Phase Splitter Guitar Effects Pedal

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Acknowledgements

I would like to thank my parents for their constant support and encouragement. I would like to thank my friend Chris Brown for help with the enclosure. I would also like to thank one of my teachers and senior project advisor Vladimir Prodanov for providing the phase splitter design and invaluable help with the project. Without their help this project would not have been possible. I would also like to acknowledge Cal Poly's Electrical Engineering department for their challenging hands on courses that helped shape me into the engineer that I am today.

Abstract

The goal of this project was to create a unique type of guitar distortion effects pedal. The initial plan was to use a Hilbert Transformer, also called a Phase Splitter, to produce a vibrato type distortion. Later during the circuit design phase, it appeared that a tremolo effect could be easily implemented in addition to the vibrato. Both the tremolo and vibrato effects were implemented in the final design. Although there are many different types of vibrato and tremolo pedals already in existence, it does not appear that any current designs use a Hilbert Transformer or phase splitter. Hopefully, this unique approach to the design will produce a new quality sound that will be enjoyed by guitar players.

I. Introduction

A clean, undistorted electric guitar signal can be a pretty dry and mundane sound. Before guitar effects were available, the guitar player usually did not receive the appreciation they deserved if they were even able to capture the attention of the audience[1]. Luckily for us, amplifier and pedal manufacturers have provided the modern guitarist with a treasure trove of digital and analog effects supplying an immense amount of tonal variety that has made the guitar a center focus of popular music. Although there is already an abundance of different available distortion effects that can create crunch, squeal, and fuzz, guitar players are constantly searching for new ones to convey their attitude and feeling and help their sound evolve.

This project seeks to create a guitar effects pedal that features a combination of vibrato and tremolo distortion effects. Though these two effects are among the earliest ever created, this project will take an alternative approach to the design and hopefully add a new flavor or color to two widely loved and recognized distortion effects. This project will attempt to achieve this with a Hilbert Transformer, which splits a signal into four equal magnitude signals that are out of phase by 90 degrees. It does not appear that any current designs use this approach, which makes this design unique.

II. Background

There is a large variety of guitar effects pedals that includes fuzz, wah, phaser, tremolo, and vibrato. The guitar effects themselves originated as early as the 1930s by guitarists seeking for something to enhance their sound. In the early days of guitar effects, there was a common belief that some kind of physical force had to act on the guitar to produce an effect. Pioneers of guitar effects would play in large rooms for reverb and rig motors to a guitar to vibrate the bridge and create vibrato. Once the amplified electric guitar became more popular, companies like Gibson and Premier began including tube-based vibrato and tremolo effect circuits in their amplifiers in the late 1940s[2].

When transistors became more widely available in the 1960s, standalone guitar effects pedals started being produced on a much larger scale. This surge of new effects pedals found its way into the possession of many satisfied guitarists as well as popular music. Fuzz pedals became particularly popular in Rock and Roll music and were used for screaming guitar sounds by renowned musicians like Jimi Hendrix. Since the popularization of guitar effects pedals, guitar players have sought after new, original, quality sounds to help their sound stand out. This project will attempt to create a new effects pedal that combines two of the earliest guitar effects, tremolo and vibrato, using a phase splitter.

III. Requirements

The main requirement of the system is to provide a distortion effect to the guitar signal. As mentioned before, the effects pedal for this project will create vibrato and tremolo distortion effects. True bypass is a standard feature that is shared by a majority of guitar effects pedals and will also be implemented by this design with a footswitch. A sturdy enclosure must also be used to protect the system's electronics and provide RF shielding. The system will be powered by a 9V battery housed in the enclosure that will be turned on when the input jack is plugged in. Upon insertion of the input jack, an LED will illuminate to indicate that the system is powered on. A distortion control will also be implemented, which will adjust the speed of the vibrato and tremolo effects. Lastly, an additional control will allow the user to adjust the volume of the output.

Summary of Requirements and Features

- Vibrato and Tremolo Distortion Effects
- True Bypass Footswitch
- 9V Battery Power Supply
- LED Power Indicator
- Distortion Control
- Volume Control

IV. Design

The Design consists of two main parts, a phase splitter and an output stage. These stages are divided into smaller subsections as shown below.

1. Phase splitter
    - Magnitude correction filter
    - RC chain
    - Four buffers
2. Ouput stage
    - Multiplexer
    - Binary counter
    - 555 Timer
    - Summing Amplifier
    - Low Pass Filter

Preliminary Design Review

To facilitate the building and integration phases, a preliminary design review was completed. This review provided specifications for different parts of the project and helped define the requirements of the different circuit parts.

Input Signal Specifications

First, knowledge about the input signal from the guitar had to be obtained. An Epiphone Les Paul Standard, shown in Figure 1, was used to supply the input signal for the device.

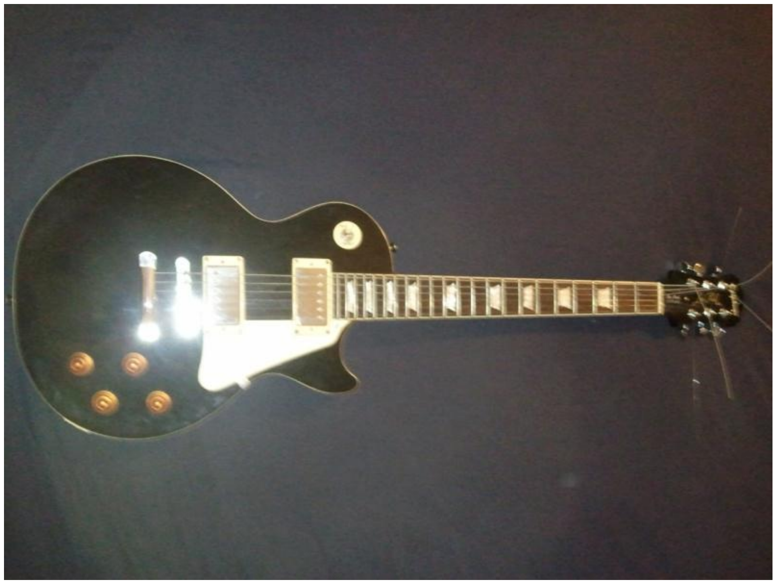


Figure 1 - Epiphone Les Paul Standard Electric Guitar

The guitar signal was viewed on an oscilloscope by connecting the output jack to a scope probe and strumming the strings. A scope capture of the guitar voltage signal from strumming the lowest string and highest string can be seen in Figures 2 and 3.

