5-2019

# Analog Musical Distortion Circuits for Electric Guitars

Timothy Douglas Sunnerberg
tds5710@rit.edu

# Analog Musical Distortion Circuits For Electric Guitars

by
Timothy Douglas Sunnerberg

Graduate Paper

Submitted in partial fulfillment
of the requirements for the degree of
Master of Science
in Electrical Engineering

Approved by:

___

Mr. Mark A. Indovina, Lecturer
*Graduate Research Advisor, Department of Electrical and Microelectronic Engineering*

___

Dr. Sohail A. Dianat, Professor
*Department Head, Department of Electrical and Microelectronic Engineering*

Department of Electrical and Microelectronic Engineering
Kate Gleason College of Engineering
Rochester Institute of Technology
Rochester, New York
May 2019

To my family and friends, who helped keep me sane throughout my tenure at RIT. To my teammates on RIT's Cross Country team, who gave me great company and times to take my mind off of academic endeavors throughout my college career. RF! Finally, to Jeri Beiter, whose work ethic and support is truly inspiring and helped keep me focused and motivated.

# Abstract

Distortion, while seen as undesirable in most contexts, has taken a different role in electronic music. Musical distortion refers to nonlinear changes in a waveform, and has been used to change the sounds of electric guitars since the 1940s and 1950s. Originally, distortion was realized with broken tubes in amplifiers or torn speaker cones, but as music evolved, so did the equipment used to produce the desired sounds. Slashed speakers turned into electronic circuits in the mid 1960s, and these electronic circuits are the focus of this paper.

Many papers discuss the digitization of analog circuits, but because most analog distortion circuits were commercial products protected by IP laws, there has not been much research in terms of the affects of different circuit topologies and their affects on sound. In this paper, a few topologies are studied with various methods of analog nonlinearities. Two topologies, called distortion and overdrive, were studied. Two nonlinearities were also examined, the diode limiter and the class B amplifier. Overall, 8 circuits were built using various combinations of nonlinearities within each circuit topology. Ultimately, the overdrive topologies were more flexible than the distortion topologies, with the class B overdrive topology being a personal favorite. The only topology that did not work well musically was the class B distortion topology.

# Declaration

I hereby declare that except where specific reference is made to the work of others, the contents of this paper are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other University. This paper is the result of my own work and includes nothing which is the outcome of work done in collaboration, except where specifically indicated in the text.

Timothy Sunnerberg

May 2019

# Acknowledgements

I would like to thank my advisor, and mentor, Mark A. Indovina, for his guidance, feedback, and sense of humor throughout this project. He happily took me on as a mentee and helped me work on a project that I found very interesting and fulfilling, and I learned a lot from him.

I would also like to thank professor Carlos Barrios. He was very helpful while I was learning the CircuitMaker layout software, and always responded to emails impressively quickly.

Finally, I would like to thank Dr. Amuso, Dr. Rabbani, Dr. Patru, and Dr. Rommel, who have have all been very influential during my time at RIT and contributed a great deal to my academic success.

# Contents

# List of Figures

# List of Tables

# Chapter 1

# Introduction

Guitar effects have been used for as long as guitar noises were converted to electric signals and amplified. Effects started simple, but quickly evolved into a market with everything from simple circuits made to boost the amplitude of the input signal to complex multi-effect units that can do anything from looping previously played lines to complex modulation and everything in between. In this paper, musical distortion is explored via analog circuits. The two main circuits that are analyzed are the popular musical distortion effects known by musicians as distortion and overdrive. In an effort to separate the specific components that cause musical distortion, most components in the circuits analyzed will be the same from one circuit to another. Overall, 8 circuit typologies were simulated, laid out, built in hardware, and tested.

In this paper, all simulations were performed using LTSpice. The schematic was then copied and laid out in Altium CircuitMaker software. Hardware was tested using a HP E3631A power supply, a LeCroy Wavestation 2022 function generator, a Tektronix TDS 2012C Oscilloscope for normal scope captures, a HP 54602B Oscilloscope for XY mode captures, and a Diligent Analog Discovery Module as a network analyzer.

## 1.1 Organization

Chapter 2 discusses previous research in the area of guitar effects and modeling different guitar effects in real time systems, in addition to presenting the reader with some background information on electric guitars in general. Chapter 3 presents and analyzes the basic circuit building blocks that are used to make the final circuits. Chapter 4 presents the final circuit designs and shows simulation results. Chapter 5 shows test results from the hardware built for this project, as well as discussing general sounds produced by these circuits. Chapter 6 discusses possible future work and the concludes the paper.

# Chapter 2

# Literature Review and Background Information

This chapter discusses other research that has occurred in the area of guitar effects and modeling, as well as going into some background on electric guitars. Some important conclusions to note from this chapter are the fact that a guitar pickup cannot be viewed as a perfect voltage source, a guitar signal from a magnetic pickup will have an output amplitude of around 100 mV to 1 V, and that a guitar operates in a frequency range of about 80 Hz to 1.2 KHz with harmonics several integer times higher than that. This chapter also establishes the basic block diagrams that will be used for the distortion and overdrive circuits that will be built.

## 2.1 Electric Guitar History and Circuit Model Basics

Guitarists have been looking for ways to amplify their instruments since the 1930s, when they could not quite keep up with their fellow brass and woodwind musicians in bigger ensembles and orchestras. Many different methods were attempted, including microphones and

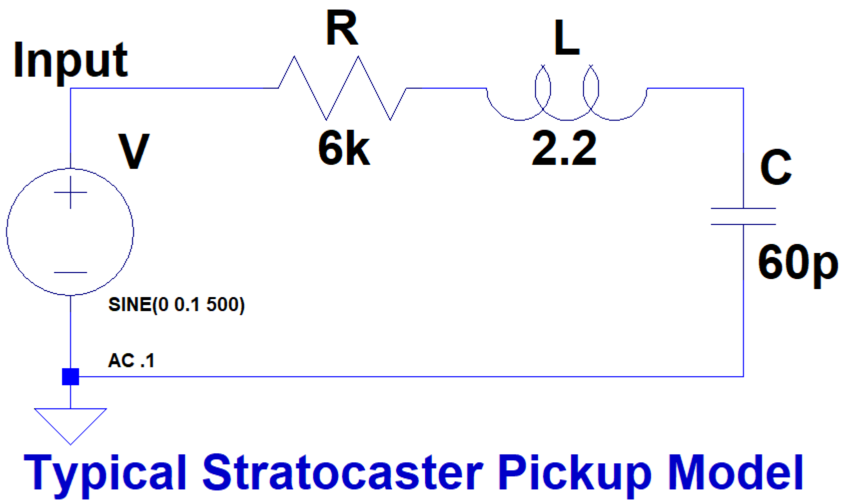


Figure 2.1: Spice model of a typical Stratocaster-style guitar pickup.

piezoelectric devices, but ultimately magnetic pickups became the standard way of electrifying guitar signals before amplification.

Magnetic pickups consist of thin wire wound around the perimeter of a magnet, making a coil. The magnet produces a magnetic field which the steel guitar strings pass through. When the guitar strings vibrate, they disrupt the magnetic field and induce a current through the pickup's coils. These currents are proportional to the strings vibrations, and can be amplified by an electronic amplifier to make the guitar sound louder. The general signals produced by guitar pickups have an amplitude from around 100 mV to 1 V. Magnetic pickups can be modeled as a voltage source with an inductor and resistor branching off in series and a capacitive load. Figure 2.1 shows this model [1–3].

A guitar pickup will generally output voltage in the range of 100 mV to 1 V in the frequency range of about 80 Hz to 1.2 KHz. Harmonics occur at integer multiples of these frequencies. When frequency response plots are shown, they will be shown up to 10 kHz on a logarithmic frequency plot to clearly show the range of the main guitar notes and several harmonics. The overall output impedance of a guitar pickup can vary from around 5 kΩ to around 12 kΩ, but a guitar pickup goes through a few more passive circuits before the signal is sent to be processed or amplified. Most guitars have on board controls, called volume and tone. The volume control is a simple voltage divider realized with a potentiometer, which allows less signal to pass to the output. The tone control is a low pass filter realized with a capacitor and a potentiometer. The volume and tone control are wired in parallel between the signal output of the guitar pickup and the output jack of the guitar.

Another important thing to consider is the fact that a guitar cable is not a perfect conductor. The longer the cable is, the more capacitance it will have between the signal conductor and the ground shielding. A typical cable will have somewhere in the range of 100 pF of capacitance per meter of length [4]. This added capacitance, despite being relatively small, acts as a low pass filter and can remove or significantly change the resonance peak that defines a guitar's sound. Figure 2.2 shows the circuit model and overall frequency response of a typical electric guitar while using a 3 meter cable.

While the cable capacitance seems relatively small, the relatively large output impedance of the guitar and the guitar control circuit means that the impedance is significant. Figure 2.3 shows the same circuit with an additional 6 meter length of cable attached.

The resonance peak has shifted from about 5.1 kHz to 3.3 kHz. In addition, the higher harmonics from the first simulation will be attenuated significantly. This effect can be entirely mitigated by an ideal source with a zero output impedance. Figure 2.4 shows that the same circuit with an ideal voltage source instead of a guitar pickup model will experience no attenuation or resonance peak.

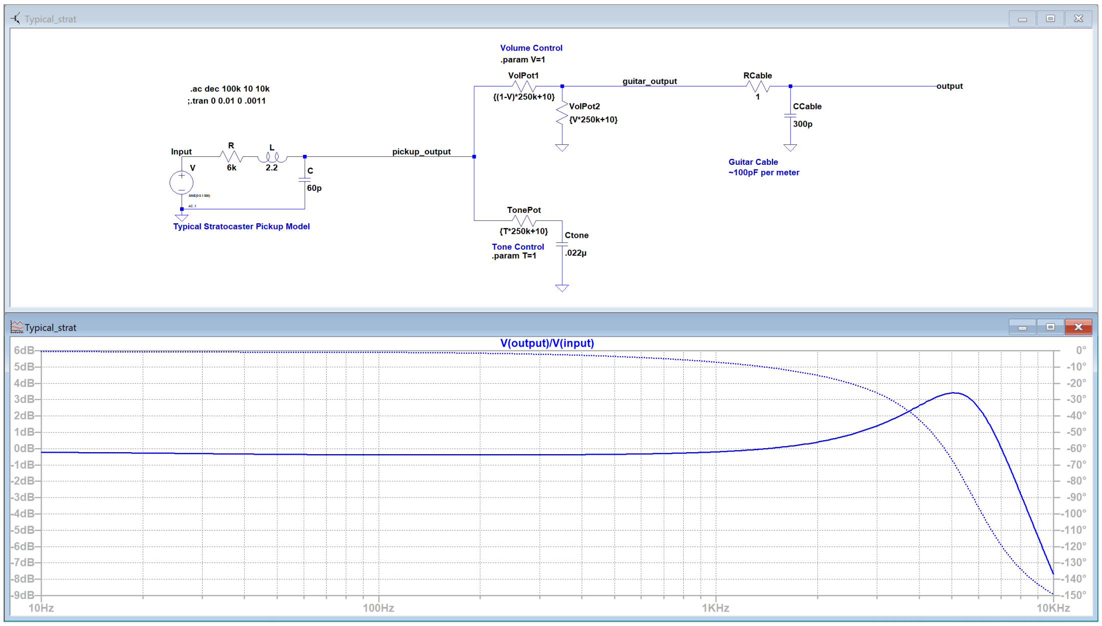


Figure 2.2: Full guitar model preceding an amplifier and its frequency response, including the pickup, the volume and tone controls, and the instrument cable.

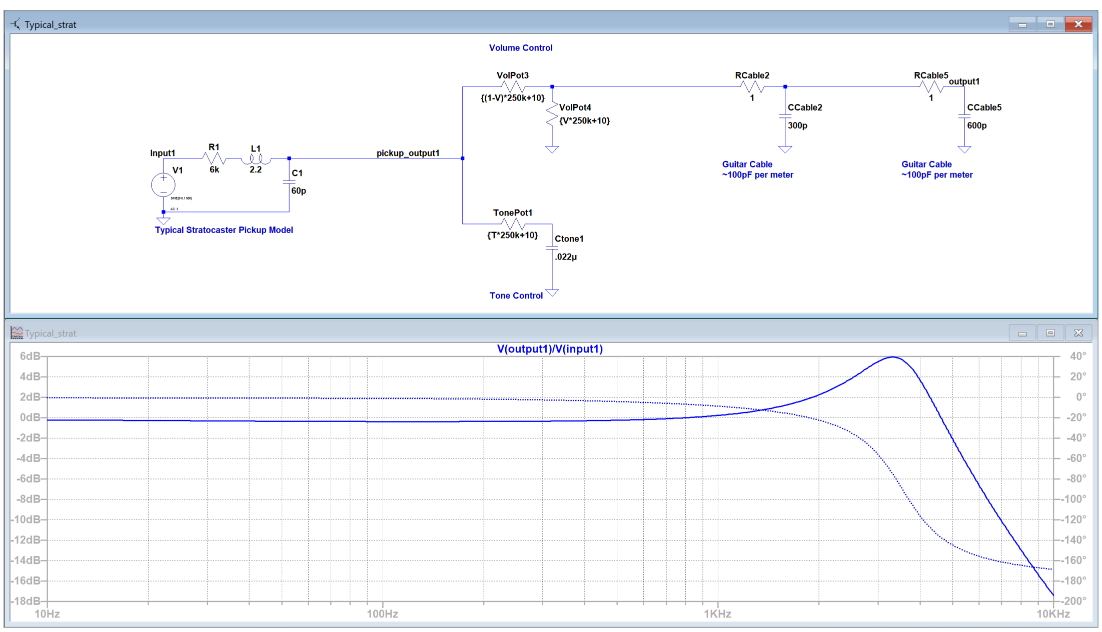


Figure 2.3: The same guitar circuit as seen in Figure 2.2 with an additional 6 meters of cable length.

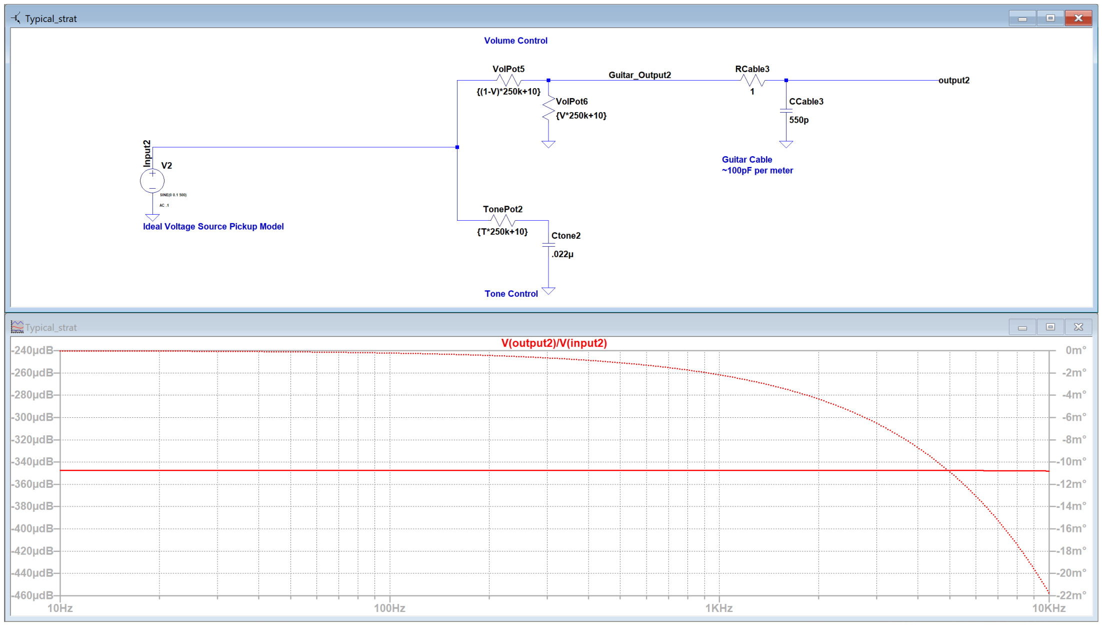


Figure 2.4: Modeling the rest of the guitar controls and cables with an ideal voltage source used in place of the pickup model reveals that the cable capacitance does not have a large impact on an ideal voltage source, despite its huge influence on real guitar electronics.

## 2.2 Methods of Guitar Distortion

While amplifying guitar signals was the first goal for electrifying guitars, it brought with it new creativity and changed the way the instrument could sound. While initially, distortion was discovered from broken amplifiers, it soon became a desirable sound. Some early electric guitar pioneers would slash their speakers or dislodge the tubes in their amplifier to create distorted sounds. In the 1960s, electronic circuits that could be placed between the guitar and amplifier were designed and sold so that distorted sounds could be achieved without altering or damaging an amplifier. These circuits are called effect pedals. Sometimes these effects are built into guitar amplifiers, but it is still common for guitarists to have separate effects in front of their amp in the signal chain[5]. While there are many different types of effects pedals, distortion is the earliest and simplest. At its most basic level, distortion operates by clipping the guitar signal against a voltage rail, whether it be the voltage rail of the amplifier itself or of an

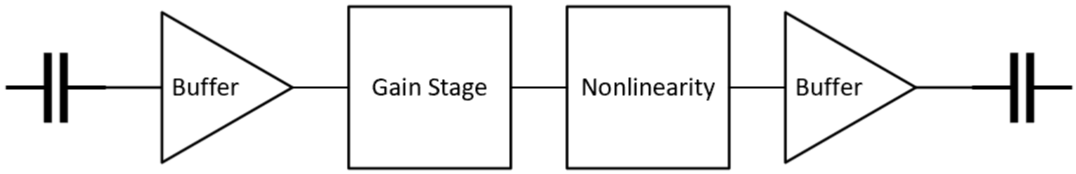


Figure 2.5: Block diagram of a distortion circuit.

op amp or transistor within the effect pedal itself. Distortion can also be created using circuit elements that introduce nonlinearities to the signal. These nonlinearities will serve as the variable for this paper. Nonlinearities add harmonic and intermodulation distortion components to a signals frequency components [6, 7]. The following sections will show the general block diagram models used in this project. There are certainly more complicated musical distortion circuits, but these circuits are kept simple overall to isolate the main nonlinearity and observe the difference the nonlinearity has on the circuits [8].

### 2.2.1 Distortion Configuration

Distortion as a guitar effect was historically made to color and change a guitar signal. Distortion pedals generally represent hard clipping distortion, where a signal is significantly or harshly cut off against a voltage rail. In this paper, distortion will refer to circuits with a nonlinearity after the main gain stage of the amplifier. Figure 2.5 shows a block diagram for a general distortion circuit [9, 10].

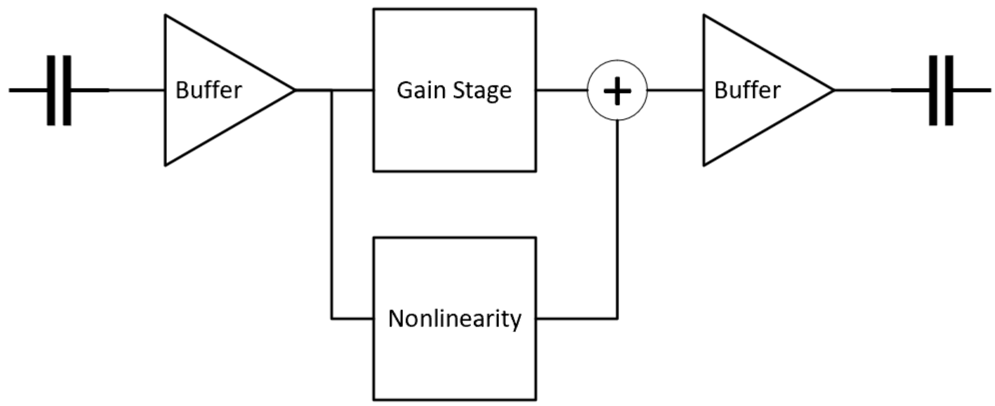


Figure 2.6: Block diagram of an overdrive circuit.

### 2.2.2 Overdrive Configuration

Overdrive is an effect that originally was intended to drive a vacuum tube amplifier to saturation by boosting the signal before it reaches the preamplifier stage. Today, many amplifiers are made with solid state transistors instead of vacuum tubes, and transistors do not clip in the same way that vacuum tubes do. Despite tube amps being rarer, more expensive, and harder to maintain, they are desirable to guitarists for the ways they sound and distort differently from solid state amplifiers. Many attempts have been made to emulate the tube amplifier sound in solid state amplifiers [11–14]. Modern overdrive techniques can mean either an effect intended to push a tube amplifier to saturation or an effect that modifies a signal to sound similar to pushing a tube amp to saturation. This generally means “soft clipping” distortion.

In this paper, an overdrive effect will be realized by a system with nonlinearity in the feedback loop of the main gain stage. A general block diagram form of overdrive circuit can be seen in Figure 2.6 [9, 10].

# Chapter 3

# Circuit Building Blocks

This chapter discusses the lower level circuits that make up the block diagrams for the main designs discussed in Chapter 2. Section 3.1 explains the need for buffers in guitar effect circuits, Section 3.2 describes the gain stages of the distortion and overdrive topology, and Section 3.3 describes the nonlinearities that will be used to create the distortion within the circuit.

