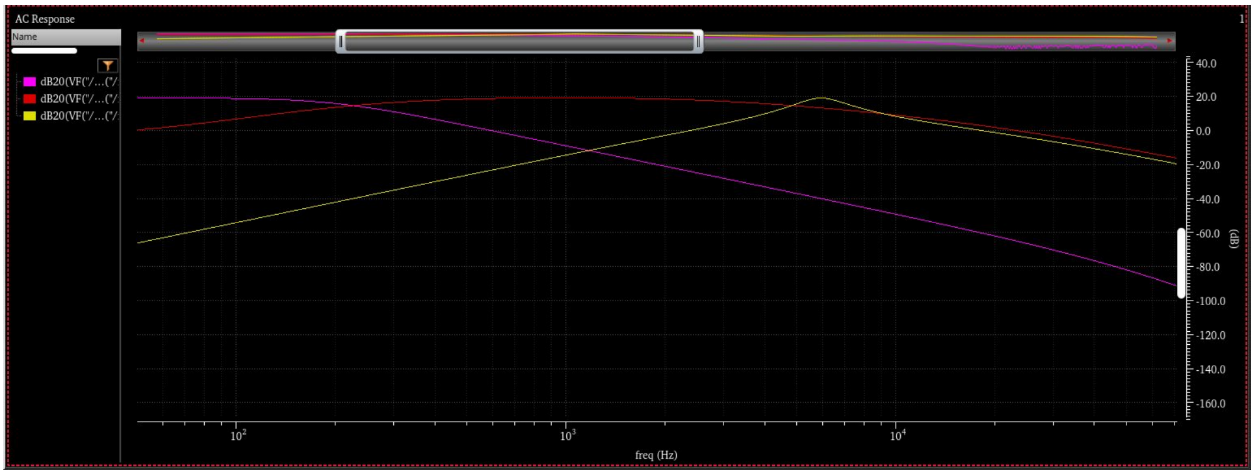

Figure 10. Filtering bands simulation with low (purple), mid (red), and high (yellow)

The layout of this low pass module is shown in Figure 11. The capacitors take up a large area, as expected. However, as we tried to reduce the value of the capacitors, we must increase the value of the resistors, thus increasing the area. For the MOS capacitors, we set the bulk to be “detached” and be on both sides of the capacitor to avoid “latch up” DRC error. For resistors with multiple segments, we must set the segments in layout manually. Otherwise, it will cause parameter mismatch when running LVS. As shown in figure 12, the layout of the low pass filter passed the DRC and LVS check.