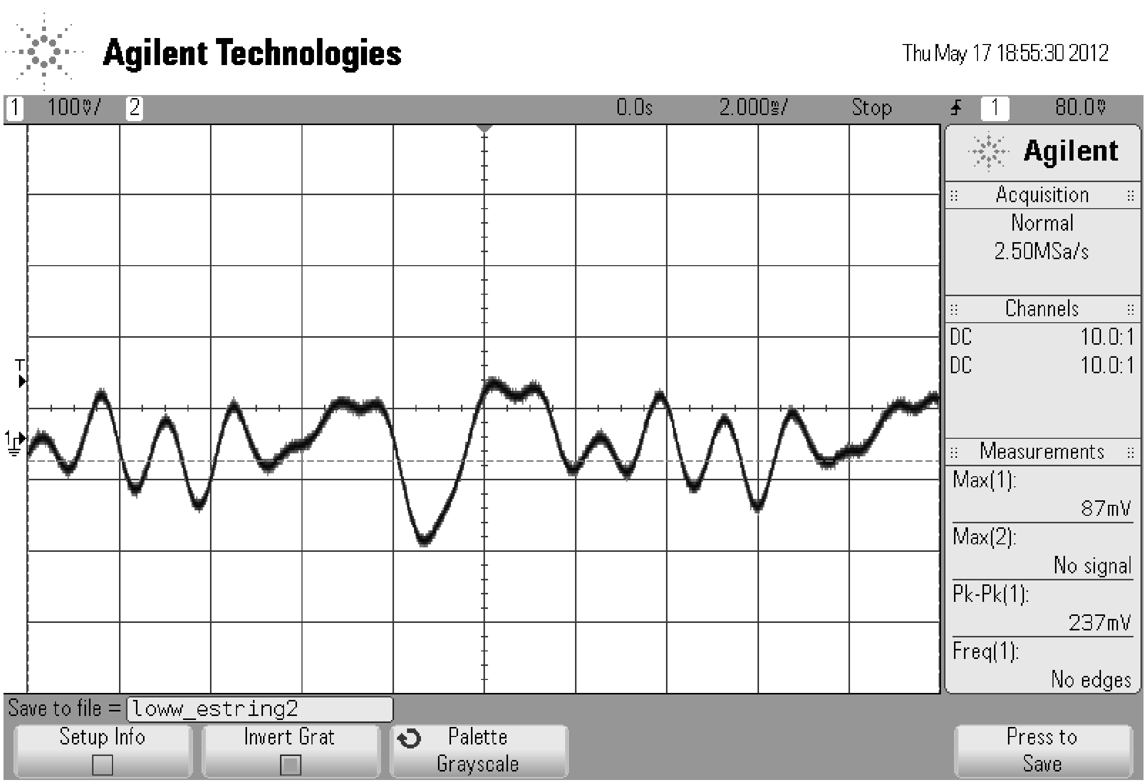


Figure 2 - Guitar voltage signal from strumming low E string

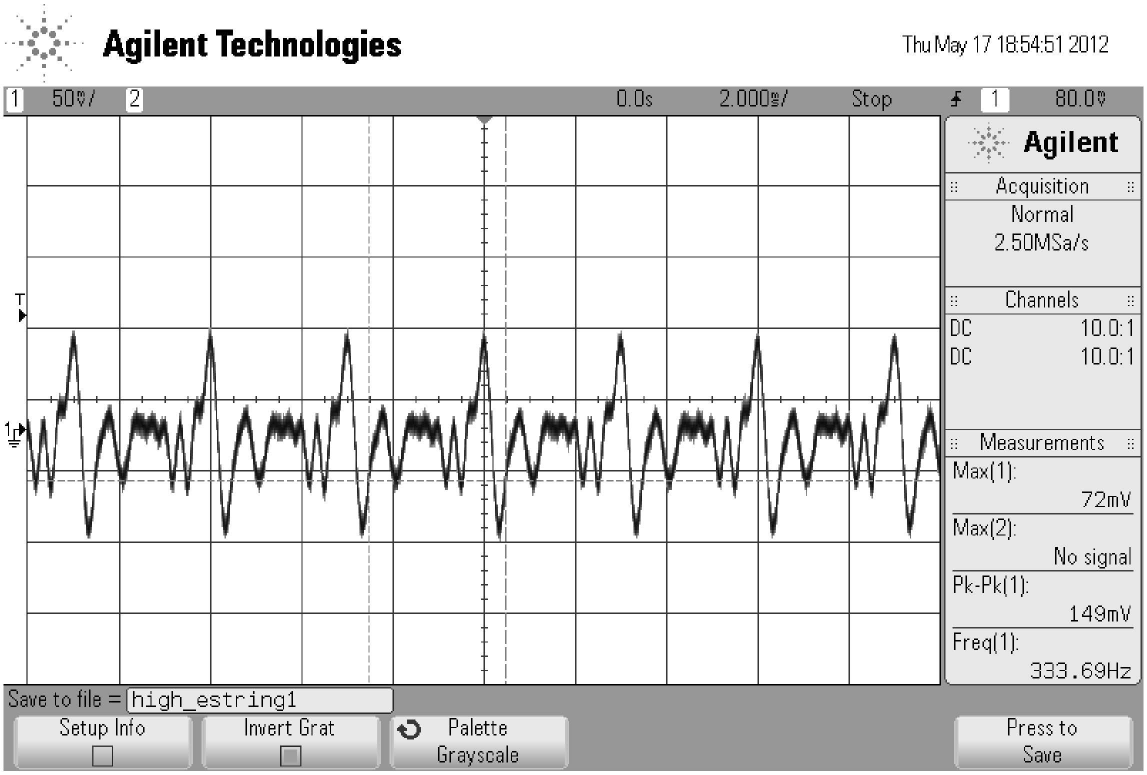


Figure 3 - Guitar voltage signal from strumming high e string

From Figures 2 and 3, it appears that the input signal for the system will typically be around 200mV$_{p\text{-}p}$. The signal will be slightly larger in magnitude if the strings are strummed harder.