## 3.1 Input and Output Buffer

Buffers are simple, unity gain amplifier circuits that have specific input and output impedance. Ideally, a system will have an infinite input impedance and zero output impedance. This is because electrical systems act as voltage dividers. With a zero output impedance going into an infinite input impedance, no signal is lost due to voltage division. For this project, a common collector bipolar junction transistor (BJT) amplifier will serve as a buffer for its high input impedance, low output impedance, and unity gain. NPN BJTs are used, with NPN referring to the doping profile of the emitter, base, and collector, respectively. Figure 3.1 shows the schematic diagram of a BJT buffer, which is the topology used in this project.

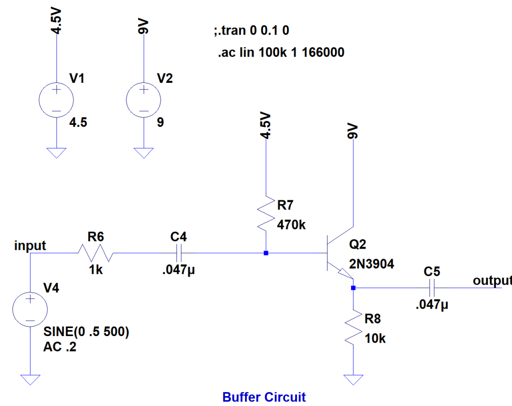


Figure 3.1: Bipolar junction transistor buffer circuit schematic.

Next, a guitar buffer's effect on a guitar model will be examined using an example. Recall how guitar cable capacitance can effect the frequency response of a guitar, which was discussed in Section 2.1. Figure 3.2 compares the guitar model discussed in Figures 2.2 and 2.3 to the same model with a BJT buffer before the extra cable length.

While the buffer is not perfect and does produce some attenuation, the longer cable length can be achieved without completely altering the frequency response of the guitar system as a whole and losing all of the higher frequency components. As guitarists, especially live performers, often need to use long lengths of cable to move around during a show, buffers are important to preserve the desired frequency response of the guitar system as a whole. Some guitars pedals are built without buffers, and some are built without them. Pedals without buffers are marketed as "True Bypass" pedals, and are often seen as superior by guitarists who do not know better [15]. In reality, a buffered pedals have their place, especially when a guitarist wants to drive large lengths of cable or several other effects pedals in their signal chain. In a guitar signal chain with multiple effects, distortion effects are often at the beginning of the chain, so all circuits designed for this project are built with buffers at the input and output.

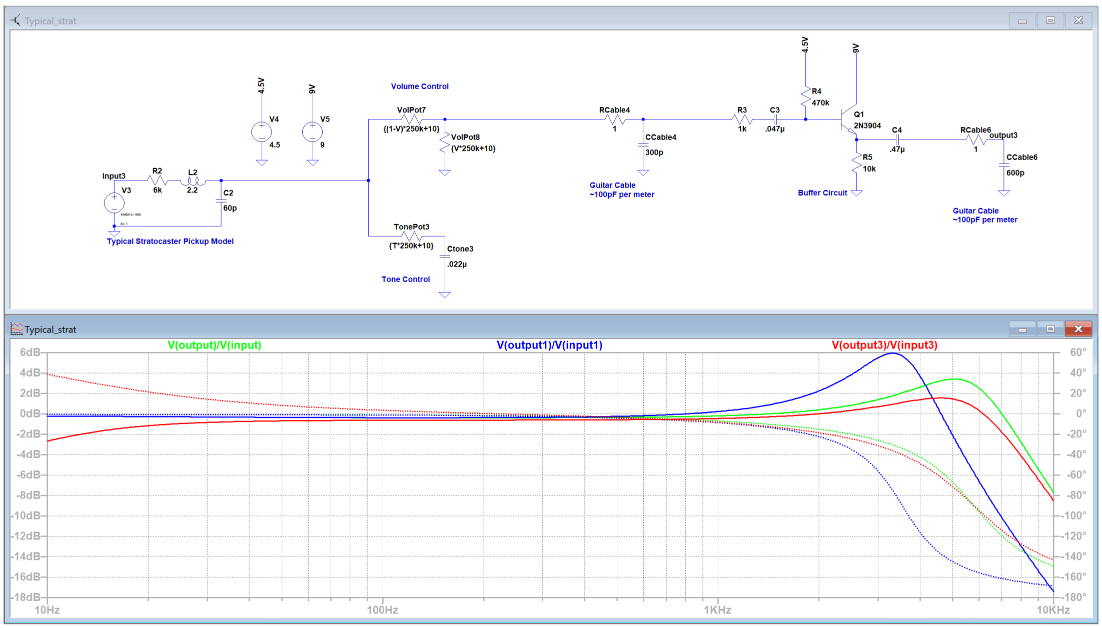


Figure 3.2: The red plot shows the frequency response of the guitar circuit with 3 meters of cable length. The green plot shows the guitar circuit with 9 meters of cable length, and the blue plot shows the guitar with 3 meters of cable, followed by a buffer circuit, then a the remaining 6 meters of cable length.

## 3.2 Gain Stage

The gain stage is the second portion of the distortion circuits used in this project. The gain stage contains an operational amplifier with a potentiometer to control the overall amount of gain put into the circuit. The basic gain stage is different depending on whether the distortion or overdrive topology is used, because the overdrive topology includes a nonlinearity in the feedback loop of the op amp while the distortion circuit is a simple negative feedback amplifier.

### 3.2.1 Distortion Gain Stage

The distortion gain stage used in this project is a simple negative feedback amplifier. Figure 3.3 shows the schematic diagram for the distortion gain stage.

A potentiometer is modeled via resistors Rb and Rt. The parameter, D, controls how much the potentiometer is turned, which takes the wiper from one end of the potentiometer to the other. This forms a voltage divider, which controls how much negative feedback is utilized by the op amp. Figure 3.4 shows the distortion gain stage's frequency response over values of D ranging from 0 to 1.

### 3.2.2 Overdrive Gain Stage

The overdrive gain stage used in this project is similar to the one used in the distortion stage, except it also has a nonlinearity in its feedback loop. Figure 3.5 shows the schematic diagram for the overdrive gain stage.

Figure 3.6 shows the frequency response without a nonlinearity at various values of parameter D.

The overall gain of the overdrive gain stage is significantly lower than that of the distortion gain stage because overdrive is a more subtle effect, while distortion tends to be harsher and

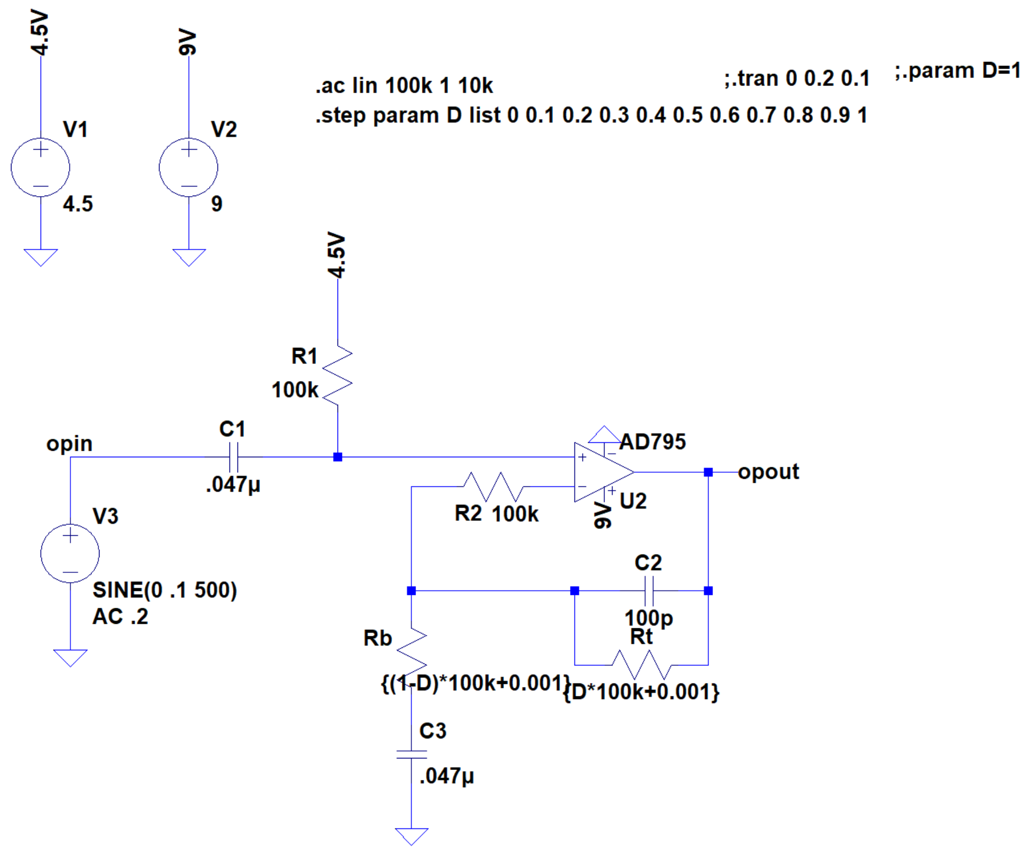


Figure 3.3: Distortion Gain Stage with potentiometer (modeled via resistors Rb and Rt) to change the amount of gain. The gain varies depending on the frequency level, and can be anywhere from 0 dB to 29 dB at a frequency of 1 kHz.

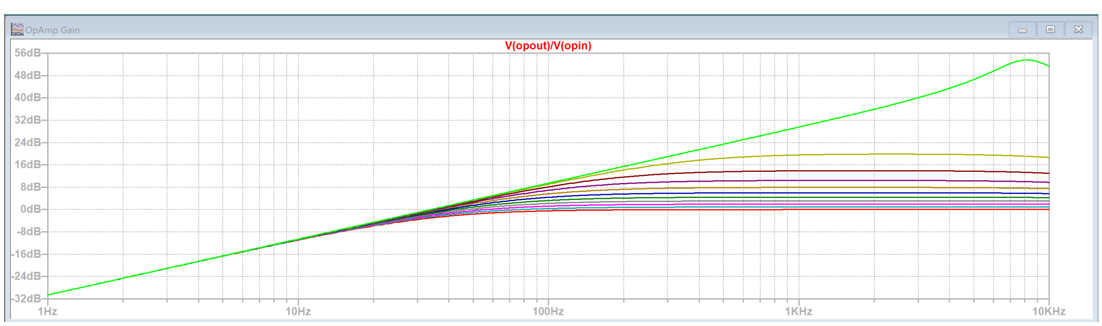


Figure 3.4: Frequency response of the distortion gain stage seen in Figure 3.3. The different plots represent the magnitude response when changing the D parameter from 0 to 1 in intervals of 0.1.

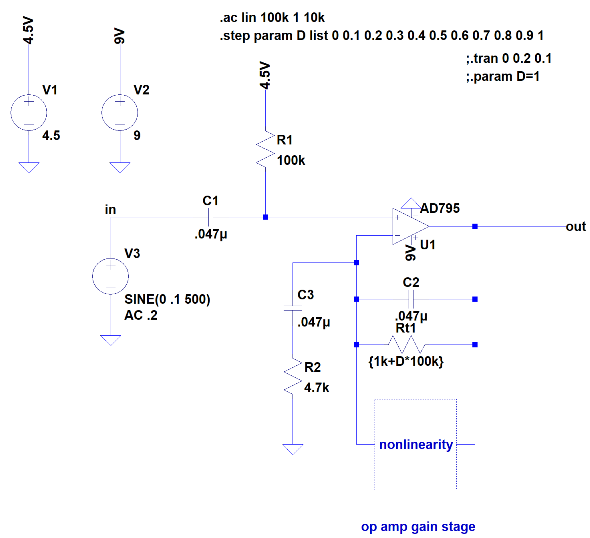


Figure 3.5: Overdrive gain stage with potentiometer to change the amount of gain. Unlike the distortion gain stage, the potentiometer is used as a rheostat and not a voltage divider.

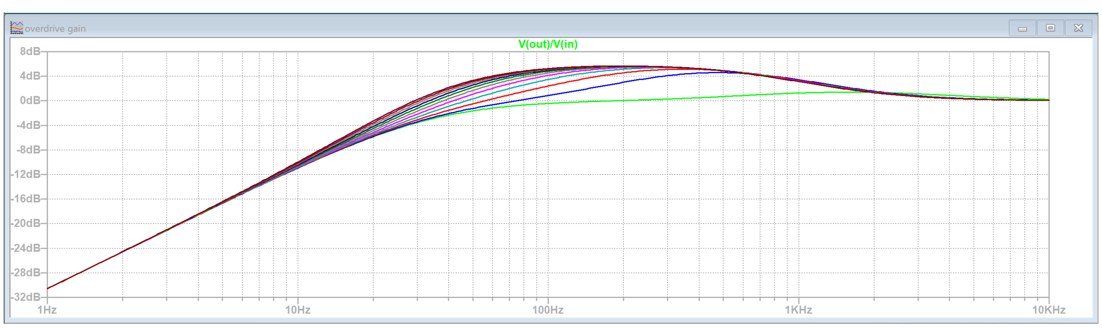


Figure 3.6: Frequency response of the overdrive gain stage without a nonlinearity. The different plots represent the magnitude response when changing the D parameter from 0 to 1 in intervals of 0.1.

louder.

## 3.3 Nonlinearity

Nonlinearities define the characteristics of distortion that a guitar pedal will supply. As discussed in Section 2.2, the nonlinearity can be placed into the circuit in different ways. Overall, the nonlinearity is probably the most important part of the overall guitar effect circuit. In this paper, we will explore two different types of nonlinearities, diode limiters and class b push/pull amplifiers.

### 3.3.1 Diode Limiter

Diode limiters are one of the most common nonlinearity elements in guitar circuits for their simplicity. Diodes are simple circuit elements that only allow current to flow in one direction. Diodes also have a forward voltage drop, which is a voltage across its two terminals that must be reached for any current to flow. In a diode limiter, two diodes are placed in parallel, which limits the high and low voltage limit to the forward voltage drop of those diodes. Figure 3.7 shows the schematic of a diode limiter nonlinearity.

The diode limiter can have different effects depending on the amplitude of the input voltage. Figure 3.8 shows the diode limiter's effect on input sine waves of amplitude 1, 2, and 10 volts.

This makes the diode limiter easy to place after an op amp with variable gain, such as the one in Figure 3.3, as changing the gain will change how much the diode limiter distorts the signal without changing the overall amplitude of the output signal. The diode limiter can also be placed in the nonlinearity block of the overdrive gain block.

Another way to get interesting results from the diode limiter is to change the semiconduct-

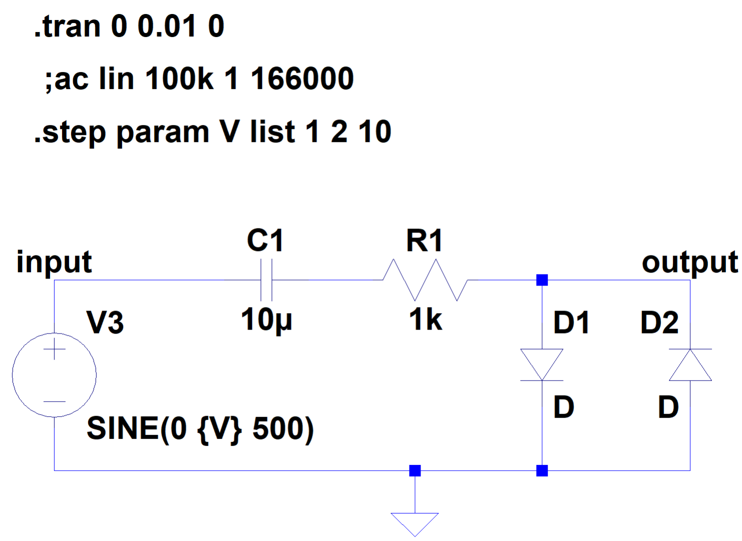


Figure 3.7: Diode limiter schematic.

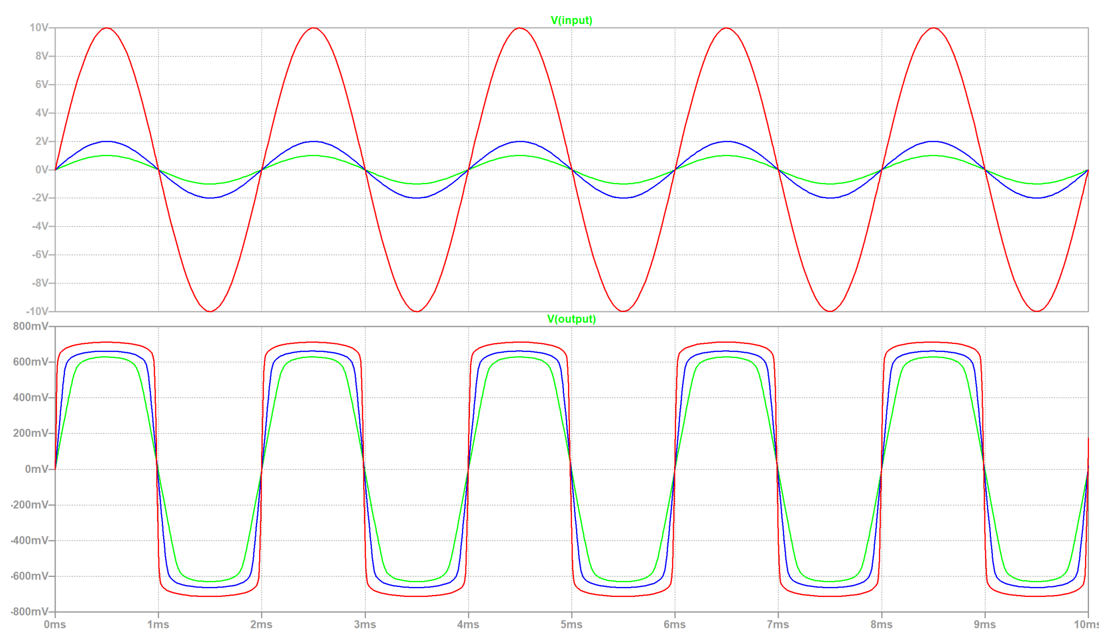


Figure 3.8: Diode limiters respond differently depending on the amplitude of their input voltage. This simulation was run with silicon diodes.

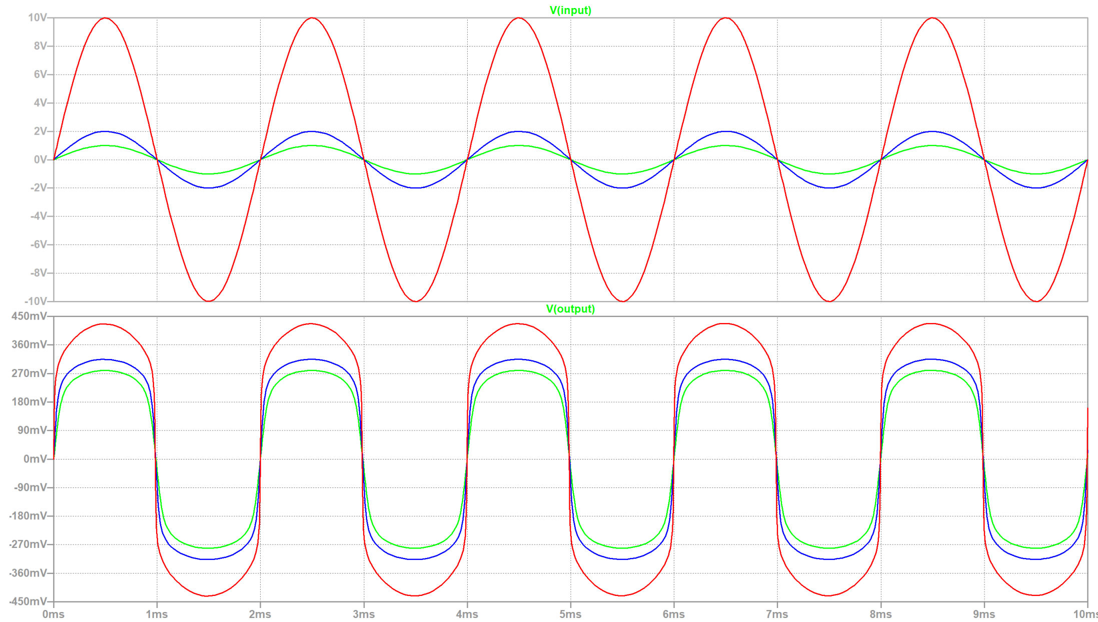


Figure 3.9: Germanium diode limiter time response. Notice the softer overall clipping compared to the silicon diodes in Figure 3.8.

ing material that the diode is made out of. Different semiconductors have different properties. The most important property for guitar circuits is the forward voltage drop. Silicon is the most common diode available, and has a forward voltage drop of around 0.7 V. Another popular material, particularly in audio circuits, is germanium. Germanium diodes have a smaller voltage drop of around 0.3 V, but the drop is less static and can be greater if larger voltages are put across them. This yields a less extreme clipping, which can be seen in Figure 3.9 [16, 17].