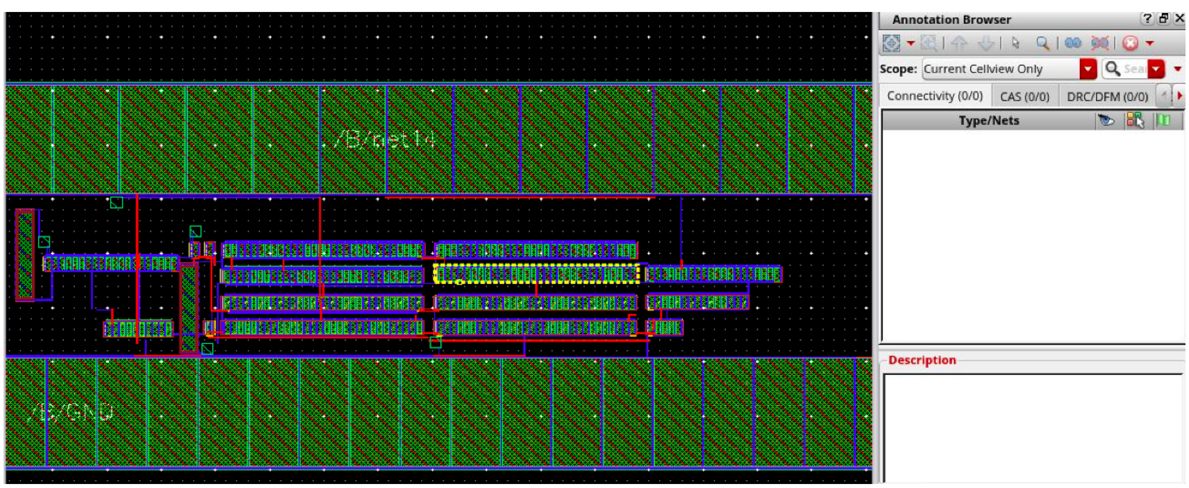

Figure 11. Low pass filter layout

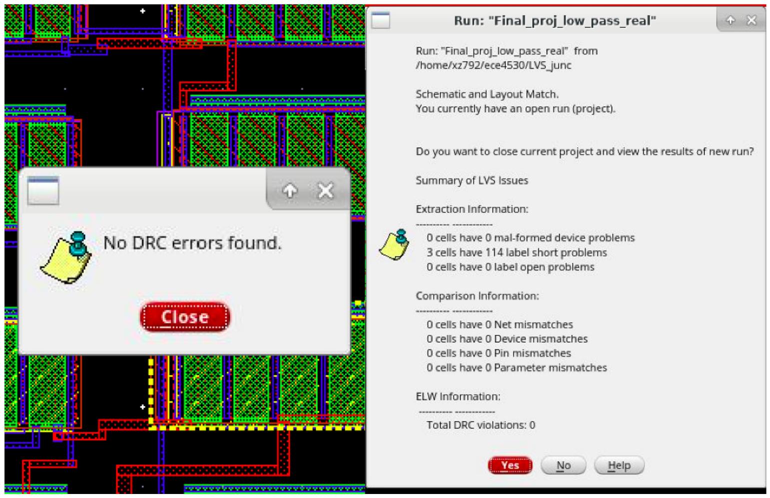

Figure 12. DRC and LVS clean

To test that our final design meets the requirements, we did simulations with both ideal sources and audio files as input songs. pwl (piecewise linear) files were generated using MATLAB and set up as voltage source in Cadence. Figures 13-15 show the test results, where the left picture shows the input voltage waveform, and the right picture shows the voltage at the gate of the transistor that controls the turning-on of the corresponding LED (purple line: low frequencies; blue line: mid-range frequencies; green line: high frequencies).

The first test's input waveform consists of sine waves at 100 Hz and 2500 Hz, and the result is as expected. The rapid dropping and rising of voltage at low frequencies is a result of the rectifier. The second test's input waveform is obtained from part of Cornell's Alma Mater "Far Above Cayuga's Waters" and modified into proper input voltage range (100 mV peak to peak). The result is also as expected, since the part consists of mostly signals from 350 Hz to 1500 Hz by looking at its FFT in MATLAB. The rapid switching of voltage as found in the picture could be due to the nonideal waveform and noise from the audio file. Finally, the third test's input waveform consists of sine waves at 150 Hz and 5000 Hz, as well as randomly generated numbers ("noise") across the input voltage range. While only LEDs associated with low and high frequencies should be turned on, all of the three voltages go high. This might be a result of the influence from the randomly generated voltages.