Amplifier Specifications

For the project demonstration, the sound of the effects pedal will be heard through a pair of headphones. Generally, analog guitar effects pedals are not capable of driving headphones. The output impedance of effects pedals is much larger than the low impedance of headphones. This impedance mismatch causes significant power losses, which prevents the system from driving headphones. To remedy this problem, the output of this effects pedal will be connected to a guitar amplifier. A Roland Micro Cube-R guitar amplifier will be used for circuit testing and the demonstration of the project at the senior project exhibition. This amplifier, shown in Figure 4, was chosen for its small size, portability, and its ability to drive a pair of headphones.

Figure 4 - Roland Micro Cube-R Guitar Amplifier

Specifications for the amplifier were collected from the user's manual on Roland's website and can be seen in Table I below[3].

	Specification
Rated Power Output	2 W
Input	-10dBu
Aux In	-10dBu
Input Jack Connector	¼" phone type
Power Supply	DC 9V AC Adaptor or AA battery.
Current Draw	185mA

Table I - Roland Micro Cube-R Guitar Amplifier Specifications

Power Supply and LED Power Indicator

Power for the guitar effects pedal will be supplied by a single 9-volt battery. The battery is connected the middle shield conductor of the input jack to turn on the circuit when the input is connected, which is illustrated in Figure 5. The battery will supply four different ICs: an op-amp

quad package, multiplexer, binary counter, and a 555 timer. Each of the ICs have different maximum supply voltages as shown in Table II below.

IC Name	Part Number	Maximum Supply Voltage
Op amp quad package	MC33204P	12 V
Multiplexer	CD4052BE	20 V
Binary Counter	SN74HC191N	7 V
555 Timer	CSS555	5.5 V

Table II - Maximum Supply Voltages of ICs

To ensure the maximum supply voltages are not exceeded for any of the ICs, a voltage regulator is used to provide a supply voltage of 5V. An LM 7805C was chosen for the voltage divider, which is connected to a 9V battery to provide the 5V reference voltage for the ICs. An LED is used to indicate when the device is on. The LED is connected in parallel with an opposite facing diode between the positive terminal and a resistor connected to ground. The circuitry for the power stage and LED power indicator is shown in Figure 5.

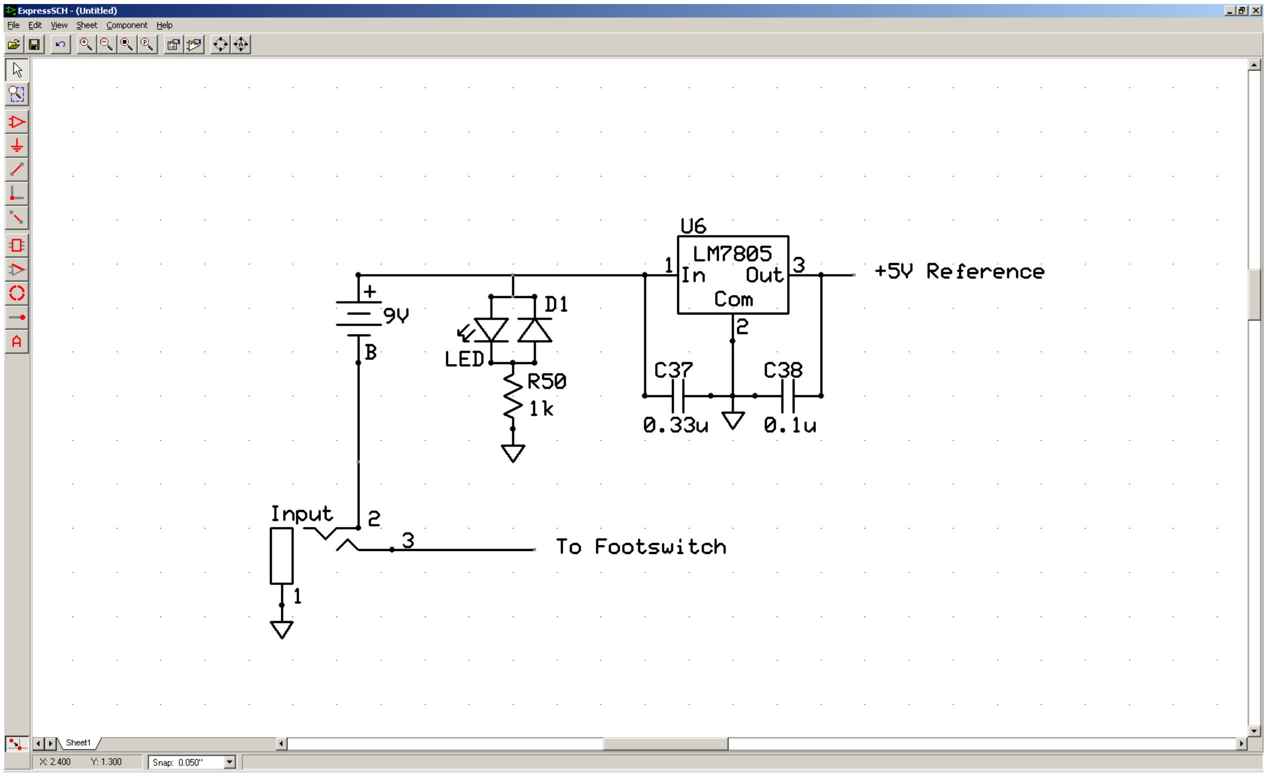


Figure 5 - Power Stage and LED Indicator Circuit

Voltage Divider and Virtual Ground

The guitar voltage signal is referenced to ground and has positive and negative voltage. To ensure that the input signal maintains a voltage level between 0V and 5V, two voltage dividers are implemented. The first voltage divider, shown in Figure 6, creates a reference voltage of 2.5V which is AC coupled to the input via a capacitor.