Overall, the frequency response of a diode limiter block is flat over the regions that we care about for our purposes, which can be seen in Figure 3.10.

### 3.3.2 Class B Push/Pull

Another nonlinearity used in this project is the class B, or push/pull amplifier [16]. A schematic for a class B amplifier can be seen in Figure 3.11. Class B push/pull amplifiers use both a NPN

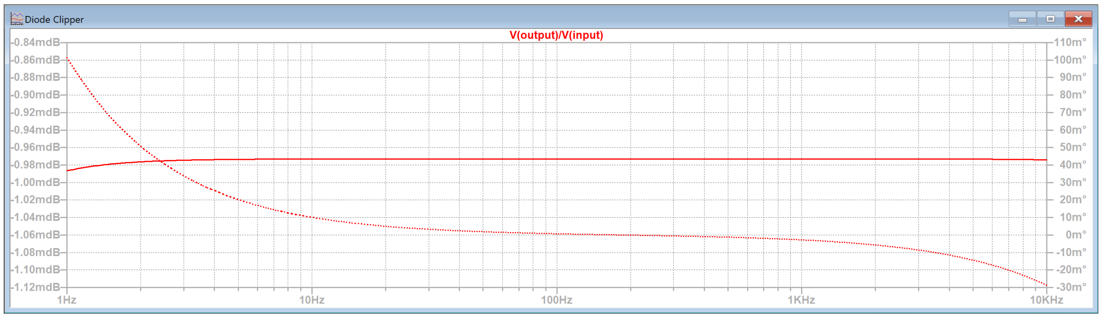


Figure 3.10: Frequency response of a diode limiter.

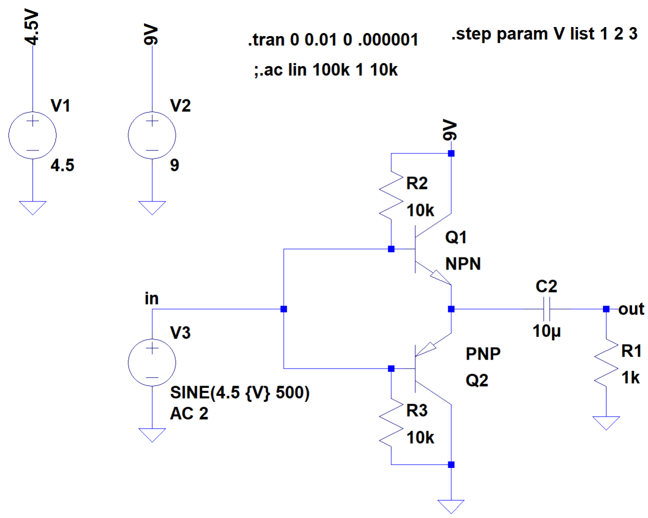


Figure 3.11: Class B Push/Pull Amplifier Schematic.

and a PNP BJT. PNP is a different doping profile for bipolar junction transistors.

Class B amplifiers are often used as transistor amplifiers that consume less power due to not being DC biased to the point that they always draw current, however, this often leads to crossover distortion. Figure 3.12 shows crossover distortion occurring in this circuit.

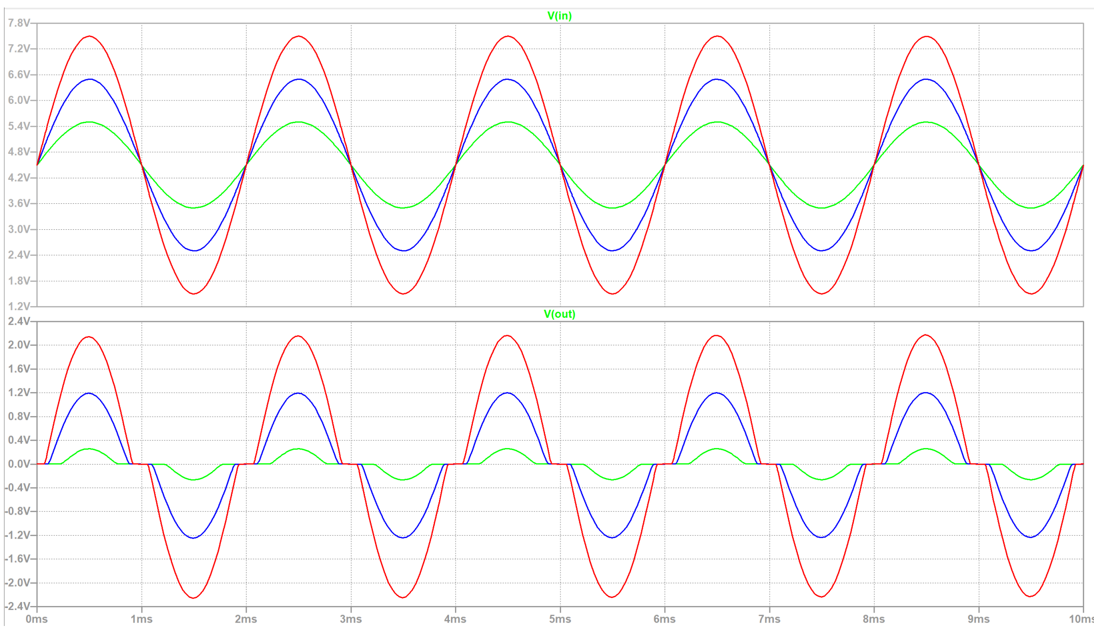


Figure 3.12: Class B Push/Pull Amplifier output signals showing crossover distortion.

# Chapter 4

# Circuit Design and Simulation

This chapter discusses the overall circuits assembled from the building blocks discussed in chapter 3, including circuit simulations. The four basic topologies are the diode limiter distortion topology discussed in Section 4.1, the diode limiter overdrive discussed in Section 4.2, the class B push/pull distortion discussed in Section 4.3, and the class B push/pull overdrive, discussed in Section 4.4.

## 4.1 Design 1 - Diode Limiter Distortion

The first circuit topology used is the diode limiter distortion topology. It follows the distortion circuit block diagram seen in Figure 2.5. The schematic for the diode limiter distortion model can be seen in Figure 4.1.

The diode limiter distortion schematic will be made with 3 different combinations; one with silicon 1N4148 diodes, one with germanium 1N34A diodes, and one mixed, with one silicon and one germanium diode.

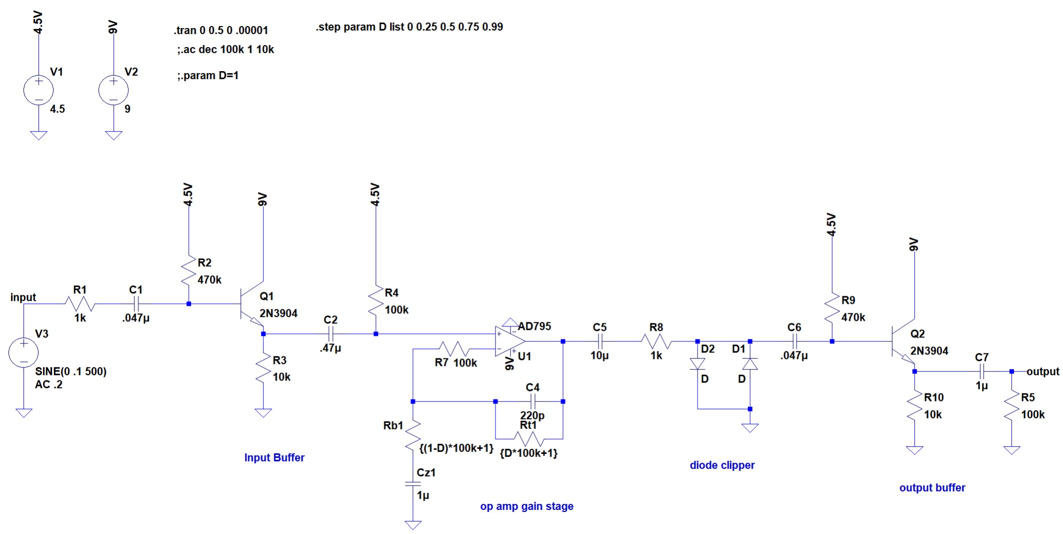


Figure 4.1: Diode limiter distortion schematic.

### 4.1.1 Design 1a - Silicon

Silicon diodes are the most common and widely available diodes. They have a forward voltage drop of about 0.7 V. Figure 4.2 shows the time domain input and output with a 500 Hz signal and parameter D set to various values.

Figure 4.3 shows the frequency response of the silicon diode limiter distortion circuit.

The large difference in the magnitude response for the same difference of D values when D is larger suggests that a logarithmic potentiometer would be best to use for this circuit.

### 4.1.2 Design 1b - Germanium

Germanium diodes are obsolete technology, but the niche applications keep them alive for circuits such as musical distortion effects and radio frequency circuits. Figure 4.4 shows the time domain output of a germanium diode limiter distortion circuit. Figure 4.5 shows the frequency response of the same circuit

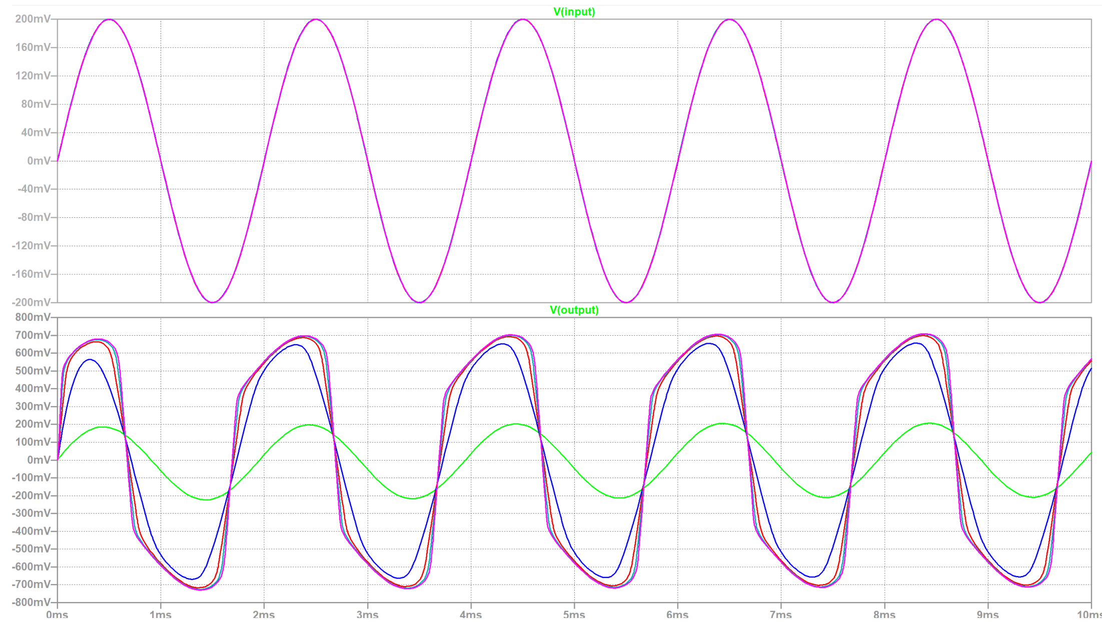


Figure 4.2: Silicon diode limiter distortion time domain input and output with a 500 Hz sinusoidal input signal and parameter D values of 0, 0.25, 0.5, 0.75, and 0.99.

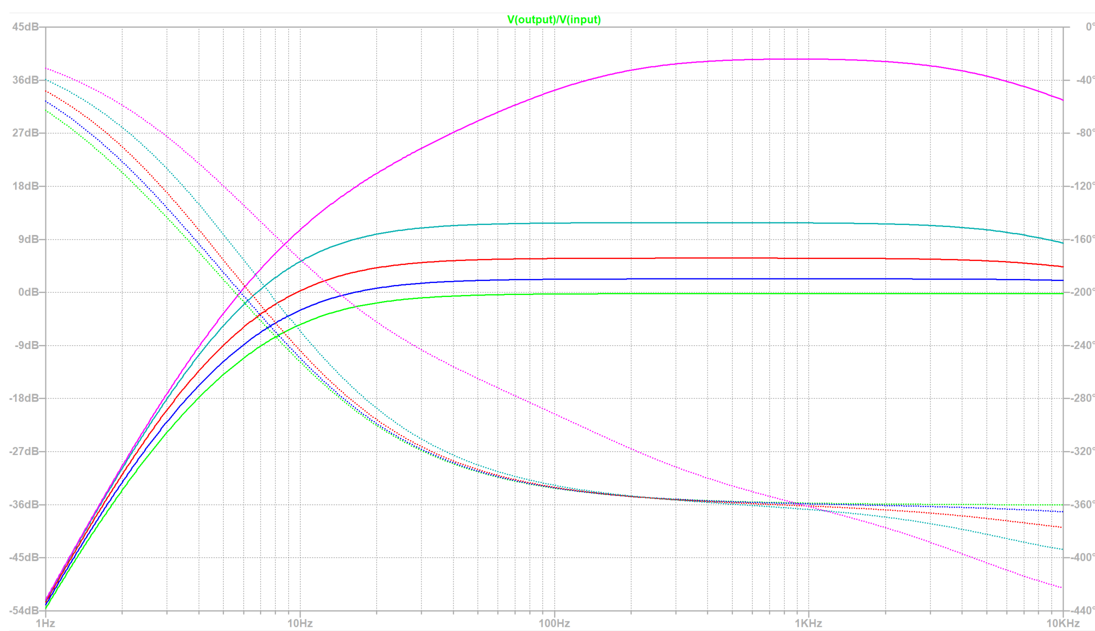


Figure 4.3: Silicon diode limiter distortion frequency response for D values of 0, 0.25, 0.5, 0.75, and 0.99.

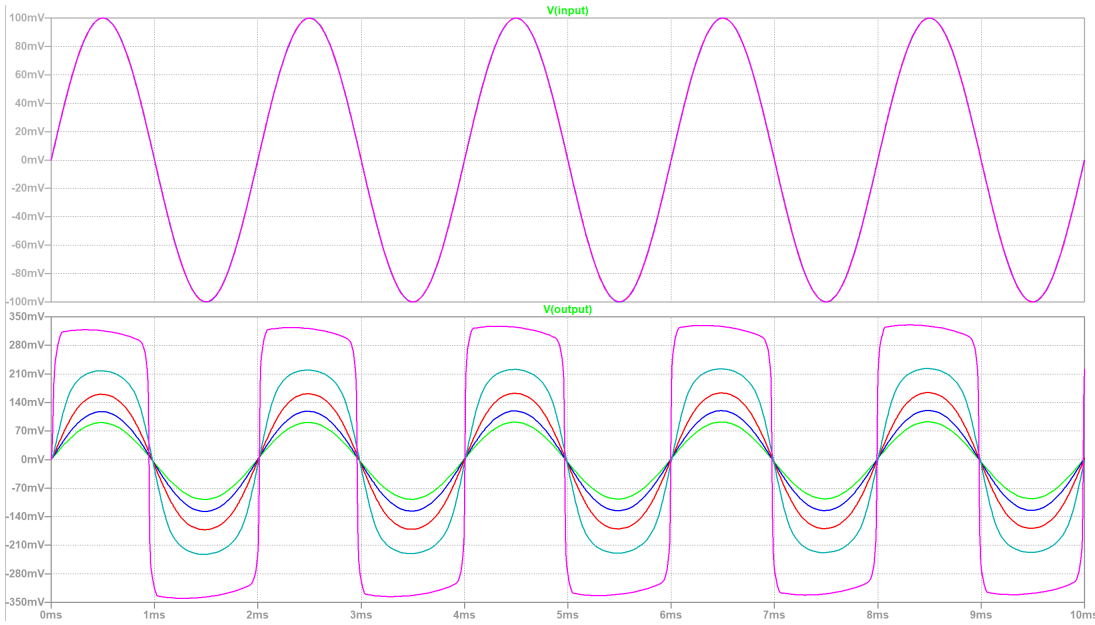


Figure 4.4: Germanium diode limiter distortion time domain input and output with a 500 Hz sinusoidal input signal and D values of 0, 0.25, 0.5, 0.75, and 0.99.

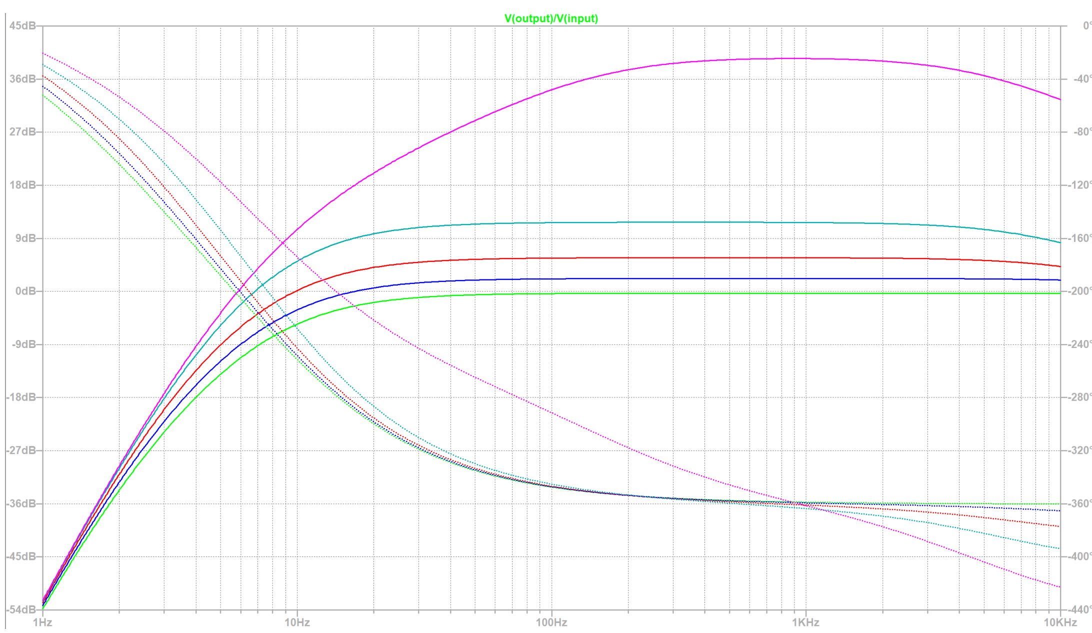


Figure 4.5: Germanium diode limiter distortion frequency response for D values of 0, 0.25, 0.5, 0.75, and 0.99.

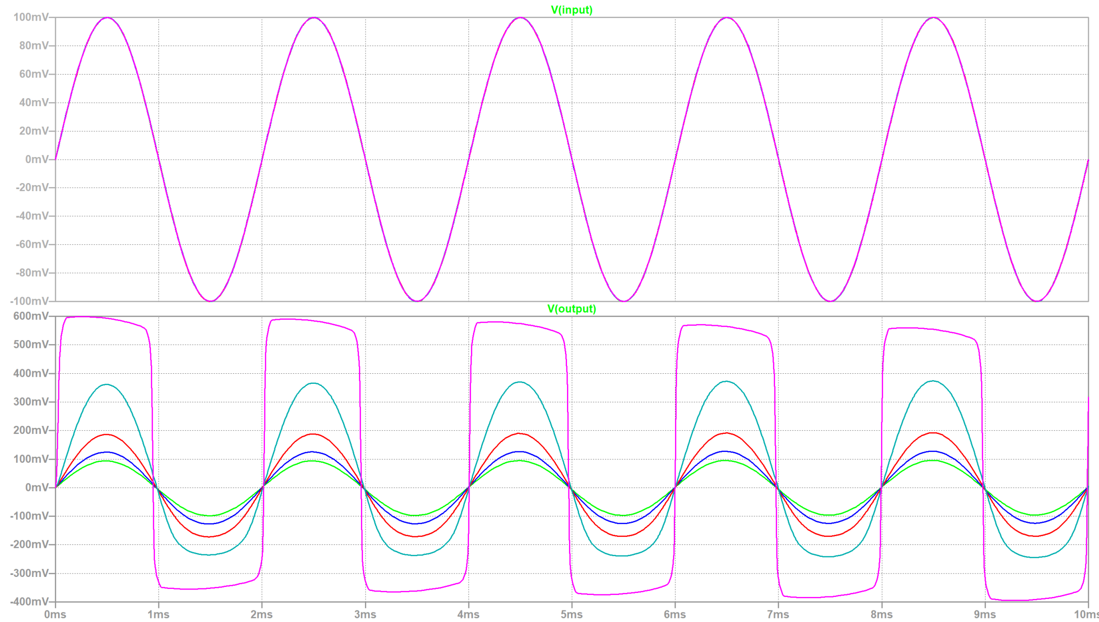


Figure 4.6: Mixed diode limiter distortion time domain input and output with a 500 Hz sinusoidal input signal and D values of 0, 0.25, 0.5, 0.75, and 0.99.

### 4.1.3 Design 1c - Mixed

Some people are of the opinion that asymmetric clipping sounds better than symmetric clipping. One way of doing this is by using diodes with different characteristics in the clipping stage. This example uses one silicon and one germanium diode. Figure 4.6 shows the time domain output of a mixed diode limiter circuit and Figure 4.7 shows the frequency response of the same circuit.