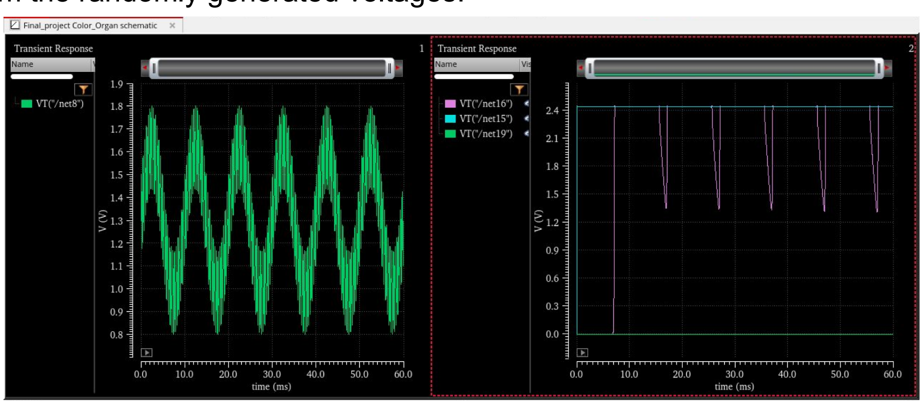

Figure 13. Simulation with low and mid-range frequencies input

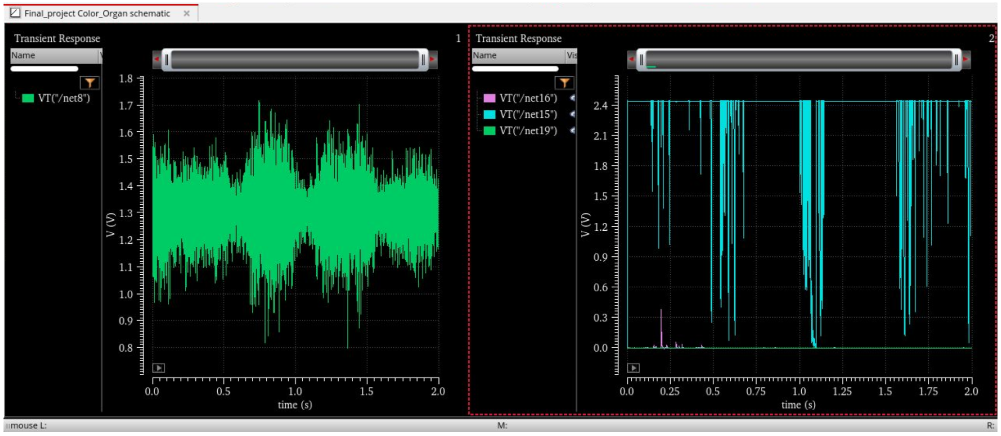

Figure 14. Simulation with a part from Cornell Alma Mater as voltage source

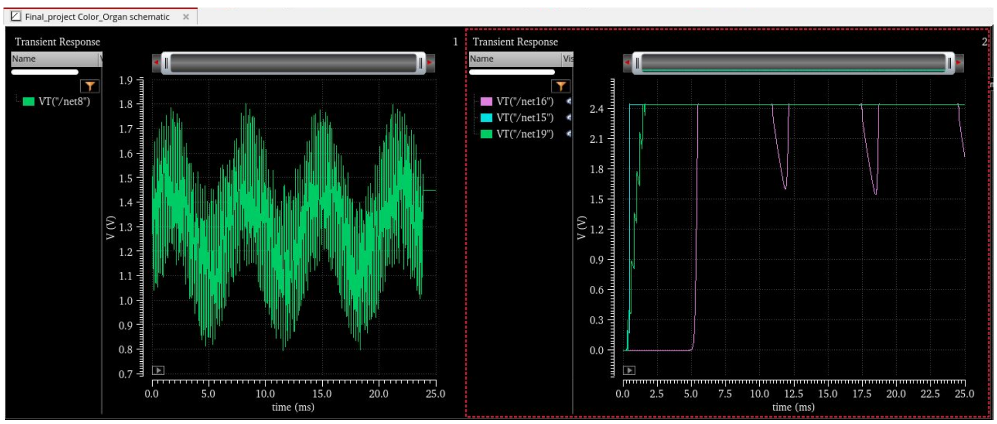

Figure 15. Simulation with low and high frequencies and random noise input

Findings

One major finding when constructing the circuits required for this project was the sizing requirements of the passive components based on the frequency range where activity takes place. Since the frequency cutoffs of the filters are in a very low range, the capacitor and resistors used need to be very large to achieve the desired cutoffs, and thus the area taken up by these components is what takes up most of the area of the design. One solution to this in a physical product could include leaving pins where the passive components are meant to go (especially the capacitors) and allowing discrete components to be placed in its place to reduce size of the integrated circuit. This would also allow for the frequency bands to be variable by choosing different valued components in the filters.

Figure of Merit and Comparison

Note about comparisons:

Because this is not a very “academically useful” circuit, and most circuits like this are not made in ICs but on much larger scale as they control larger lights, most of the similar circuits we could find online were either hobbyist level ones for learning or commercial high power ones. Neither of these typically contained much information on the fine details so getting useful parameters to compare was difficult. We found two circuits to compare, one found on the Jameco Electronics website (Cunningham) and another on an electronics website (Tindie)

Characteristic	Our Circuit	Jameco Circuit	Comercial Circuit
Out of band Attenuation	-40dB	N/A	N/A
Power supply voltage	2.5v	12v	12v
Current consumption	39.161 mA	N/A	N/A
Number of channels	3	3	5

Conclusion

In the end the circuit did overall function in the way which we intended. The response of the bands was sharp enough to believe that the lights would look good if the circuit was actually constructed. There is a little bit of mixing between the high and mid range frequencies, but this is to be expected as the frequency ranges are quite close to each other and analog filters are not perfect. In the future it is possible more channels could be added. We initially intended to replace the LED stage with a converter to a PWM signal in order to control the LEDs with the duty cycle of a PWM wave, but found that we were having enough problems with getting the rest of the circuit to work and did not have time to get to it. It is possible in the future that this could be added.

References:

Cunningham, Collin. “Build a LED Color Organ | Circuit Skills Video Collin Cunningham.” *Jameco Electronics*, Jameco Electronics, https://www.jameco.com/Jameco/workshop/video/ledcolororgan.html. Accessed 21 December 2022.

MAXIM. *Low-Cost, Micropower, SC70/SOT23-8, Microphone Preamplifiers with Complete Shutdown*. Data sheet for microphone. 2001. *datasheetcatalog.com*, https://cdn-shop.adafruit.com/datasheets/MAX4465-MAX4469.pdf.

Tindie. “Color Organ 5 Channel PWM Controller LCH5T by mc_kit on Tindie.” *Tindie*, https://www.tindie.com/products/mc_kit/color-organ-5-channel-pwm-controller-lch5t/. Accessed 21 December 2022.