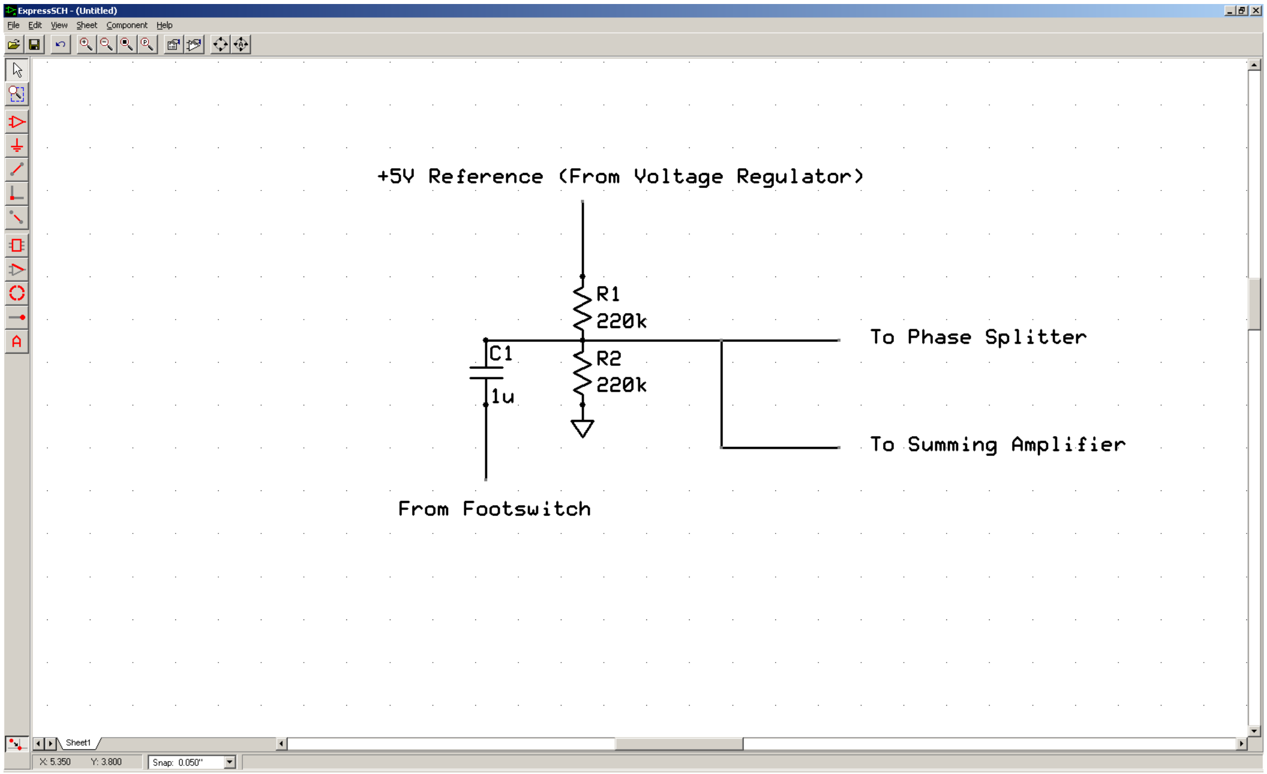


Figure 6 - Voltage Divider for Input Signal Offset

The voltage divider of Figure 6 keeps the input signal centered at the reference voltage and between ground and 5V to avoid clipping. A second voltage divider, shown in Figure 7, also supplies a 2.5V reference voltage and uses a buffer to produce a virtual ground for other op amps in the signal path.

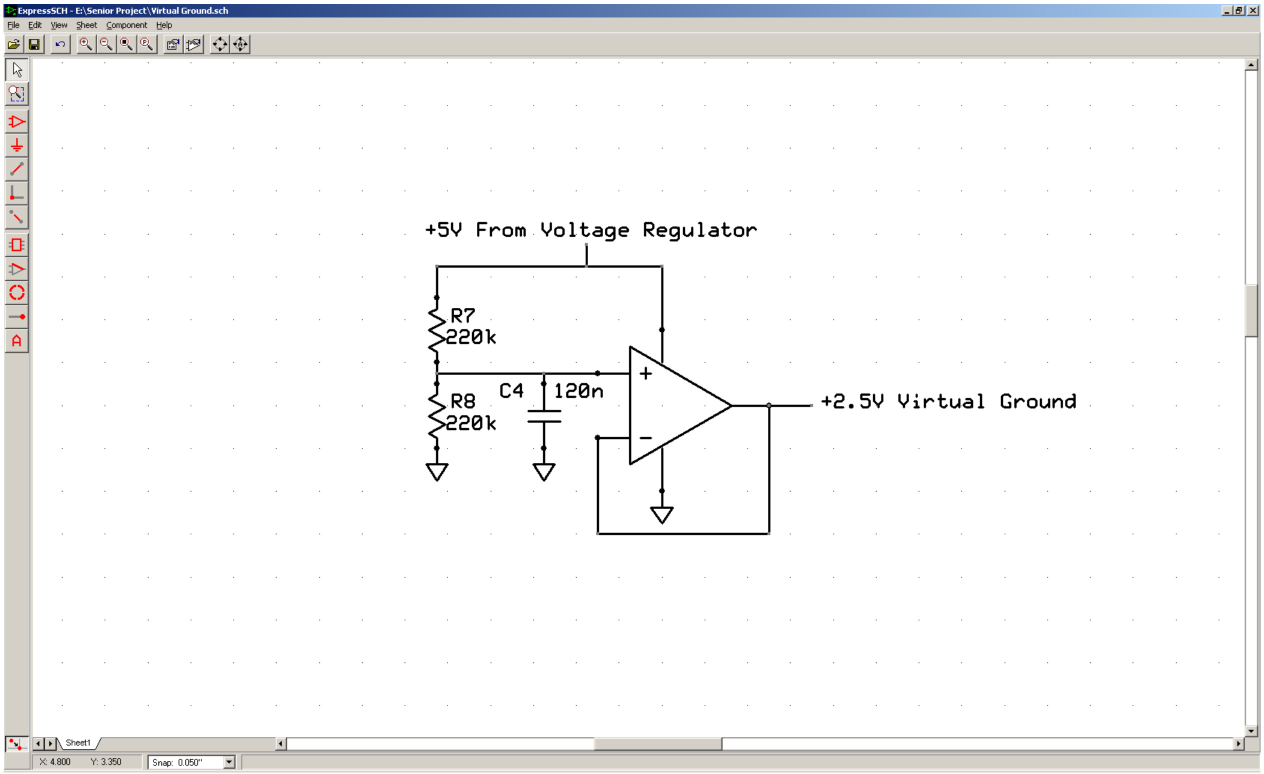


Figure 7 - Voltage Divider for Virtual Ground

The voltage divider of Figure 7 also features a capacitor, which creates a low pass filter to reduce noise on the voltage rail[4].