## 4.2 Design 2 - Diode Limiter Overdrive

The second circuit topology used the diode limiter nonlinearity in the overdrive block diagram configuration seen in Figure 2.6. The schematic for this circuit can be seen in Figure 4.8.

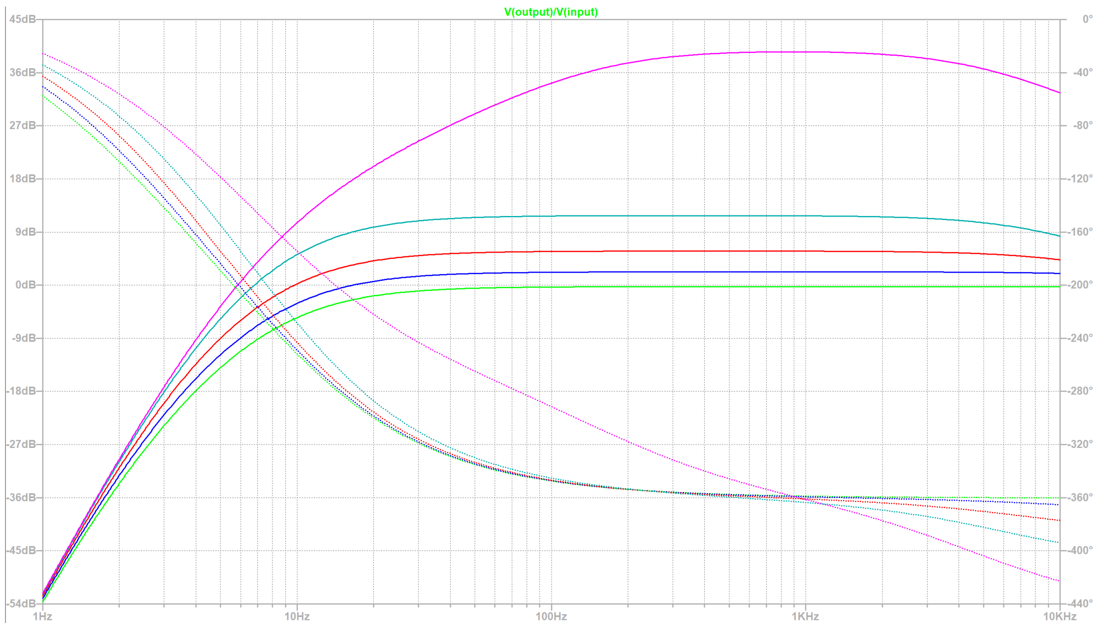


Figure 4.7: Mixed diode limiter distortion frequency response for D values of 0, 0.25, 0.5, 0.75, and 0.99.

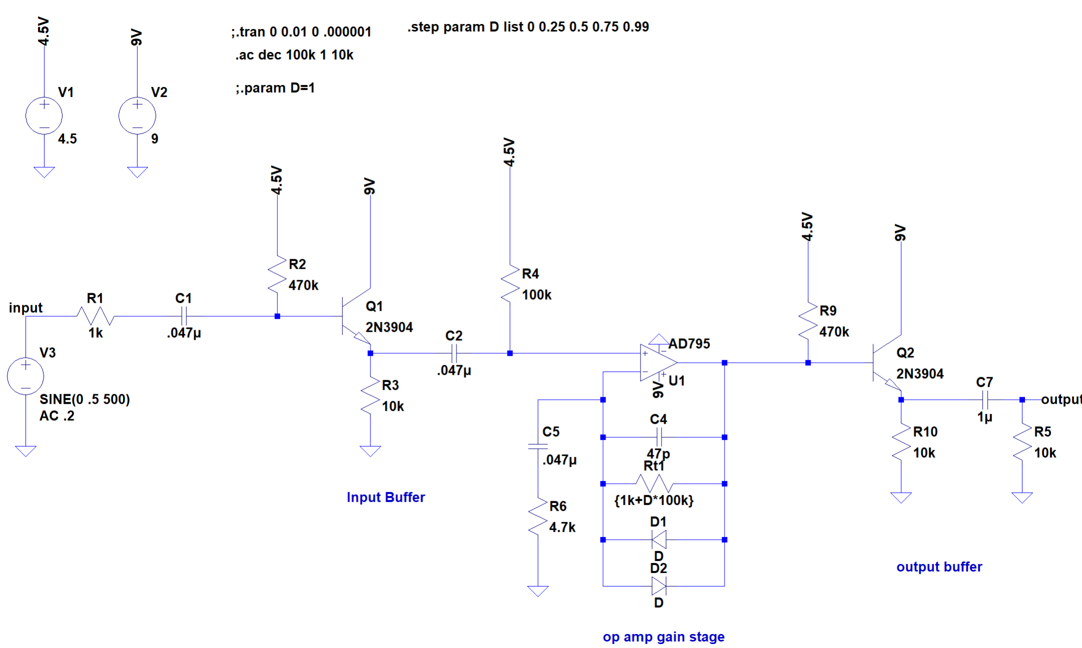


Figure 4.8: Diode limiter overdrive schematic.

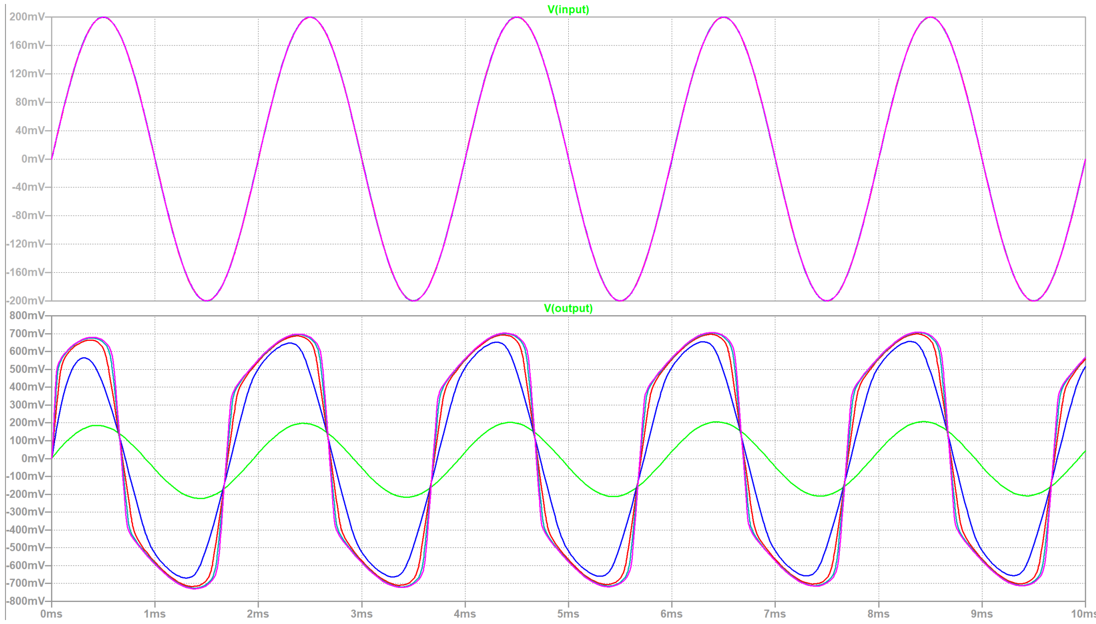


Figure 4.9: Silicon diode limiter overdrive time domain input and output with a 500 Hz sinusoidal input signal and parameter D values of 0, 0.25, 0.5, 0.75, and 0.99.

### 4.2.1 Design 2a - Silicon

Figure 4.9 shows the time domain response of the silicon diode limiter overdrive with an input sine wave at 500 Hz and the D parameter set to 1. Figure 4.10 shows the frequency response of the same circuit

### 4.2.2 Design 2b - Germanium

Figure 4.11 shows the time domain response of the germanium diode limiter overdrive with an input sine wave at 500 Hz and the D parameter set to 1. Figure 4.12 shows the frequency response of the same circuit.

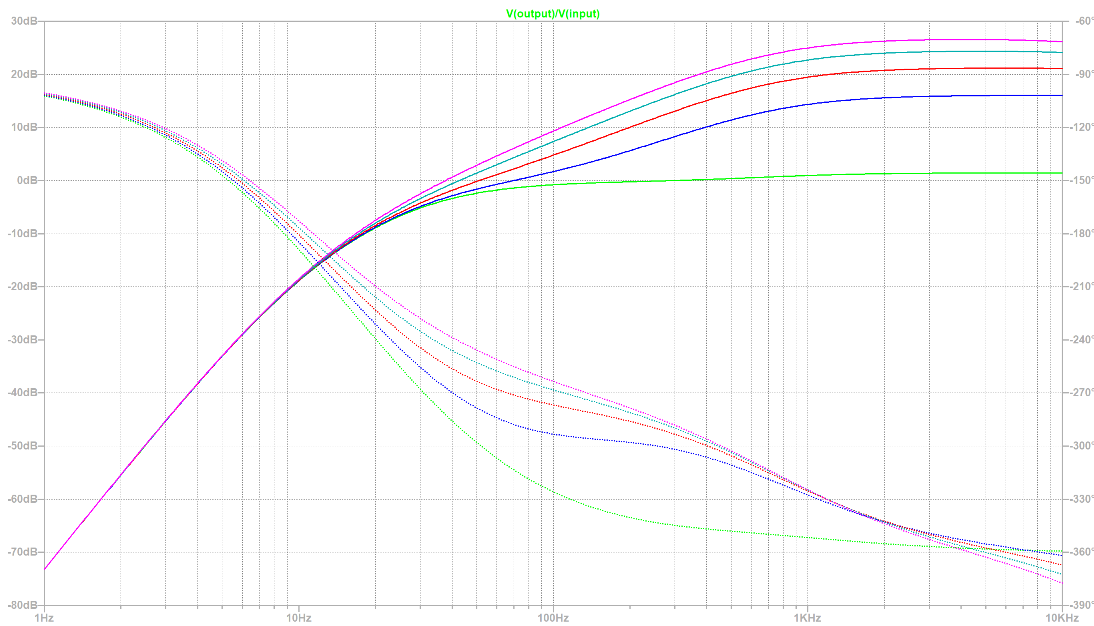


Figure 4.10: Silicon diode limiter overdrive frequency response for D values of 0, 0.25, 0.5, 0.75, and 0.99.

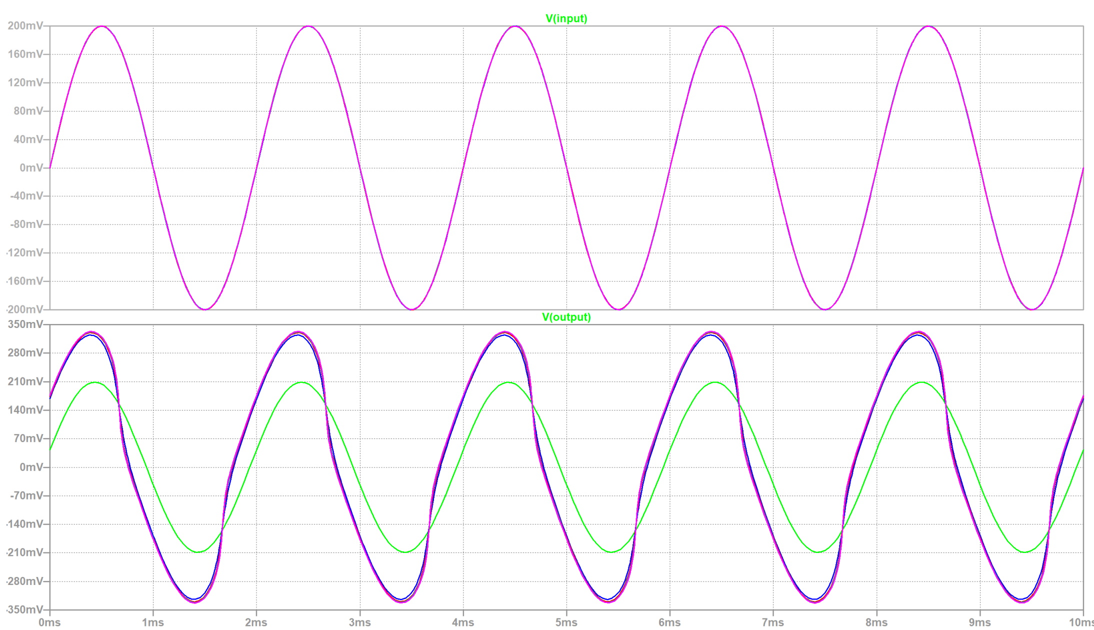


Figure 4.11: Germanium diode limiter overdrive time domain input and output with a 500 Hz sinusoidal input signal and parameter D values of 0, 0.25, 0.5, 0.75, and 0.99.

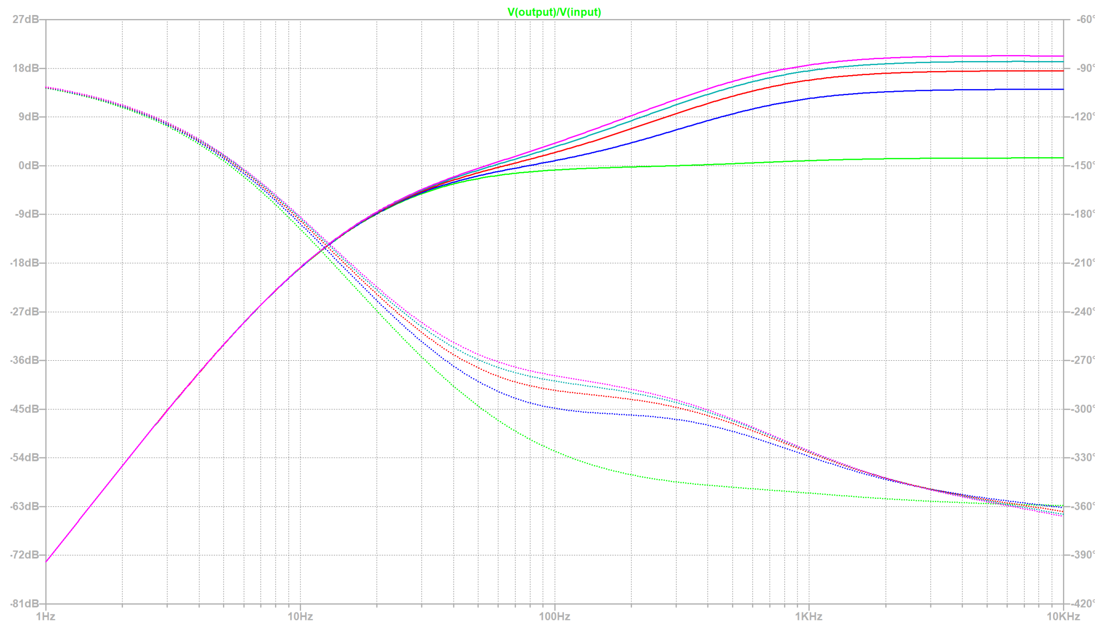


Figure 4.12: Germanium diode limiter overdrive frequency response for D values of 0, 0.25, 0.5, 0.75, and 0.99.

### 4.2.3 Design 2c - Mixed

Figure 4.13 shows the time domain output of a mixed diode limiter circuit and Figure 4.14 shows the frequency response of the same circuit.

## 4.3 Design 3 - Class B Push/Pull Distortion

This section presents the class B push/pull distortion circuit based of the distortion block diagram in Figure 2.5 and the class B push/pull nonlinearity in Figure 3.11. This topology features crossover distortion. Figure 4.15 shows the schematic of the class B push/pull distortion circuit.

To demonstrate the effect of the gain stage on crossover distortion, Figure 4.16 shows the time domain response to a 500 Hz sinusoidal input signal with various D values.

As can be seen, the frequency remains the same, but more signal gets through as the gain

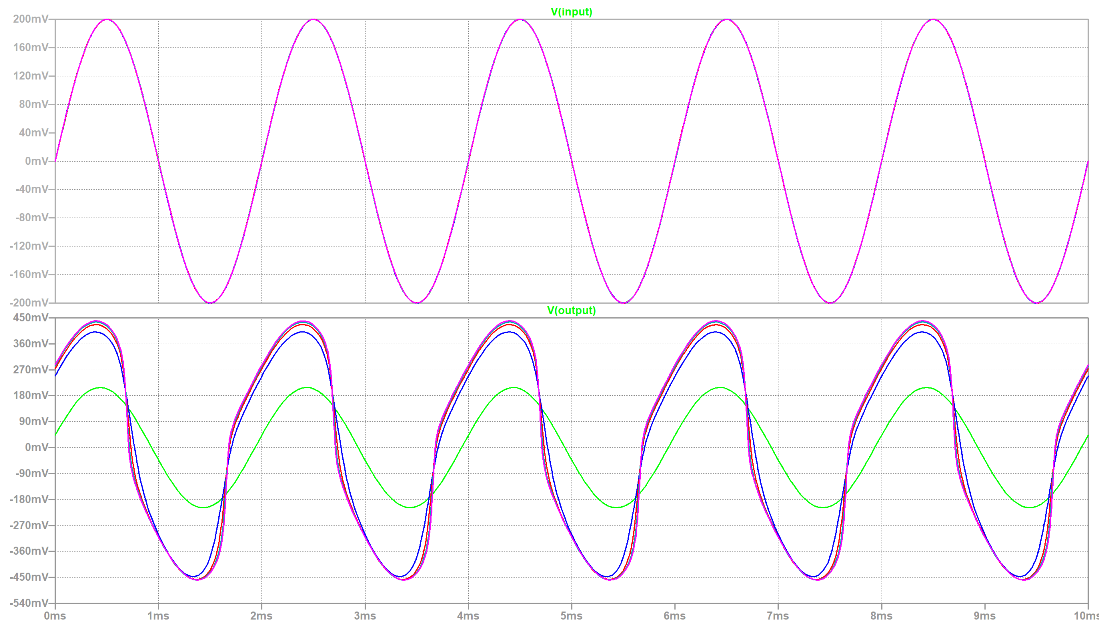


Figure 4.13: Mixed diode limiter overdrive time domain input and output with a 500 Hz sinusoidal input signal and parameter D values of 0, 0.25, 0.5, 0.75, and 0.99.

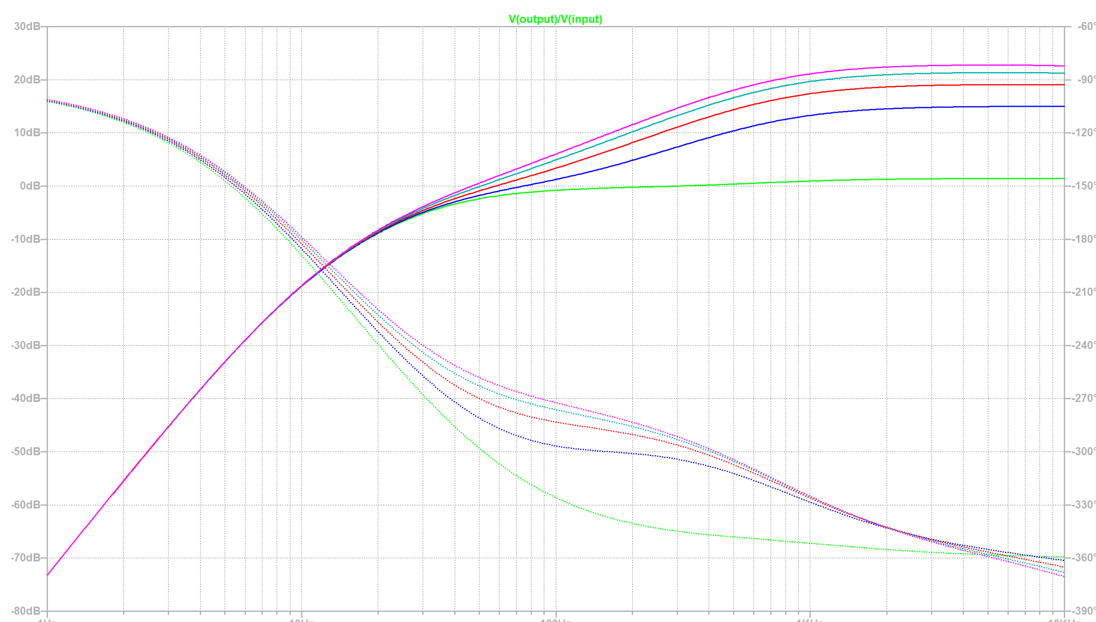


Figure 4.14: Mixed diode limiter overdrive frequency response for parameter D values of 0, 0.25, 0.5, 0.75, and 0.99.

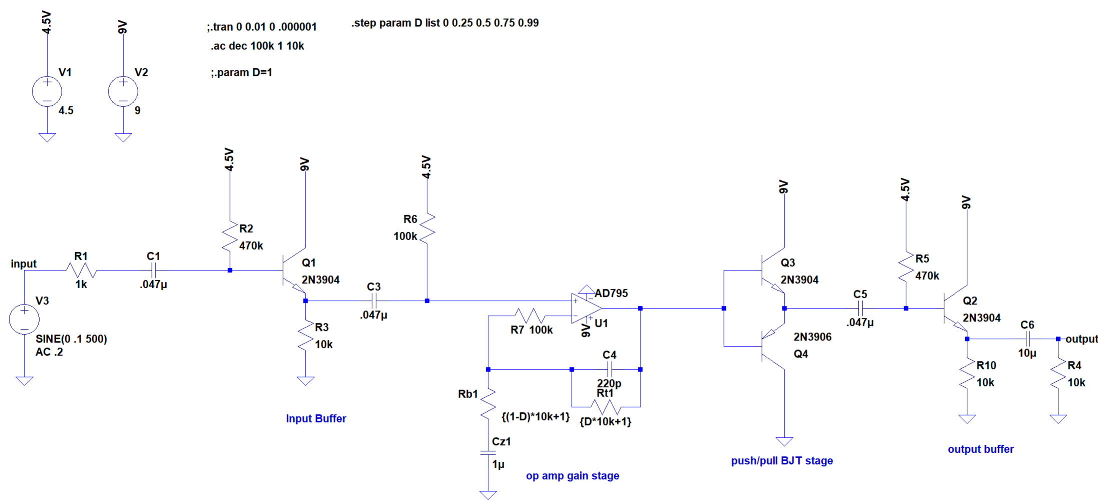


Figure 4.15: Class B push/pull distortion schematic.

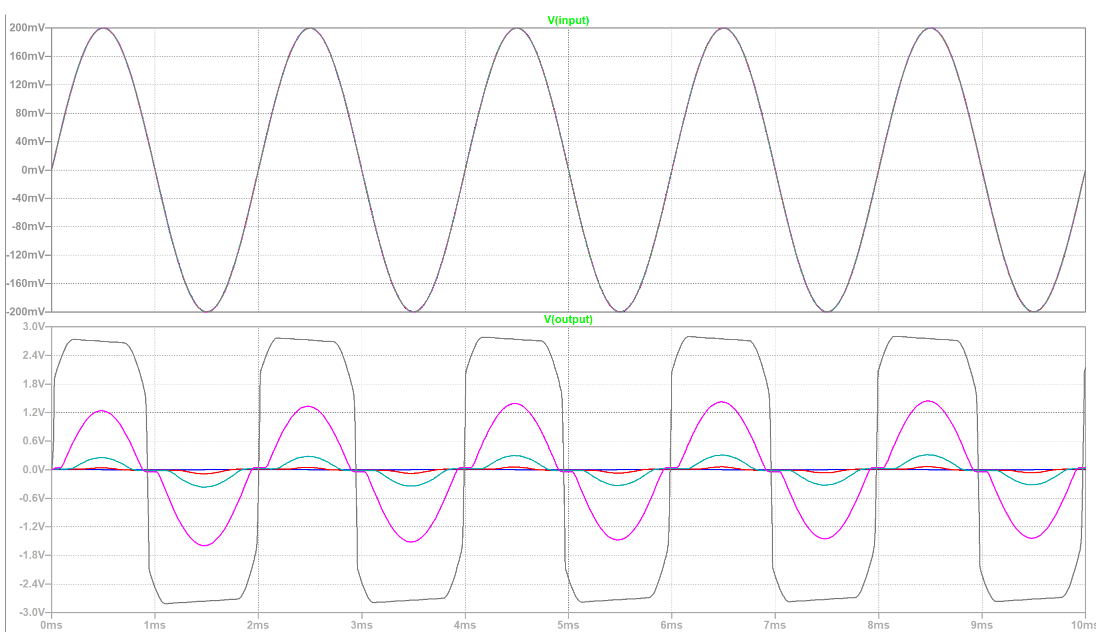


Figure 4.16: Class B push/pull distortion time domain response to a 500 Hz sinusoidal input with parameter D values of 0, 0.25, 0.6, 0.75, 0.9, and 1.

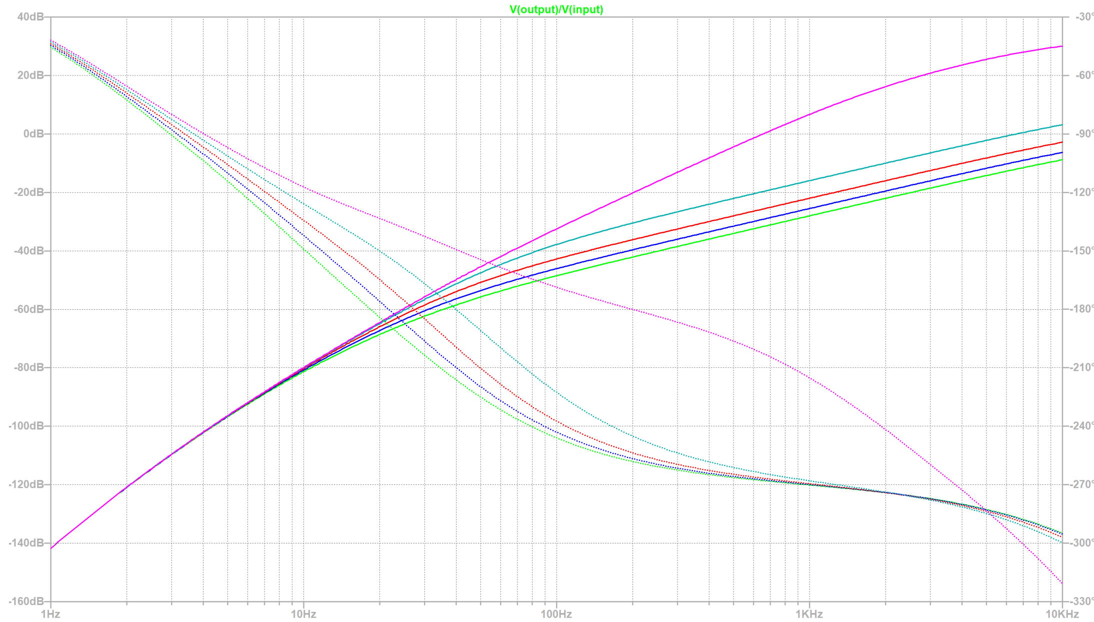


Figure 4.17: Class B push/pull distortion frequency response for parameter D values of 0, 0.25, 0.5, 0.75, and 0.99.

increases. Figure 4.17 shows the frequency response of this circuit for various D values.

The frequency response changes more between higher values of D, which suggests that a potentiometer with a logarithmic taper would be the best fit for this circuit.

## 4.4 Design 4 - Class B Push/Pull Overdrive

This section presents the class B push/pull overdrive circuit based off the overdrive block diagram in Figure 2.6 and the class B push/pull nonlinearity in Figure 4.15. The schematic for the class B push/pull overdrive is in Figure 4.18.

Figure 4.19 shows the time domain response of this circuit to a 500 Hz sinusoid, and Figure 4.20 shows the frequency response for different values of parameter D.

The frequency response changes more for lower values of D, which suggests that a potentiometer with a reverse logarithmic taper would be the best fit for this circuit.

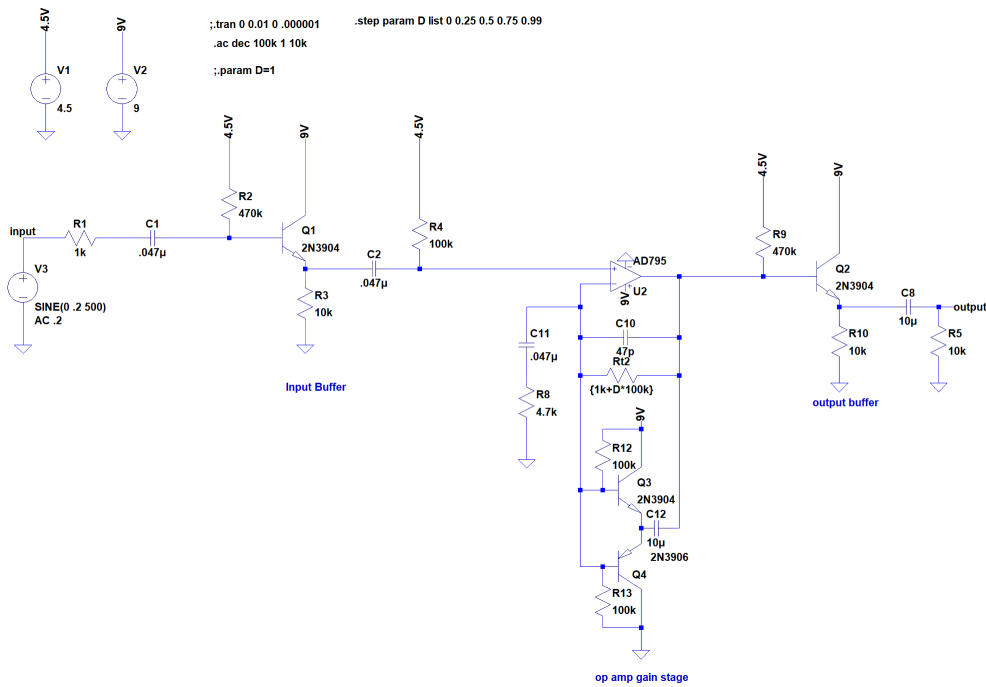


Figure 4.18: Class B push/pull overdrive schematic.

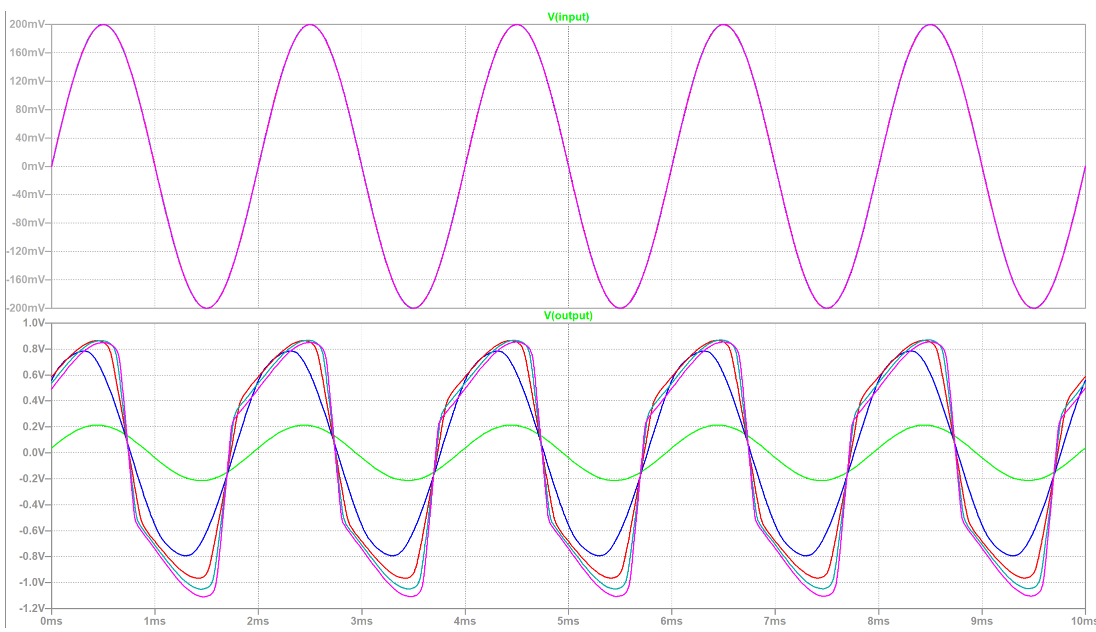


Figure 4.19: Class B push/pull overdrive time domain input and output with a 500 Hz sinusoidal input signal and parameter D values of 0, 0.25, 0.5, 0.75, and 0.99.

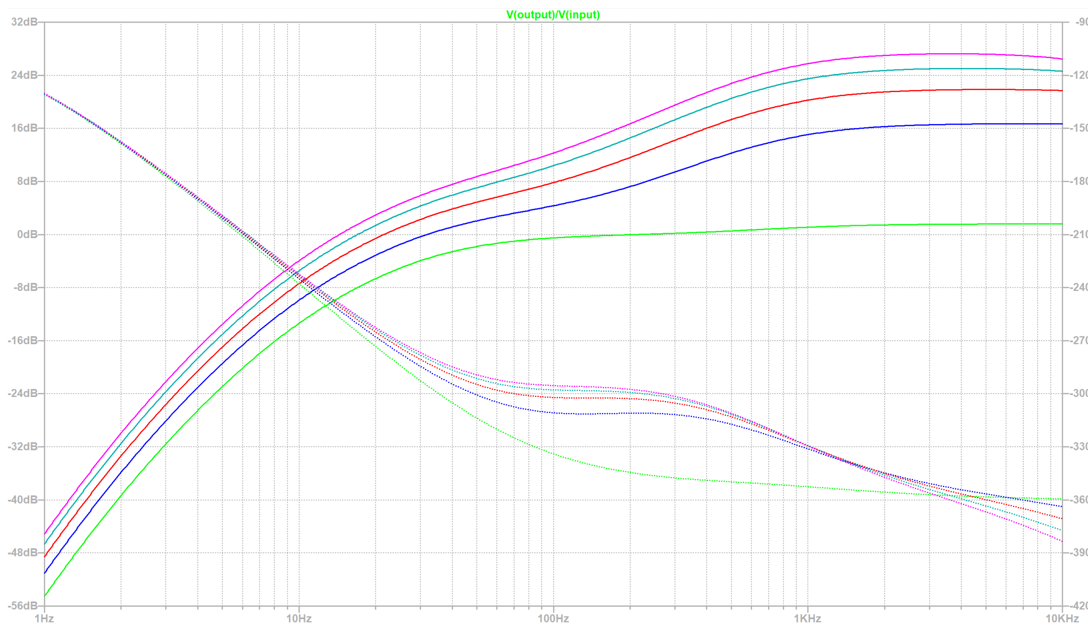


Figure 4.20: Class B push/pull overdrive frequency response for parameter D values of 0, 0.25, 0.5, 0.75, and 0.99.

# Chapter 5

# Hardware and Test

This chapter discusses the hardware that was built for this project, as well as test results. Section 5.1 discusses the layout of the circuit schematics, section 5.2 discusses tests done on the hardware, and section 5.3 discusses how the circuits sound.

## 5.1 Layout

The schematics were first drawn and simulated in LTSpice, and then were recreated, along with the printed circuit board (PCB) layout, using Altium CircuitMaker software. The 8 circuits discussed in Chapter 4 were created in 4 different projects within CircuitMaker, one for each overarching topology. A few changes were made for layout housekeeping. For example, decoupling capacitors were added close to the op amp in all circuits to filter noise out between the high and low voltage rails. Another decoupling capacitor was added between the 4.5 V input and ground. These are not necessary in the simulation circuits because all power supplies are ideal in the simulations. Pictures from the CircuitMaker program containing the CircuitMaker schematics and board layers can be found in Appendix I.

Figure 5.1: Fix to prevent large DC voltages at the output of the circuit upon power on.

### 5.1.1 Layout Mistakes

A few mistakes were made on the layouts, however, they were all fixable. The first mistake occurred on all 4 board topologies. The last capacitor in the output buffer stage needs to be connected to ground via a resistor to speed up the capacitors charging a prevent a large DC voltage from being present at the output when the circuits are powered on. DC voltages can cause damage amplifiers and speakers. This is easily fixable with a resistor connecting the signal terminal of the output jack to the ground terminal of the output jack, which is large enough to accommodate the extra hardware. Figure 5.1 shows this fix.

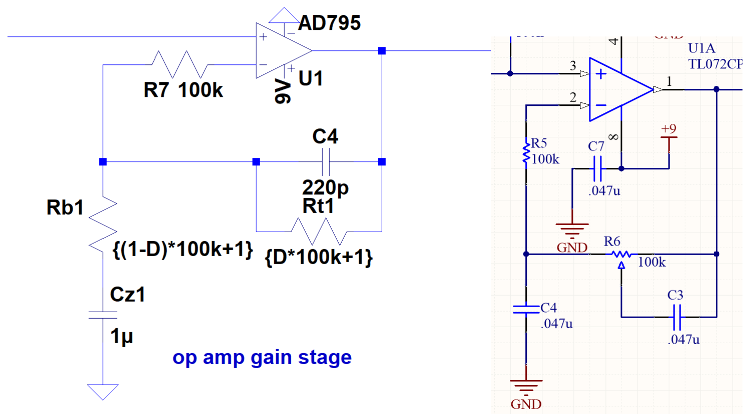


Figure 5.2: Mistake in the layout of the distortion topology potentiometer. The right image is the correct schematic and the left image is the one that was created in layout. The middle lug of the potentiometer should connect to the 100 kΩ resistor attached to the negative terminal of the op amp.

Another mistake occurred on the circuits that use the distortion block diagram topology. The potentiometers were not laid out correctly. Figure 5.2 compares the schematics to highlight this mistake.

Another issue was a ringing noise when the potentiometer was turned for full gain within the distortion circuits. This was caused by a low resistance for the schematic value of Rb1. 4.7 kΩ resistors can be used between capacitor C4 and the third terminal of the potentiometer to reduce the noise. These mistake was easily fixed by cutting the copper trace between R5 and C4 and soldering a wire between R5 and the middle terminal of the potentiometer. Figure 5.3 shows this fix.

## 5.2 Tests

All 8 circuit topologies were tested with an input sine wave to compare to the simulations from Chapter 4. The circuits were also tested with an network analyzer via the Analog Devices

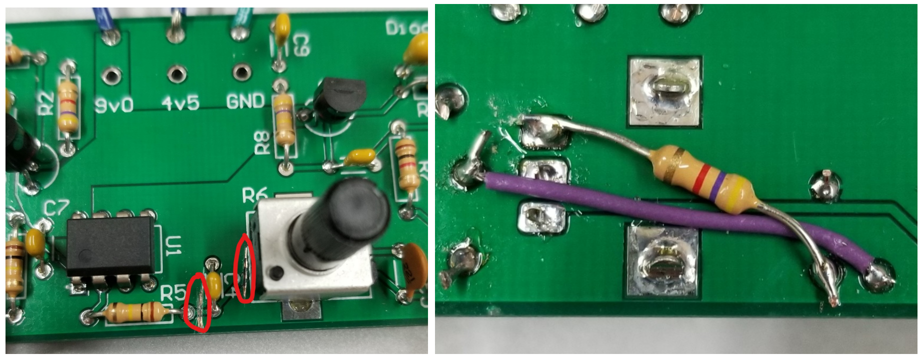


Figure 5.3: Fix for the distortion topology potentiometer layout mistake.
Left: traces that need to be cut on the top of the distortion topology printed circuit board.
Right: connections made on the back of the board using a wire and a 4.7 kΩ resistor.

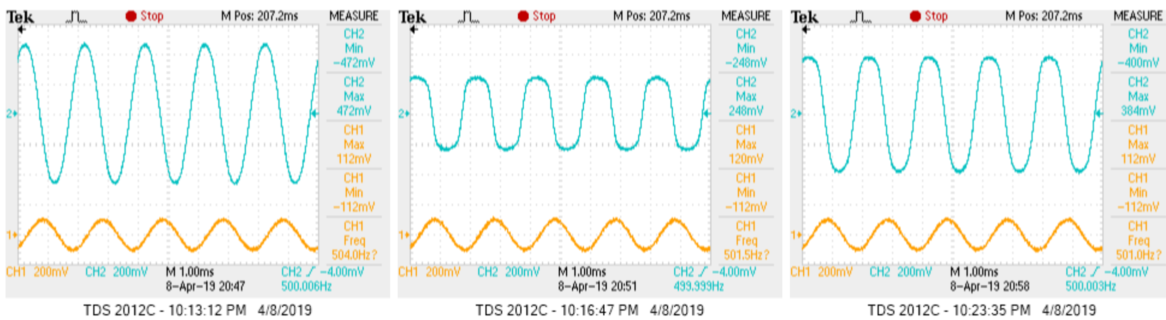


Figure 5.4: Left: Silicon diode limiter distortion oscilloscope capture. Middle: Germanium diode limiter distortion oscilloscope capture. Right: Mixed diode limiter distortion oscilloscope capture.

Analog Discovery Module. All network analyzer plots are shown with a 100 mV input signal. The circuits were also tested using an XY oscilloscope and a frequency sweeper.

### 5.2.1 Diode Limiter Distortion

Figure 5.4 shows oscilloscope captures for all 3 topologies of the diode limiter distortion circuit with the potentiometer turned to max gain.