Distortion Design

The function of the effects pedal is to produce vibrato and tremolo like distortion effects. Vibrato and tremolo effects are achieved by two main parts of the circuit. The first part of the circuit is a Hilbert Transformer, also called a phase splitter circuit, and the second is an output stage. The purpose of the phase splitter is to take the input signal and create four signals equal in magnitude to the input, with approximately 90° degree phase shifts from each other. A Matlab plot, shown in Figure 8, illustrates the function of the phase splitter circuit.

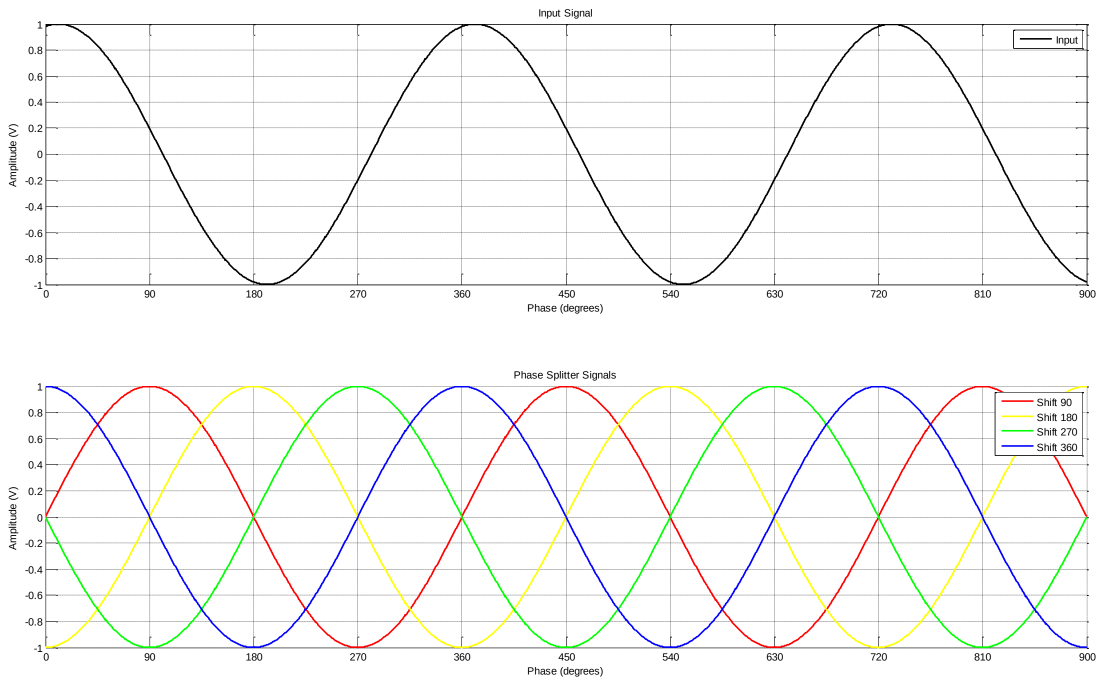


Figure 8 - Phase Splitter Input and Output Signals

The output stage switches between the phase-shifted signals at a speed controlled by the user via a multiplexer controlled by a binary counter that uses a clock frequency from a 555 timer. As a result, the output signal of the multiplexer continually switches by 90 degrees. Switching between two of the out of phase signals momentarily increases the frequency heard and produces frequency modulation, which is a vibrato effect. By adding the switching output of the multiplexer to the input signal from the guitar with a summing amplifier, addition and cancellation of the out of phase signals will cause the resulting signal to have varying amplitude. The change in amplitude of the signal is essentially a tremolo effect. Figure 9 illustrates the effects of the tremolo and vibrato distortion on the input signal.

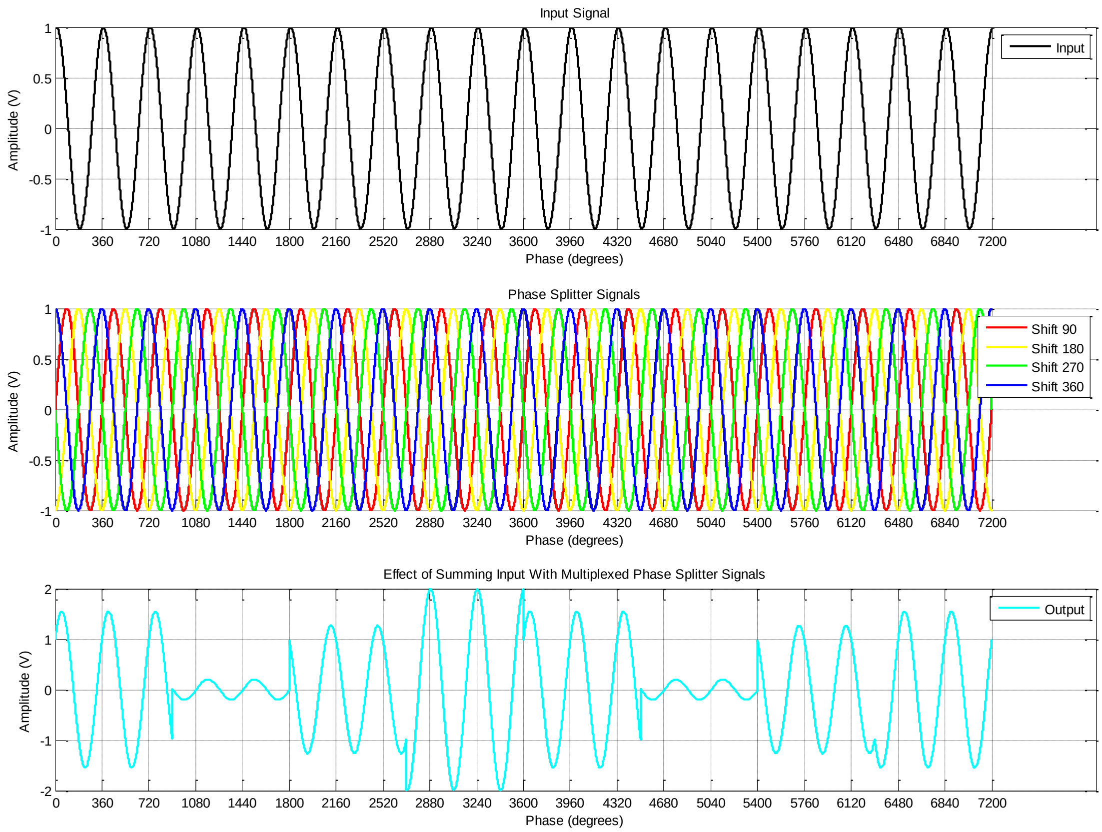


Figure 9 - Phase Splitter Signals and Tremolo and Vibrato Effects

True Bypass Footswitch Design

To implement the true bypass feature, a 3PDT footswitch was included in the design. The footswitch is connected to the input and output of the circuit as well as the input and output of the effects chain. Figure 10 illustrates the wiring of the 3PDT footswitch[5].

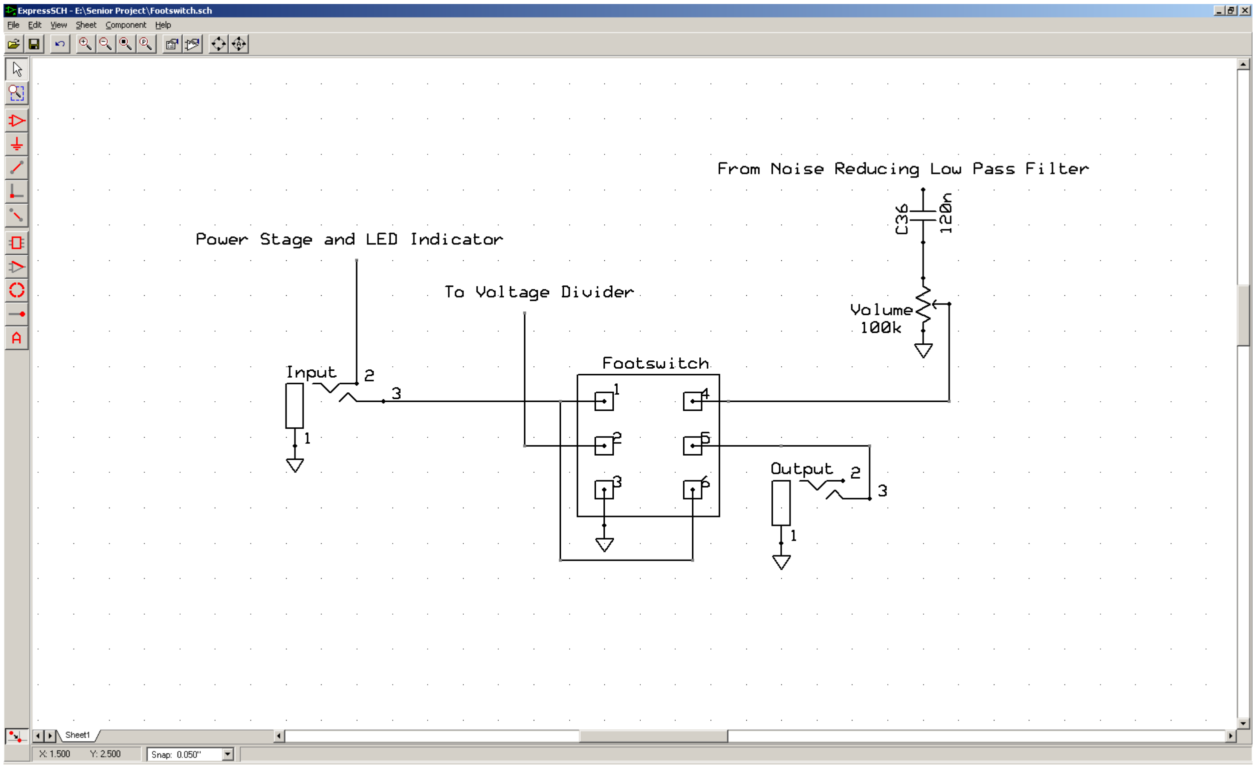


Figure 10 - True Bypass Footswitch

When the footswitch is engaged, the input guitar signal bypasses the rest of the circuitry and is sent straight to the output. This feature is useful for connecting several effects pedals in series because it allows the user to turn on or off desired effects without adjusting cable connections. When the effects pedal is used alone it allows the user to switch between the distortion effect and a clean guitar signal with the push of a button.

Critical Design Review

A critical design review was also conducted to complete the design of the circuits that enable the distortion effect and single supply operation.

Phase Splitter Design

Before breadboard circuit construction, the phase splitter circuit was simulated using Pspice. The initial phase splitter circuit schematic is shown in Figure 11 below.