The silicon diode limiter distortion did not clip as it did in the simulations from Figure 4.2, and acted more as a boost. This could be due to variations in the 100 kΩ potentiometer not

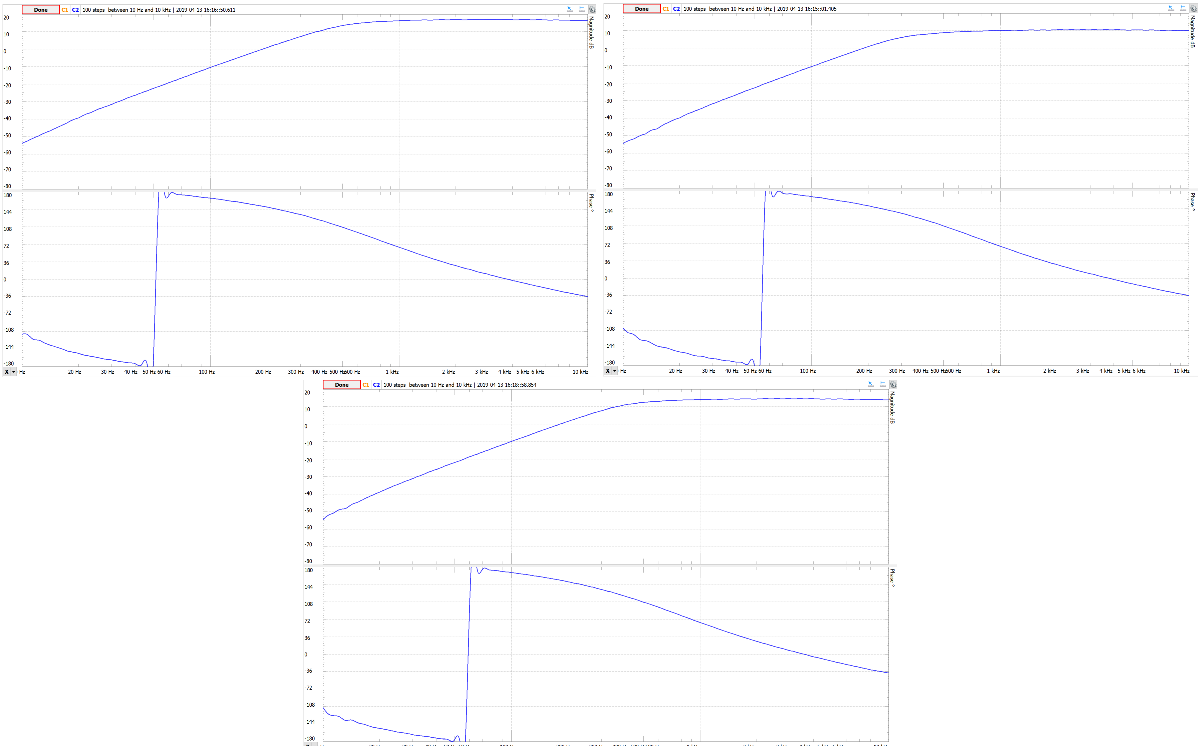

Figure 5.5: Top left: Silicon diode limiter distortion network analyzer capture.
Top right: Germanium diode limiter distortion network analyzer capture.
Bottom: Mixed diode limiter distortion network analyzer capture.

reaching the full gain that was expected. It could also be because the operational amplifier was simulated with ideal power supplies [18].

Figure 5.5 shows the frequency response of the diode limiter distortion circuits obtained from the Analog Discovery Module network analyzer.

Figure 5.6 shows scope captures a frequency sweep using an oscilloscope in XY mode.

### 5.2.2 Diode Limiter Overdrive

Figure 5.7 shows oscilloscope captures for all 3 topologies of the diode limiter distortion circuit with the potentiometer turned to max gain.

Figure 5.8 shows the frequency response of the diode limiter distortion circuits obtained


Figure 5.6: Top left: Silicon diode limiter distortion frequency sweep with XY scope.
Top right: Germanium diode limiter distortion frequency sweep with XY scope.
Bottom: Mixed diode limiter distortion frequency sweep with XY scope.

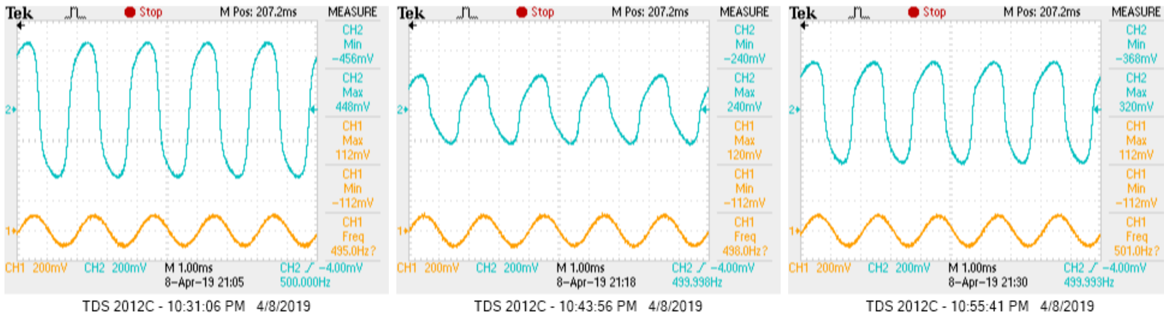


Figure 5.7: Left: Silicon diode limiter overdrive oscilloscope capture.
Middle: Germanium diode limiter overdrive oscilloscope capture.
Right: Mixed diode limiter overdrive oscilloscope capture.

from the Analog Discovery Module network analyzer.

Figure 5.9 shows scope captures a frequency sweep with an oscilloscope in XY mode.

### 5.2.3 Class B Push/Pull Distortion

Figure 5.10 shows oscilloscope captures for all 3 topologies of the diode limiter distortion circuit with the potentiometer turned to max gain.

Figure 5.11 shows the frequency response of the diode limiter distortion circuits obtained from the Analog Discovery Module network analyzer.

Figure 5.12 shows scope captures using a frequency sweeper and an oscilloscope in XY mode.

### 5.2.4 Class B Push/Pull Overdrive

Figure 5.13 shows oscilloscope captures for all 3 topologies of the diode limiter distortion circuit with the potentiometer turned to max gain.

Figure 5.14 shows the frequency response of the diode limiter distortion circuits obtained from the Analog Discovery Module network analyzer.

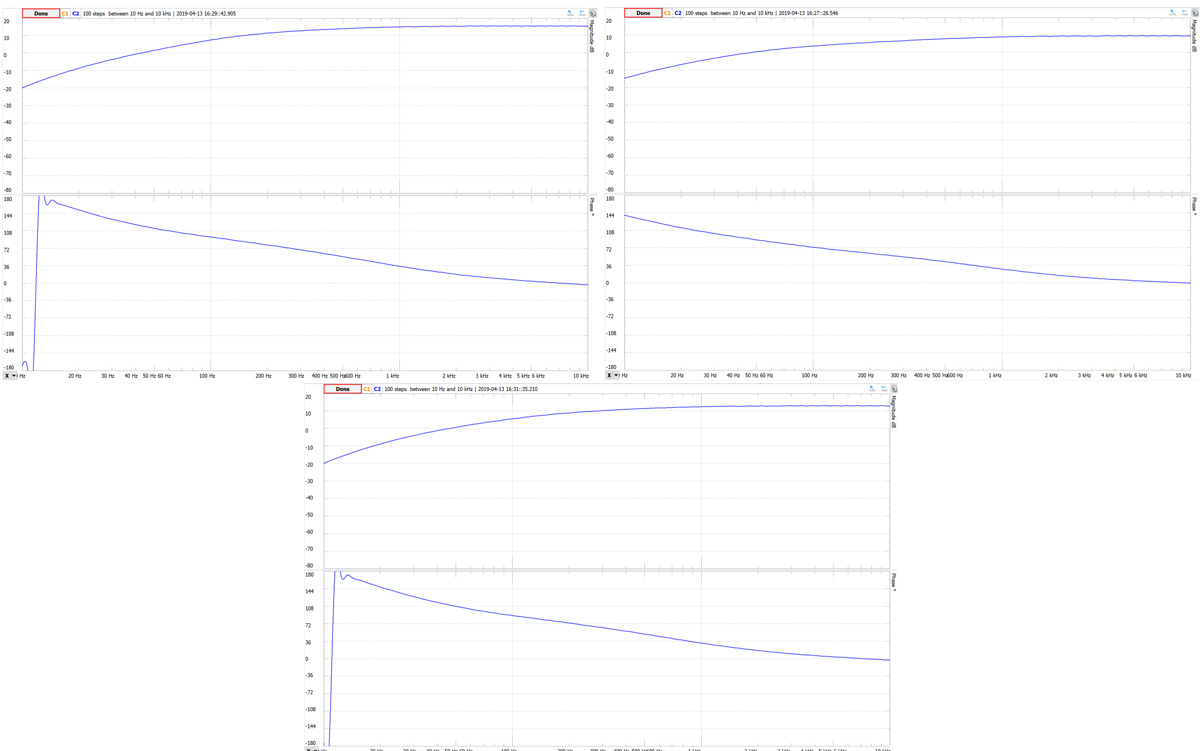


Figure 5.8: Top left: Silicon diode limiter overdrive network analyzer capture.
Top right: Germanium diode limiter overdrive network analyzer capture.
Bottom: Mixed diode limiter overdrive network analyzer capture.

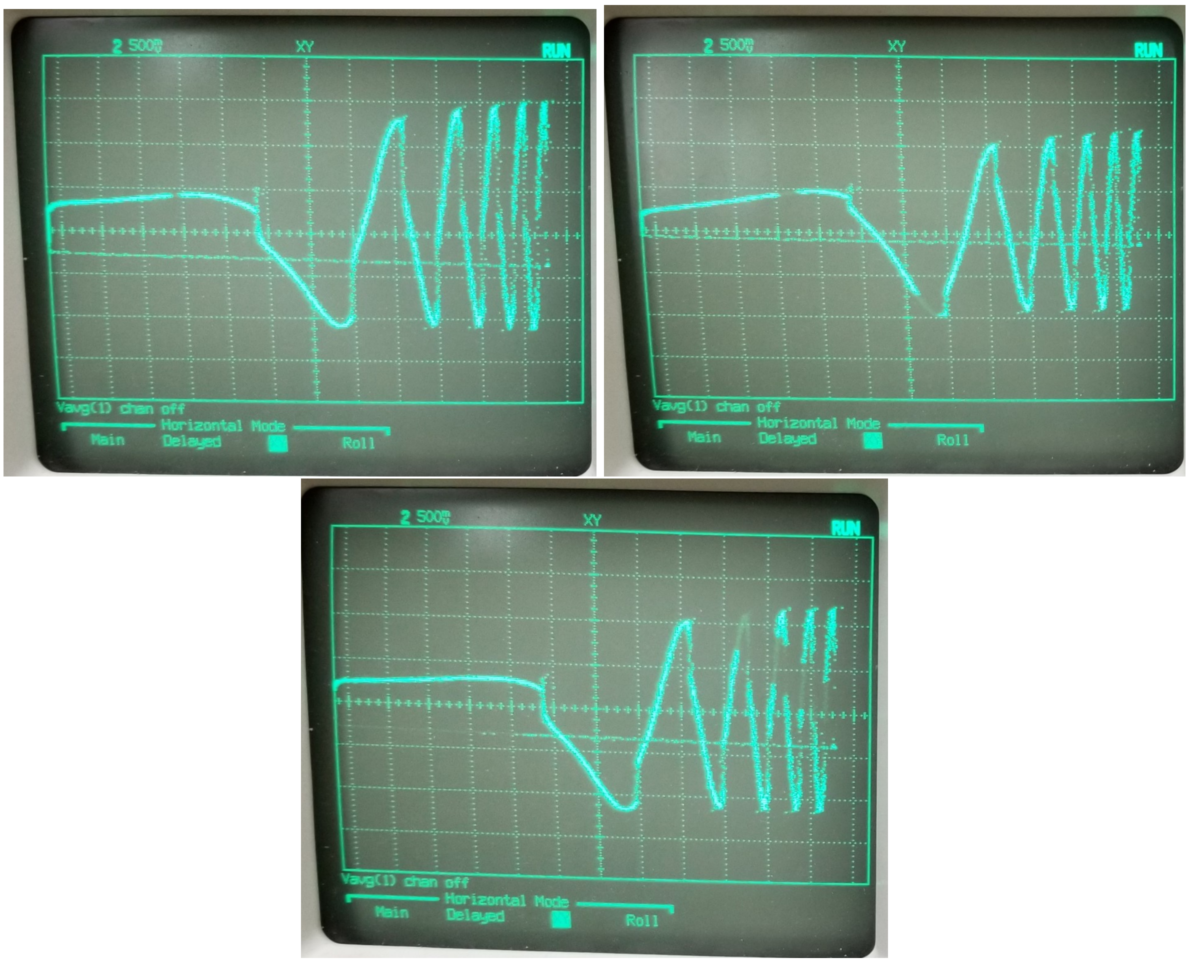


Figure 5.9: Top left: Silicon diode limiter distortion frequency sweep with XY scope. Top right: Germanium diode limiter distortion frequency sweep with XY scope. Bottom: Mixed diode limiter distortion frequency sweep with XY scope.

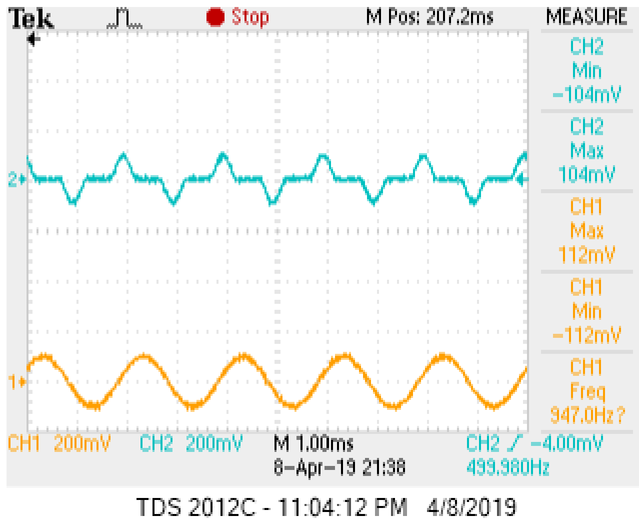


Figure 5.10: Class B push/pull distortion oscilloscope capture.

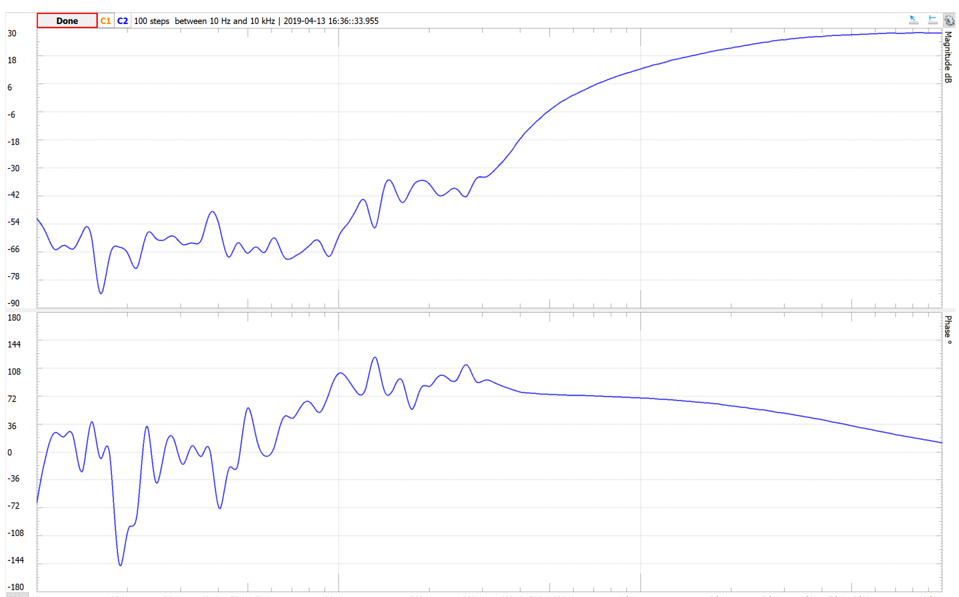


Figure 5.11: Class B push/pull distortion network analyzer capture.

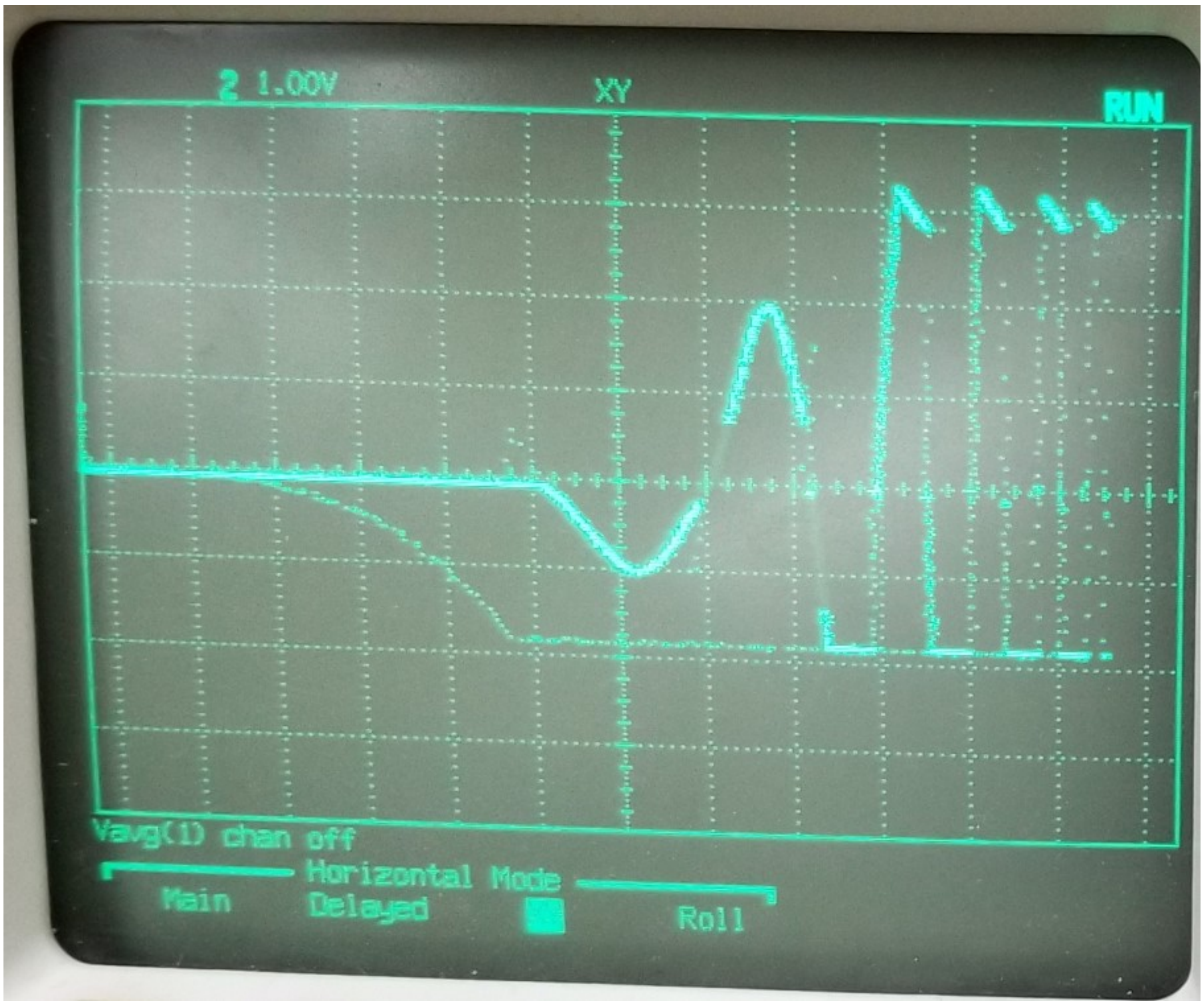


Figure 5.12: Class B distortion frequency sweep with XY scope.

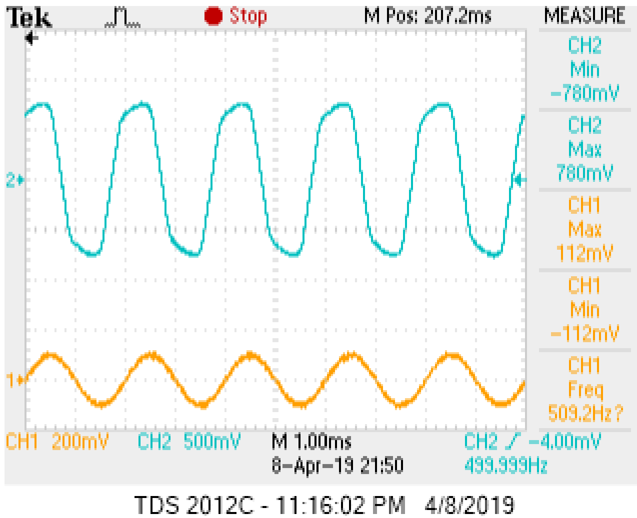


Figure 5.13: Class B push/pull overdrive oscilloscope capture.