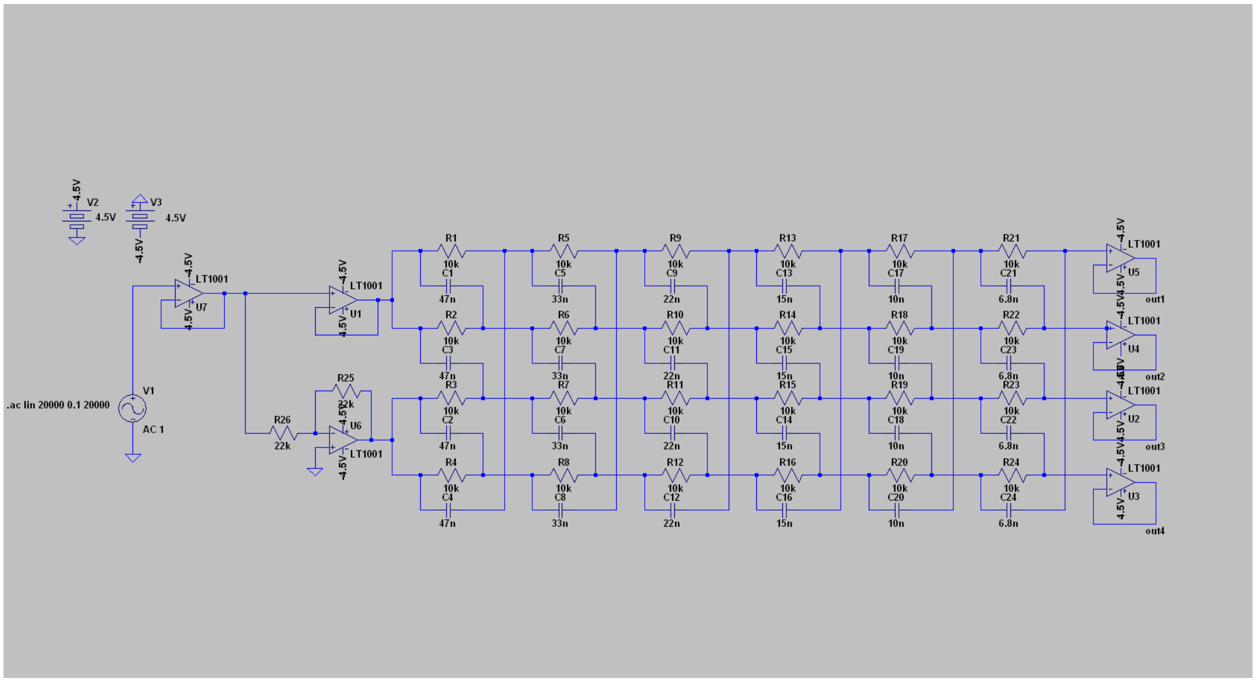


Figure 11 - Initial Phase Splitter Circuit Schematic

The circuit of Figure 11 features an inverting amplifier, which splits the input into two signals that are out of phase by 180 degrees. The circuit also features a six stage poly phase RC network that creates four output signals that are phase shifted from one another by 90 degrees. The buffers at the end of the RC network prevents connections at the output from disrupting the phase splitter circuit's operation[6]. The simulation performed illustrates the magnitude and phase response of the phase splitter over a range of 0 to 3kHz as shown in Figure 12.

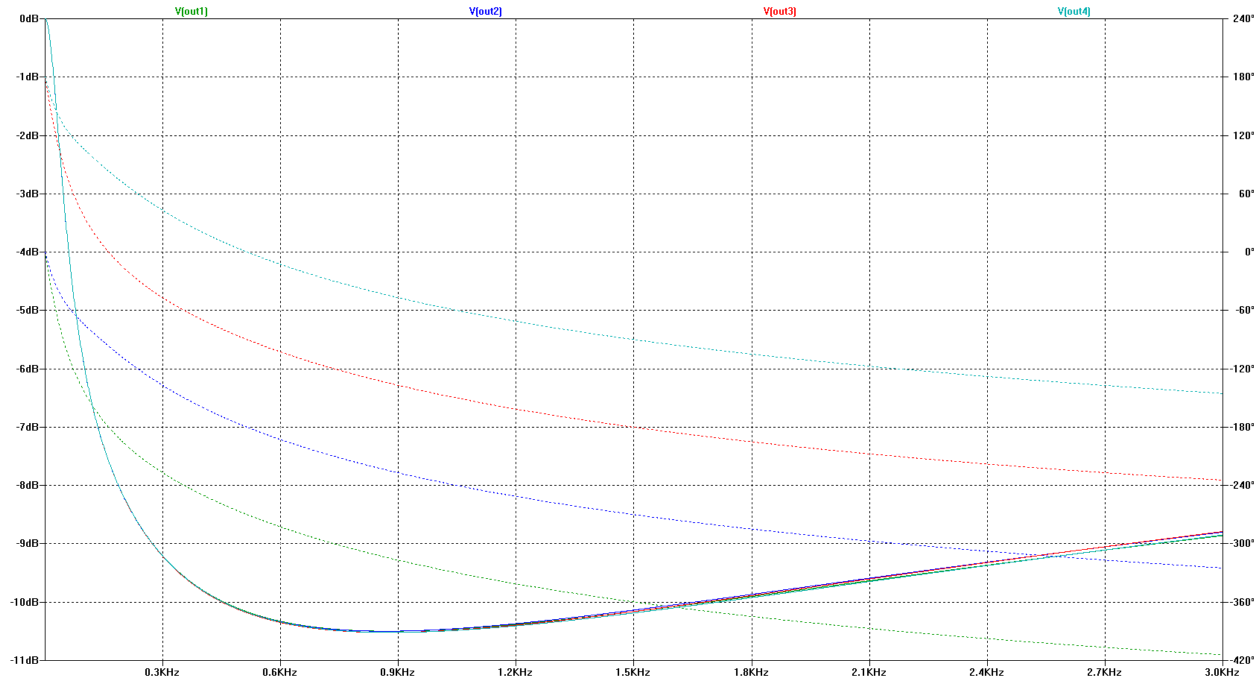


Figure 12 - Initial Phase Splitter Simulated Frequency Response

The simulated frequency response in Figure 12 shows that the phases of the four outputs are shifted approximately 90 degrees from each other. The 90 degree phase shifts between the outputs is constant for a large frequency range with the exception of frequencies near DC. As expected, the magnitude response is also nearly the same for all four outputs. The magnitude response however is not constant, which would cause unwanted filtering or equalization to the guitar signal. To solve this problem, a magnitude correction circuit was added to the design[7]. Figure 13 below shows the final phase splitter circuit design. A simulation in Pspice was also done for this circuit, which is shown in Figure 14.