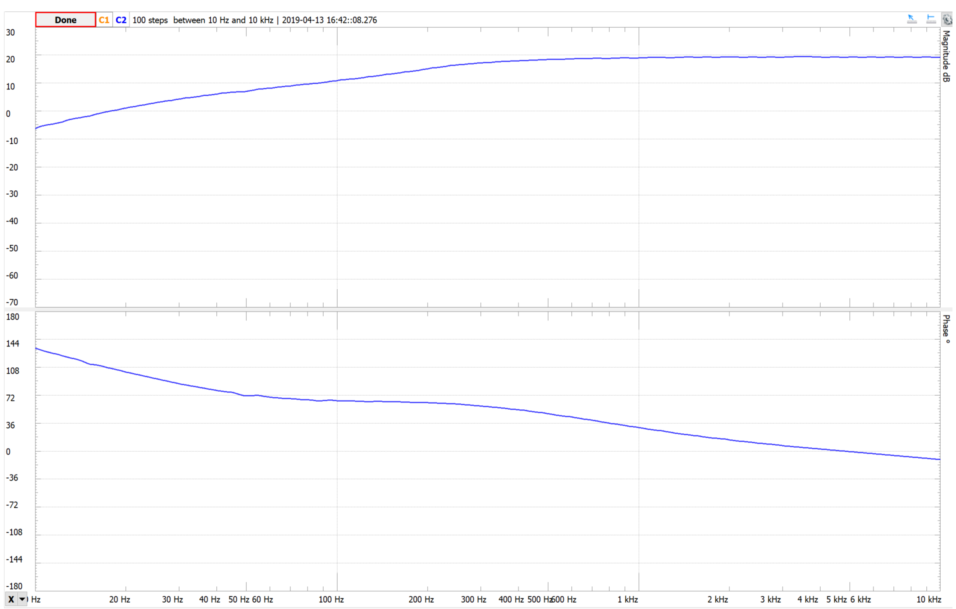


Figure 5.14: Class B push/pull overdrive network analyzer capture.

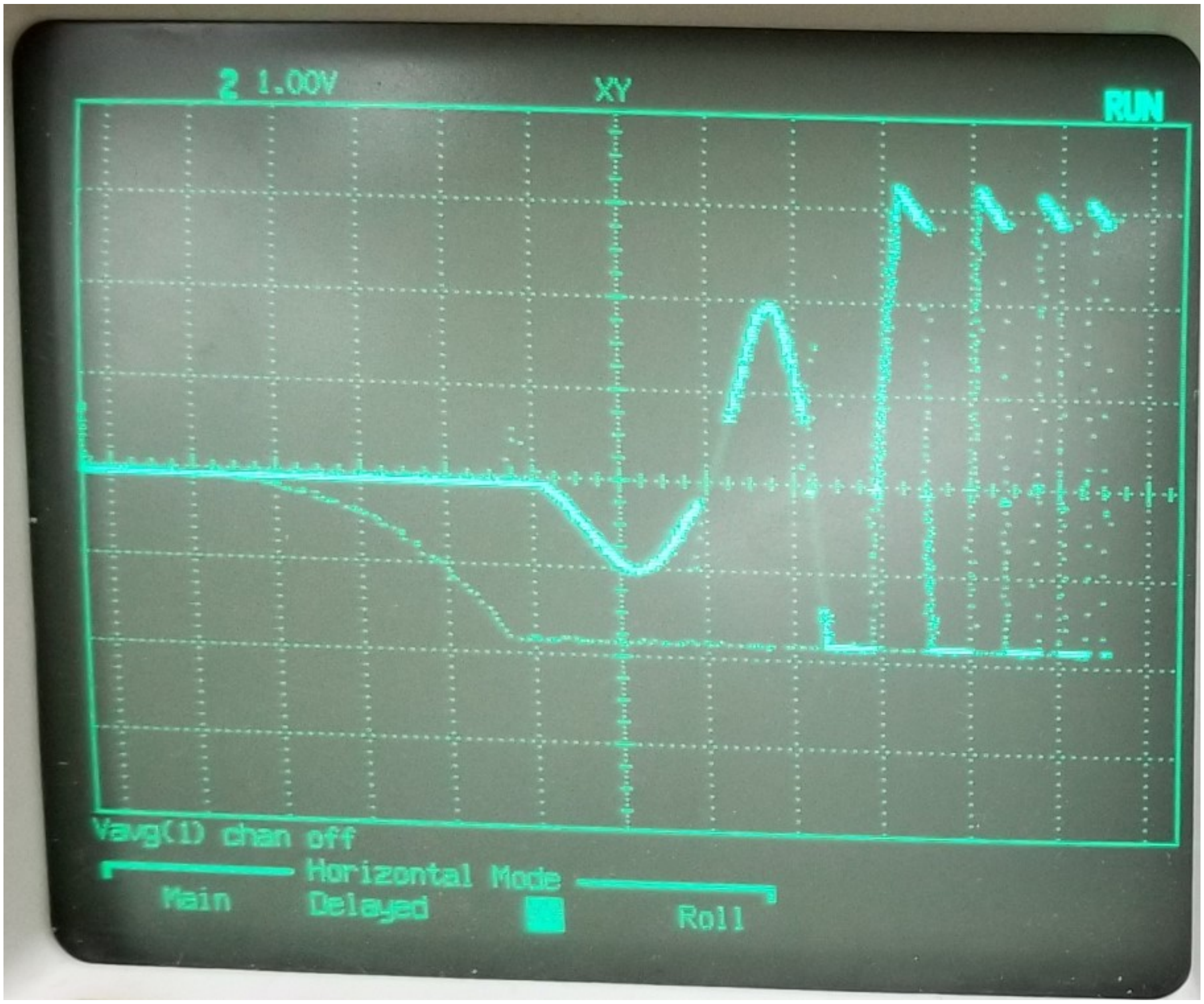


Figure 5.15: Class B overdrive frequency sweep with XY scope.

Figure 5.15 shows scope captures using a frequency sweeper and an oscilloscope in XY mode.

## 5.3 Sound

This section describes the overall sound of each circuit. It is important to keep in mind that sound is subjective, and different people will like different sounds. What may sound good to one person could sound awful to someone else. I will try to use general terms to describe the sounds of each circuit, but it is important to note that it is difficult to be entirely subjective [19, 20]. The guitar used is a custom built Stratocaster using Warmoth and Fender brand parts and components. The guitar is plugged into the effect circuit, and then the effect circuit is plugged into an Orange Crush 12 amplifier. The Orange Crush 12 is a cheap solid state practice amplifier. Unfortunately a vacuum tube amplifier was not available.

The following are some words commonly used to define guitar sounds and a general description of what they mean:

**Articulate** - each individual note is discernible fairly clearly as an individual note.

**Bright** - overall high end is apparent. Guitar notes and chords shine through the distortion.

**Clean** - guitar sound without any effects.

**Dirty** - a lot of distortion is added to the circuit.

**Fizzy** - buzz-saw type of noise that does not last very long.

**Muddy** - each notes blend together and it is hard to discern one note from another when multiple notes are played at once.

**Sustain** - the length of time that the signal can be heard before it fades to nothing. Longer sustain is desirable.

### 5.3.1 Diode Limiter Distortion

The diode limiter distortion circuits had some mistakes initially. The first mistake caused a constant buzzing noise when the gain potentiometer was turned all the way for maximum gain. The second mistake was that the potentiometer itself way laid out incorrectly. Section 5.1.1 discusses these mistakes and their fixes.

Overall, the diode limiter distortion circuits were surprisingly quieter than expected. They are fairly articulate, but not as articulate as some of the other designs. They also become quiet and muddy when the gain potentiometer is rolled off, making the effect adjustments less usable.

The silicon diode limiter distortion circuit could use more gain, as right now it does not quite reach the forward voltage required for clipping at maximum gain with guitar signals, especially with single note lines. Chords are articulate and have a bit of a dirty growl. The germanium diode limiter distortion circuit is more broken up. It is fairly aggressive without being too loud. It is much dirtier than the silicon diode limiter distortion, but it is still clear and not muddy. The mixed diode limiter distortion circuit is the dirtiest of the 3, but it is still articulate overall.

### 5.3.2 Diode Limiter Overdrive

The diode limiter overdrive circuits sound great. Overall, they are articulate, and turning the gain all the way down is audibly the same as not having the effect on at all, meaning the gain knob is dynamic and very useful. The diode overdrive circuits are louder than the diode distortion circuits.

The silicon configuration sounds great. It is overall very articulate. The germanium configuration is also articulate, if not a bit quieter than the silicon version. The mixed diode configuration is louder and a bit dirtier than either the silicon or germanium versions.

### 5.3.3 Class B Push/Pull Distortion

The Class B Push/Pull Distortion circuit did not pan out very well. The output is very quiet, fizzy, and lacks any sustain. It may be a more usable effect with more built in gain, but the circuit is useless in its current form. With a boost in front of the class B push/pull distortion circuit to increase the overall gain of the input signal, the circuit is fizzy and has a random decaying quality where the sound cuts in and out. Overall, this circuit may have niche uses, but it is not an especially musical effect.

### 5.3.4 Class B Push/Pull Overdrive

The Class B Push/Pull Overdrive circuit was a surprising hit. It is not a very dirty effect, but it acts almost like a clean boost circuit. It is very bright and articulate. It pairs really well with the neck pickup, but it is almost too bright and piercing to use with the bridge pickup. This circuit would be interesting to use with a tube amplifier, where it would probably act as a good overdrive circuit to boost tubes into saturation.

# Chapter 6

# Conclusions

This chapter discusses future work that could be done to further this project as well as draws some conclusions about this project.

## 6.1 Project Conclusions

This project tested the viability of several different musical distortion circuits for electric guitars, and it was confirmed that both the distortion and overdrive configurations, even in a simplified form lacking a tone stack or volume control, are competent circuits and can produce guitar signals that sound good. Diode limiters are simple nonlinearities, but they provide a great base sound in audio distortion circuits. The overdrive configuration tends sound a bit better than the distortion configuration for my personal taste, especially the overdrive made using the class B push/pull amplifier nonlinearity, which was surprising. The class B push/pull nonlinearity is not the best circuit for the distortion configuration, as it is not a very musical sounding effect. Overall, this was a very interesting project and I learned a lot about some circuits that I had been using for years before I studied electrical engineering.

## 6.2 Future Work

There are a few things that could be built off of this project. Aside from fixing the layout mistakes mentioned in Section 5.1.1, one of the biggest improvements that could be done with these circuits is adding some basic power circuitry using the spare op-amp to create a virtual ground so that the circuits can be powered by a 9 volt battery instead of a dual power supply. This change would make the circuits much more accessible and usable outside of a lab environment.

Another interesting thing for these circuit overall would be the addition of a tone stack. Tone stacks are filter stages that changes the shape of the frequency response of the filter [10]. A potentiometer as a voltage divider at the output would be a good addition to a few of these circuits to lower the volume of the effect, and a switch to bypass the sound changing circuitry is a staple in all pedals on the market. These were not included in the circuits for this paper with the goal of keeping these circuits as simple and inexpensive as possible.

Finally, it would be interesting to implement these circuits in the digital domain as real time filters. There are several techniques that can be used to realize real time audio circuits in the digital domain such as table preconstruction, discrete time modeling, wave digital filters, numerical methods of solving ordinary differential equations, the K-method, Newton's method, and coefficient modulated all pass digital filters [21–26].

# Bibliography


[1] Helmuth E. W. Lemme. The Secrets of Electric Guitar Pickups. *Electronic Musician*, pages 66–72, dec 1986. URL: https://www.princeton.edu/ssp/joseph-henry-project/electric-guitar-pickup/Guitar-Pickup-Theory.pdf.

[2] Richard Mark French. *Engineering the Guitar*. Springer US, Boston, MA, 2008. doi:10.1007/978-0-387-74369-1.

[3] alexkenis. Guitar pickup theory 6b: Coil shape part 2 - winding capacitance, 2016. URL: https://alexkenis.wordpress.com/2016/04/07/guitar-pickup-theory-6b-blog-coil-shape-part-2-winding-capacitance/.

[4] Huw Price. All About... Cables, 2017. URL: https://guitar.com/guides/essential-guide/cables/.

[5] Gordon L Amidon, Ann Arbor, Related U S Application Data, Primary Examiner, Thurman K Page, Assistant Examiner, and James M Spear. Pat No 4495640: Adjustable Distortion Guitar Amplifier, 1985. arXiv:arXiv:1208.5721, doi:10.1016/j.(73).

[6] Piet Wambacq and Willy Sansen. Distortion Analysis of Analog Integrated Circuits. In

Mohommed Ismail, editor, *Distortion Analysis of Analog Integrated Circuits*. Kluwer Academic Publishers, Boston, MA, 1998.

[7] Piet Wambacq, Georges G.E. Gielen, Peter R. Kinget, and Willy Sansen. High-frequency distortion analysis of analog integrated circuits. *Computer-Aided Design of Analog Integrated Circuits and Systems*, (November 2014):333–343, 2002. doi:10.1109/9780470544310.ch27.

[8] Kai-Chieh Huang. King of Tone Guitar Pedal Modeling with Nodal Analysis & Table Preconstruction Method. Technical report, Stanford, 2014-2017??

[9] David T Yeh, Jonathan S. Abel, and Julius O Smith. Simplified, physically-informed models of distortion and overdrive guitar effects pedals. *Int. Conference on Digital Audio Effects (DAFx-07)*, 10:189–196, 2007. doi:10.1016/S0741-5214(96)70258-6.

[10] David Te-Mao Yeh. *Digital Implementation of Musical Distortion Circuits by Analysis and Simulation*. PhD thesis, Standford, 2009.

[11] Usov S. Shashkov P., Khomutov G., Yerokhin A. Pat No 8275477 B2: Method and Apparatus for Distortion of Audio Signals and Emulation of Vacuum Tube Amplifiers, 2012. doi:10.1126/science.Liquids.

[12] Ivan Cohen and Thomas Hélie. Real-time simulation of a guitar power amplifier. *Int. Conference on Digital Audio Effects (DAFx-10)*, 13, 2011. arXiv:hal-00631752.

[13] J Macak and J Schimmel. Real-time guitar tube amplifier simulation using an approximation of differential equations. *Int. Conference on Digital Audio Effects (DAFx-10)*, 13:1–8, 2010. URL: http://dafx10.iem.at/papers/MacakSchimmel{_}DAFx10{_}P12.pdf.

[14] Jyri Pakarinen and David T. Yeh. A Review of Digital Techniques for Modeling Vacuum-Tube Guitar Amplifiers. *Computer Music Journal*, 33(2):85–100, 2009. doi:10.1162/comj.2009.33.2.85.

[15] Brian Neunaber. When is True Bypass Appropriate, 2014. URL: https://neunaber.net/blogs/neunaber-audio-blog/13827985-when-is-true-bypass-appropriate.

[16] Denton J. Dailey. Guitar Effects Circuits. In *Electronics for Guitarists*, chapter 5, pages 129–147. Springer, 1st edition, 2011. URL: http://link.springer.com/10.1007/978-1-4419-9536-0, arXiv:arXiv:1011.1669v3, doi:10.1007/978-1-4419-9536-0.

[17] Hirokazu Oda, Akira Hiroki, Takaaki Sano, and Takaya Oyama. Germanium diode modeling for sound effect circuit design. *2014 IEEE International Meeting for Future of Electron Devices, Kansai (IMFEDK)*, pages 1–2, 2014. URL: http://ieeexplore.ieee.org/document/6867059/, doi:10.1109/IMFEDK.2014.6867059.

[18] Takaya Oyama, Akira Hiroki, and Takaaki Sano. Macromodeling of operational amplifiers for sound effect circuit design. *IMFEDK 2014 - 2014 International Meeting for Future of Electron Devices, Kansai*, 2014. doi:10.1109/IMFEDK.2014.6867058.

[19] Harris M Berber and Cornelia Fates. "Heaviness" in the Perception of Heavy Metal Guitar Timbres The Match of Perceptual and Acoustic Features Over Time. In Paul D. Greene and Thomas Porcello, editors, *Wired for Sound: Engineering and Technologies in Sonic Cultures*, chapter 9, pages 181–197. Wesleyan University Press, 2005.

[20] a Marui and Wl Martens. Timbre of nonlinear distortion effects: Perceptual attributes beyond sharpness. *Proc. of the Conference of Interdisciplinary ...*, (March

2005):10–12, 2005. URL: http://oicrm.org/wp-content/uploads/2012/03/MARUI{_}A{_}CIM05.pdf.

[21] Massimo Conti, Simone Orcioni, Marco Caldari, and Franco Ripa. Real Time Implementation of Fuzz-Face Electric Guitar Effect. In Natividad Martinez Madrid and Ralf E.D. Seepold, editors, *Intelligent Technical Systems*, chapter 7, pages 89–100. Springer, 2009. doi:10.1007/978-1-4020-9823-9.

[22] Rafael C.D. Paiva, Stefano D'Angelo, Jyri Pakarinen, and Vesa Välimäki. Emulation of operational amplifiers and diodes in audio distortion circuits. *IEEE Transactions on Circuits and Systems II: Express Briefs*, 59(10):688–692, 2012. doi:10.1109/TCSII.2012.2213358.

[23] David T Yeh, Jonathan S. Abel, and Julius O Smith. Simulation of the Diode Limiter in Guitar Distortion Circuits By Numerical Solution of Ordinary Differential Equations. *Int. Conference on Digital Audio Effects (DAFx-07)*, 10:1–7, 2007.

[24] David T. Yeh. Automated physical modeling of nonlinear audio circuits for real-time audio effects - Part II: BJT and vacuum tube examples. *IEEE Transactions on Audio, Speech and Language Processing*, 20(4):1207–1216, 2012. doi:10.1109/TASL.2011.2173677.

[25] Jussi Pekonen. Coefficient-Modulated First-Order Allpass Filter As Distortion Effect. *Int. Conference on Digital Audio Effects (DAFx-08)*, 11(1):4–8, 2008.

[26] David T Yeh, Jonathan S Abel, and Julius O Smith. Automated Physical Modeling of Nonlinear Audio Circuits For Real-Time Audio Effects - Part I: Theoretical Development. *IEEE Transactions on Audio, Speech, and Language Processing*,

18(4):728–737, 2010. URL: http://ieeexplore.ieee.org/document/5280324/, doi:10.1109/TASL.2009.2033978.

# Appendix I

# Layout

This appendix contains images of the schematic and layout files from Altium CircuitMaker.

## I.1 Diode Limiter Distortion

The first circuit created is the diode limiter distortion. Figure I.1 shows the CircuitMaker schematic. Figure I.2 shows the front and back layout of the board. Figure I.1 shows a 3D model of the board.

## I.2 Diode Limiter Overdrive

The first circuit created is the diode limiter overdrive. Figure I.4 shows the CircuitMaker schematic. Figure I.5 shows the front and back layout of the board. Figure I.6 shows a 3D model of the board.

## I.3 Class B Push/Pull Distortion

The first circuit created is the diode limiter distortion. Figure I.7 shows the CircuitMaker schematic. Figure I.8 shows the front and back layout of the board. Figure I.9 shows a 3D model of the board.

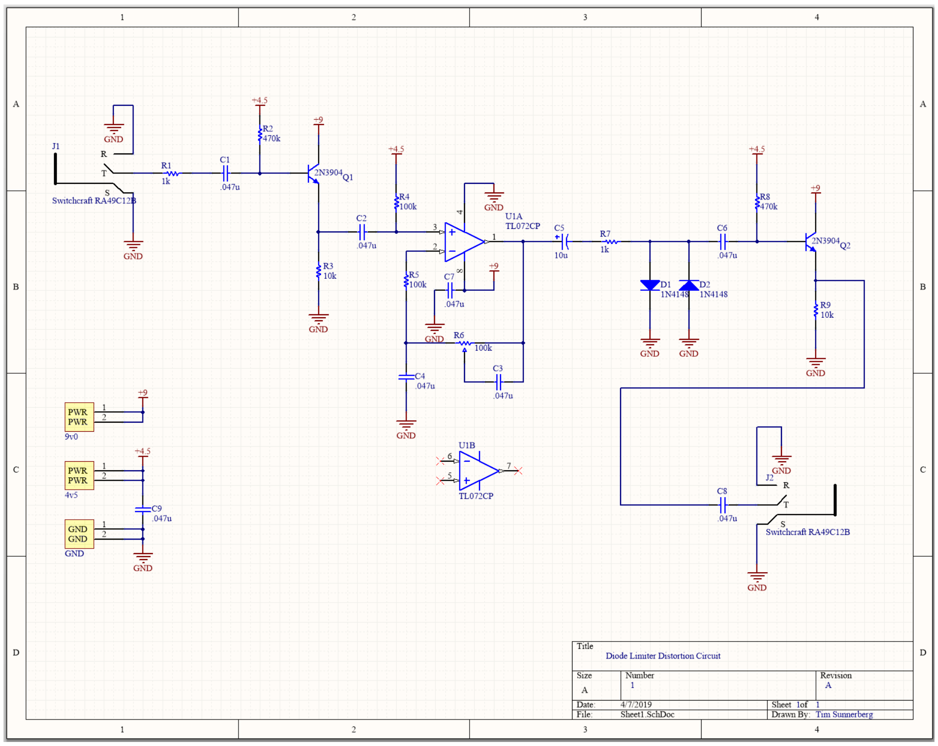


Figure I.1: CircuitMaker schematic of the diode limiter distortion circuit.

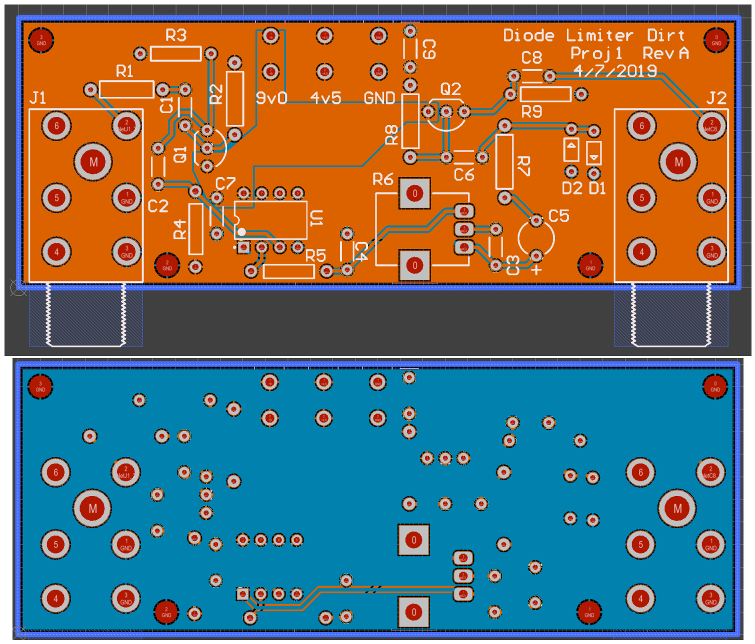


Figure I.2: CircuitMaker layout of the diode limiter distortion circuit.
Top: layout of top layer of the printed circuit board.
Bottom: layout of bottom layer of the printed circuit board.

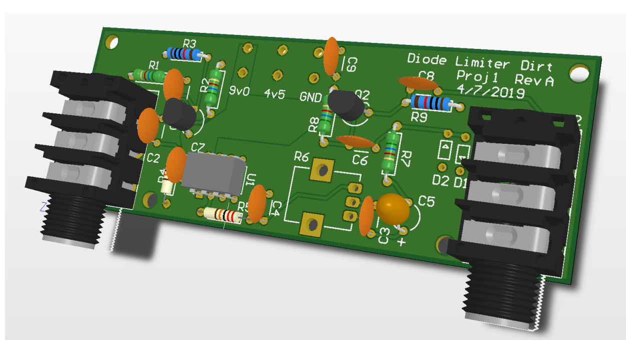


Figure I.3: CircuitMaker 3D model of the diode limiter distortion layout.

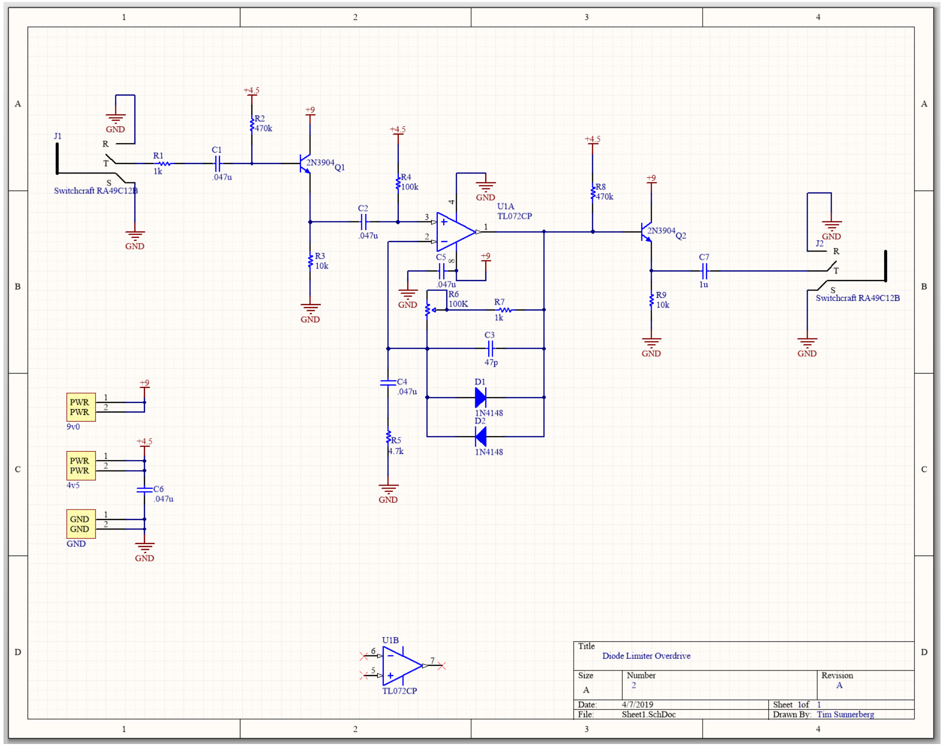


Figure I.4: CircuitMaker schematic of the diode limiter overdrive circuit.

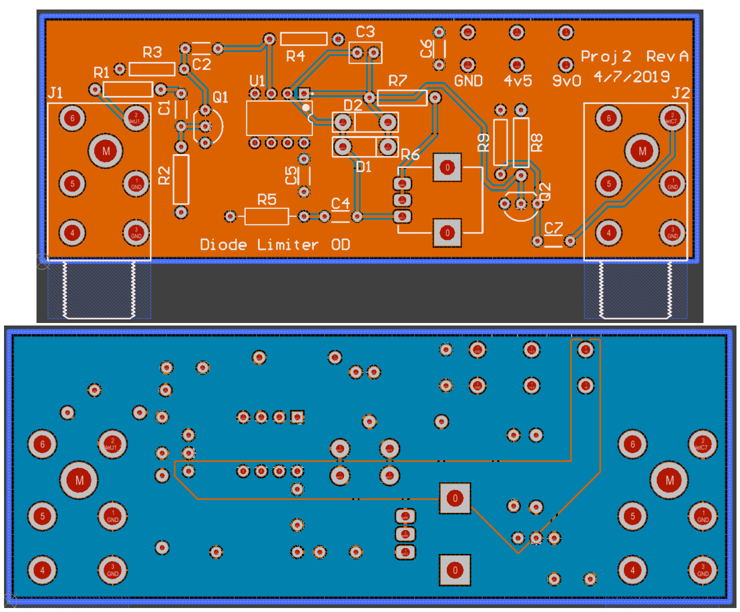


Figure I.5: CircuitMaker layout of the diode limiter overdrive circuit.
Top: layout of top layer of the printed circuit board.
Bottom: layout of bottom layer of the printed circuit board.

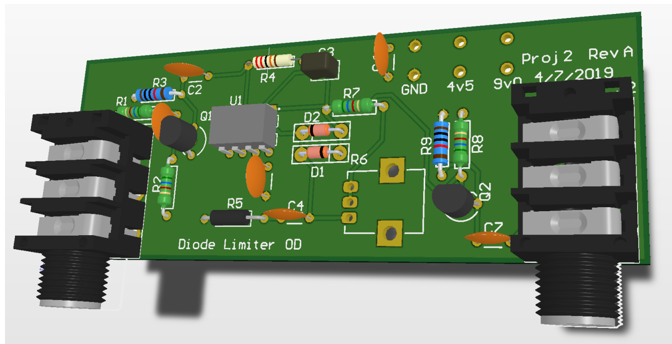


Figure I.6: CircuitMaker 3D model of the diode limiter overdrive layout.

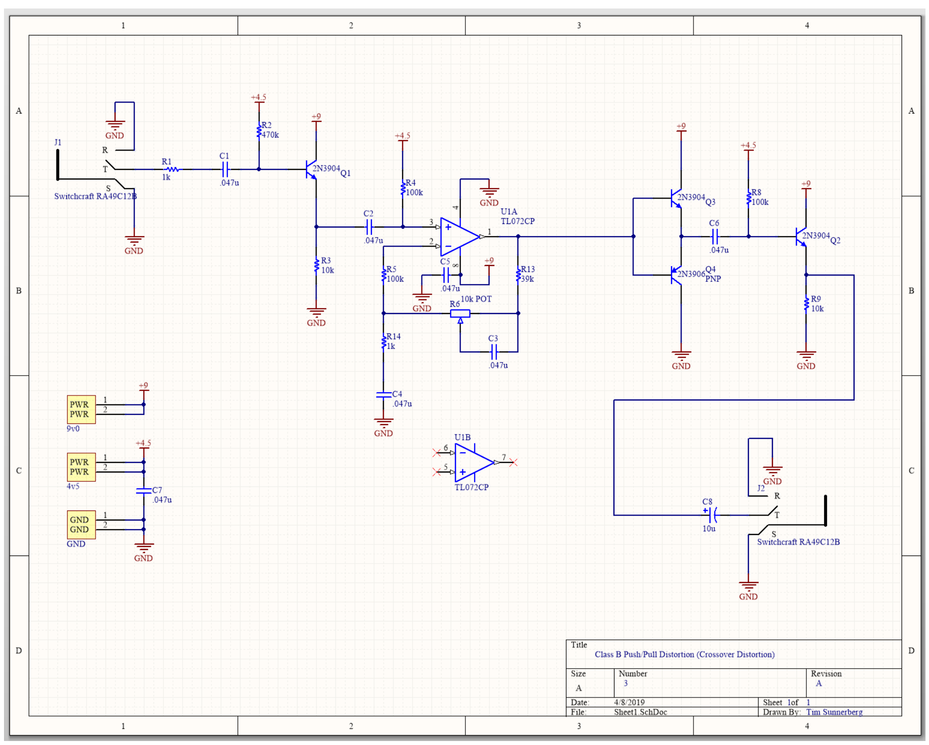


Figure I.7: CircuitMaker schematic of the class B push/pull distortion circuit.

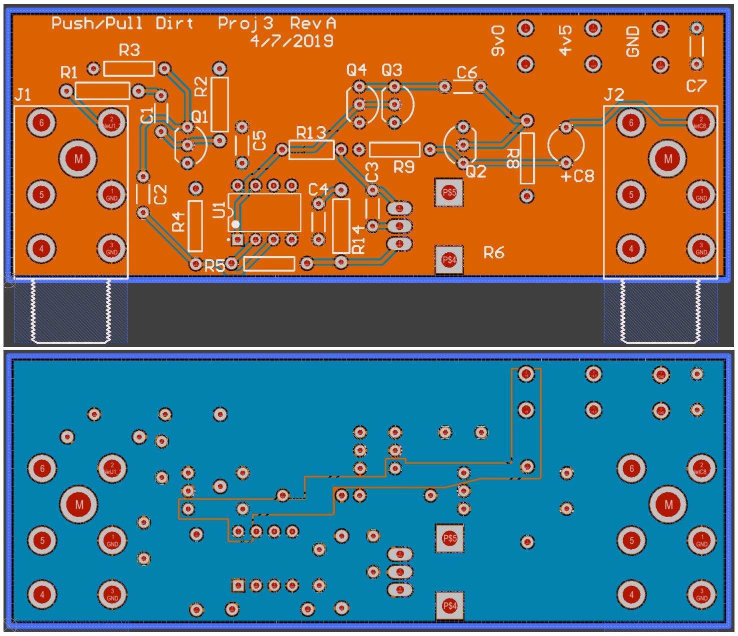


Figure I.8: CircuitMaker layout of the class B push/pull distortion circuit.
Top: layout of top layer of the printed circuit board.
Bottom: layout of bottom layer of the printed circuit board.

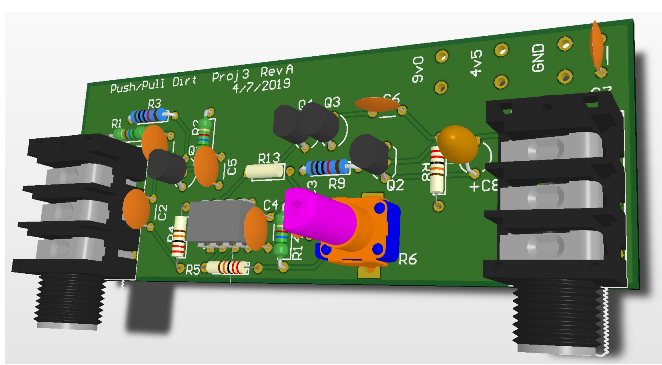


Figure I.9: CircuitMaker 3D model of the class B push/pull distortion layout.

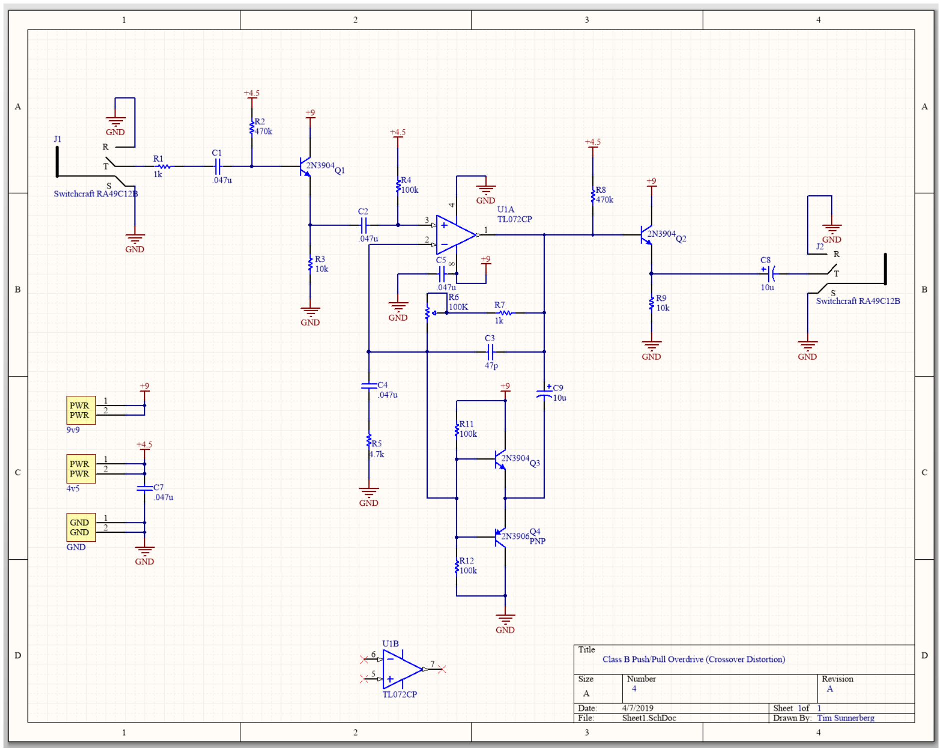


Figure I.10: CircuitMaker schematic of the class B push/pull overdrive circuit.

## I.4 Class B Push/Pull Overdrive

The first circuit created is the diode limiter distortion. Figure I.10 shows the CircuitMaker schematic. Figure I.11 shows the front and back layout of the board. Figure I.12 shows a 3D model of the board.

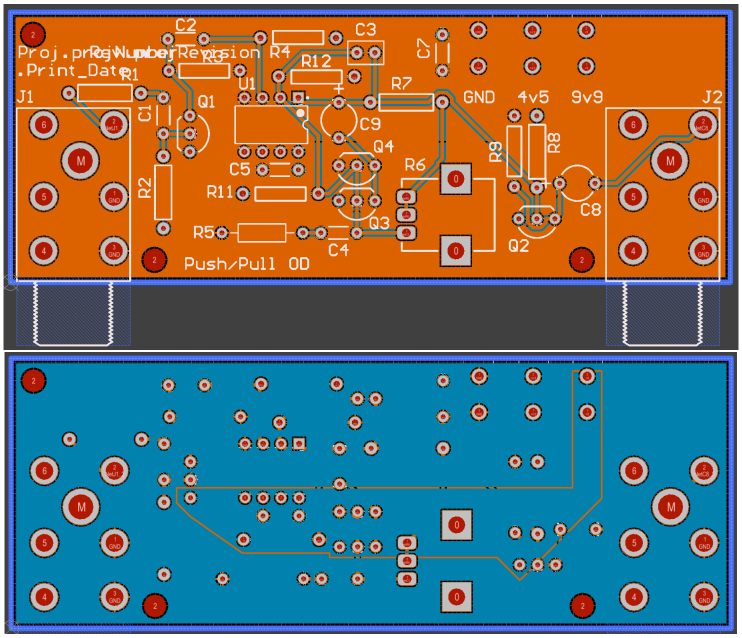


Figure I.11: CircuitMaker layout of the class B push/pull overdrive circuit.
Top: layout of top layer of the printed circuit board.
Bottom: layout of bottom layer of the printed circuit board.

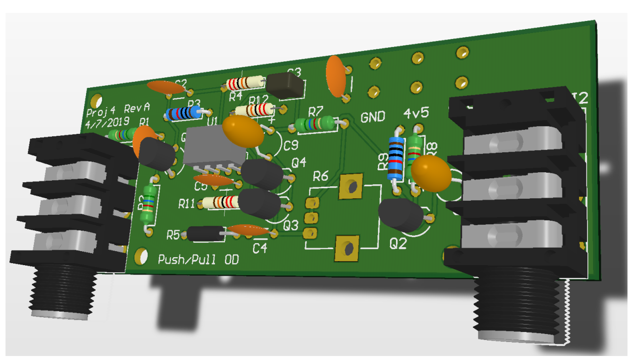


Figure I.12: CircuitMaker 3D model of the class B push/pull overdrive layout

# Appendix II

# Bill of Materials

This appendix contains the bill of materials (BOM) for each board.

# II.1 Diode Limiter Distortion BOM

Table II.1: Diode Limiter Distortion BOM.

| Part | Value | Quantity | Reference Designator | Notes |
|---|---|---|---|---|
| Resistor | 1k | 2 | R1, R7 | |
| Resistor | 10k | 2 | R3, R9 | |
| Resistor | 100k | 2 | R4, R5 | |
| Resistor | 470k | 2 | R2, R8 | |
| Potentiometer | 100k | 1 | R6 | |
| Capacitor | .047u | 7 | C1, C2, C4, C5, C6, C8, C9 | |
| Capacitor | 220p | 1 | C3 | Different from schematic |
| Capacitor | 10u | 1 | C5 | |
| Diode | Si, Ge, or mix | 2 | D1, D2 | N4148 or 1N34 |
| BJT | NPN | 2 | Q1, Q2 | 2N3904 |
| Op Amp | | 1 | U1 | TL072CP |
| 1/4" Jack | | 2 | J1, J2 | Switchcraft RA49C12B |

## II.2 Diode Limiter Overdrive BOM

Table II.2: Diode Limiter Overdrive BOM.

| Part | Value | Quantity | Reference Designator | Notes |
|---|---|---|---|---|
| Resistor | 1k | 2 | R1, R7 | |
| Resistor | 4.7k | 1 | R5 | |
| Resistor | 10k | 2 | R3, R9 | |
| Resistor | 100k | 1 | R4 | |
| Resistor | 470k | 2 | R2, R8 | |
| Potentiometer | 100k | 1 | R6 | |
| Capacitor | .047u | 5 | C1, C2, C4, C5, C6 | |
| Capacitor | 220p | 1 | C3 | Different from schematic |
| Capacitor | 1u | 1 | C7 | |
| Diode | Si, Ge, or mix | 2 | D1, D2 | N4148 or 1N34 |
| BJT | NPN | 2 | Q1, Q2 | 2N3904 |
| Op Amp | | 1 | U1 | TL072CP |
| 1/4" Jack | | 2 | J1, J2 | Switchcraft RA49C12B |

## II.3 Class B Push/Pull Distortion BOM

Table II.3: Class B Push/Pull Distortion BOM.

| Part | Value | Quantity | Reference Designator | Notes |
|---|---|---|---|---|
| Resistor | 1k | 2 | R1, R14 | |
| Resistor | 10k | 2 | R3, R9 | |
| Resistor | 39k | 1 | R13 | |
| Resistor | 100k | 3 | R4, R5, R8 | |
| Resistor | 470k | 1 | R2 | |
| Potentiometer | 10k | 1 | R6 | |
| Capacitor | .047u | 7 | C1, C2, C3, C4, C5, C6 | |
| Capacitor | 10u | 1 | C8 | |
| BJT | NPN | 3 | Q1, Q2, Q3 | 2N3904 |
| BJT | PNP | 1 | Q4 | 2N3906 |
| Op Amp | | 1 | U1 | TL072CP |
| 1/4" Jack | | 2 | J1, J2 | Switchcraft RA49C12B |

## II.4 Class B Push/Pull Overdrive BOM

Table II.4: Class B Push/Pull Overdrive BOM.

| Part | Value | Quantity | Reference Designator | Notes |
|---|---|---|---|---|
| Resistor | 1k | 2 | R1, R7 | |
| Resistor | 4.7k | 1 | R5 | |
| Resistor | 10k | 2 | R3, R9 | |
| Resistor | 100k | 3 | R4, R11, R12 | |
| Resistor | 470k | 2 | R2, R8 | |
| Potentiometer | 100k | 1 | R6 | |
| Capacitor | 47p | 1 | C3 | |
| Capacitor | .047u | 5 | C1, C2, C4, C5, C7 | |
| Capacitor | 10u | 2 | C8, C9 | |
| BJT | NPN | 3 | Q1, Q2, Q3 | 2N3904 |
| BJT | PNP | 1 | Q4 | 2N3906 |
| Op Amp | | 1 | U1 | TL072CP |
| 1/4" Jack | | 2 | J1, J2 | Switchcraft RA49C12B |