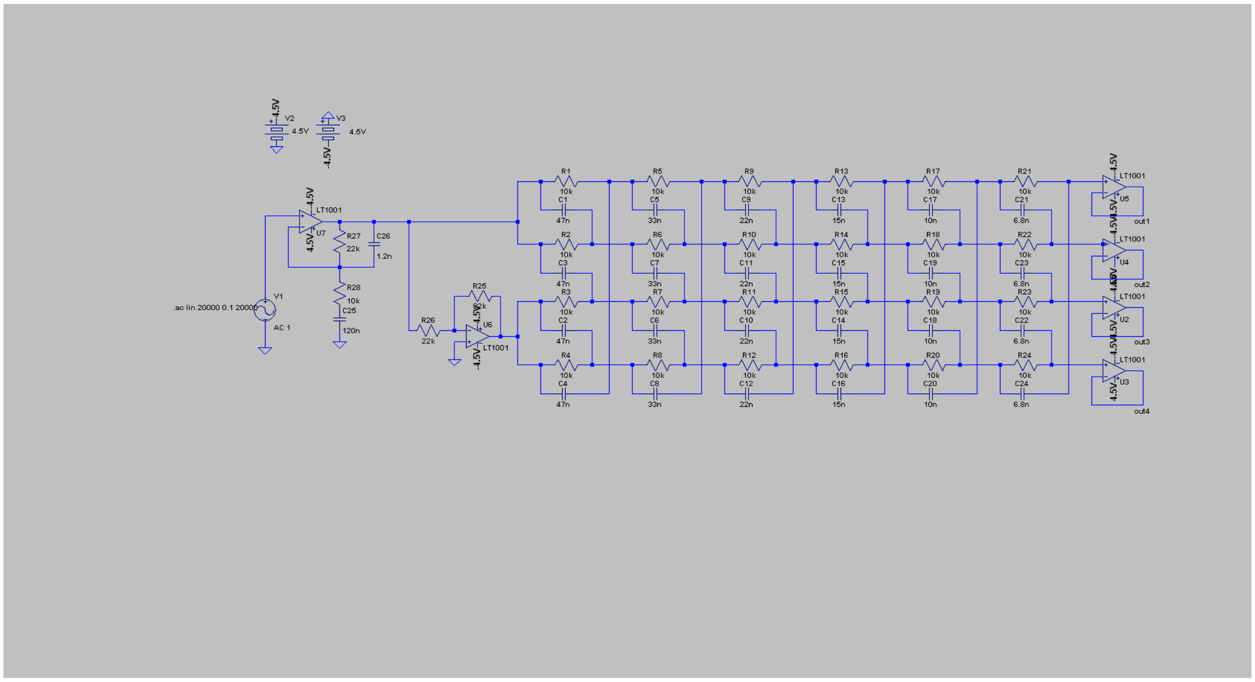


Figure 13 - Final Phase Splitter Circuit Schematic

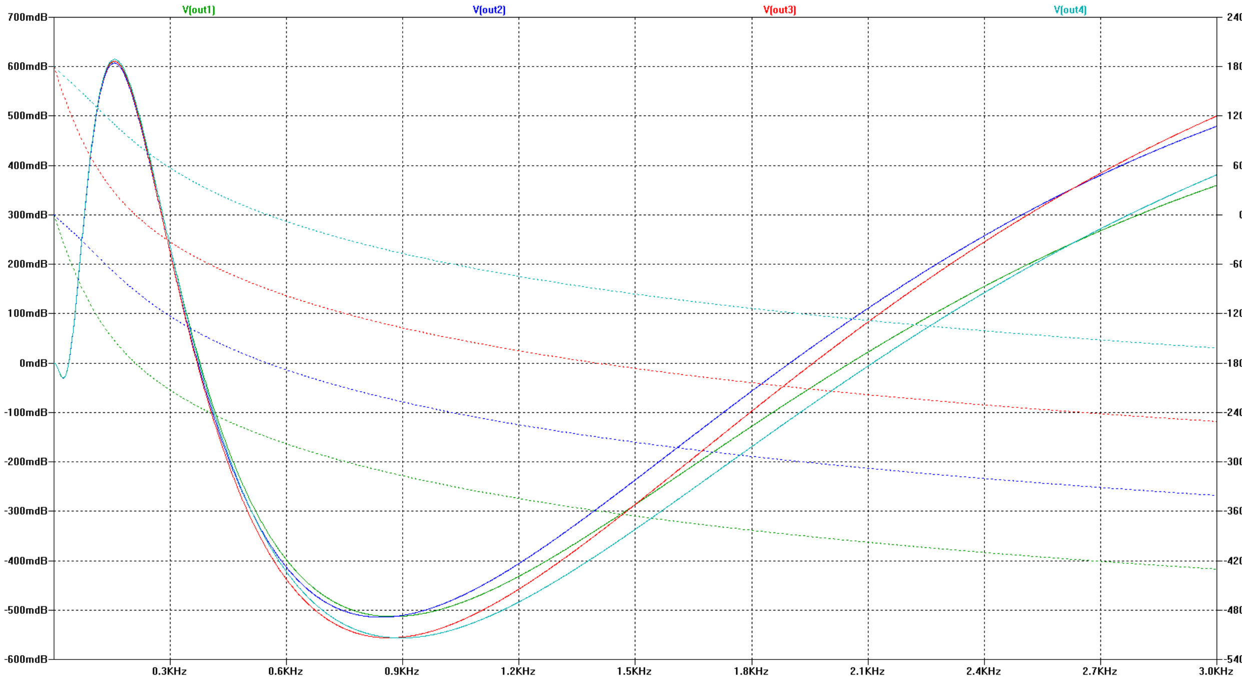


Figure 14 - Final Phase Splitter Simulated Frequency Response

The simulated frequency response of Figure 14 yielded the same 90 degree phase shifts, with a reasonably flat magnitude response for the four outputs.

Timer and Speed Control Design

The speed of the tremolo and vibrato distortion effects is controlled by a 555 timer (CSS555). A potentiometer connected to the timer allows the user to adjust the speed of the distortion. By experimenting with the speed of the clock (the output of the 555 timer), it was found that if the clock frequency was too fast, the distortion effect sounded unpleasant. As a result, a (~1Hz to ~50Hz) range was imposed on the clock frequency, which allowed the timer circuit's components to be calculated as shown below[8].

$$f_{CLK} = \frac{1.44}{[(R_A + 2R_B) \cdot C_T]}$$

$$Let\ R_B = 1M\Omega\ Pot\ and\ C_T = 1\mu F\ Capacitor$$

$$Let\ f_{CLK} = 50Hz\ @\ R_B = 0\Omega,$$

$$50Hz = \frac{1.44}{(R_A) \cdot (1\mu F\ )}$$

$$\Rightarrow R_A = 28.8k\Omega \rightarrow Use\ 27k\Omega\ Resistor$$

$$Calculate\ f_{CLK}\ @\ R_B = 1M\Omega,$$

$$f_{CLK} = \frac{1.44}{[\left(27k\Omega + 2(1M\Omega)\right) \cdot (1\mu F)]}$$

$$f_{CLK} = 0.71\ Hz$$

Using these calculated component values, the timer circuit shown in Figure 15 was constructed.

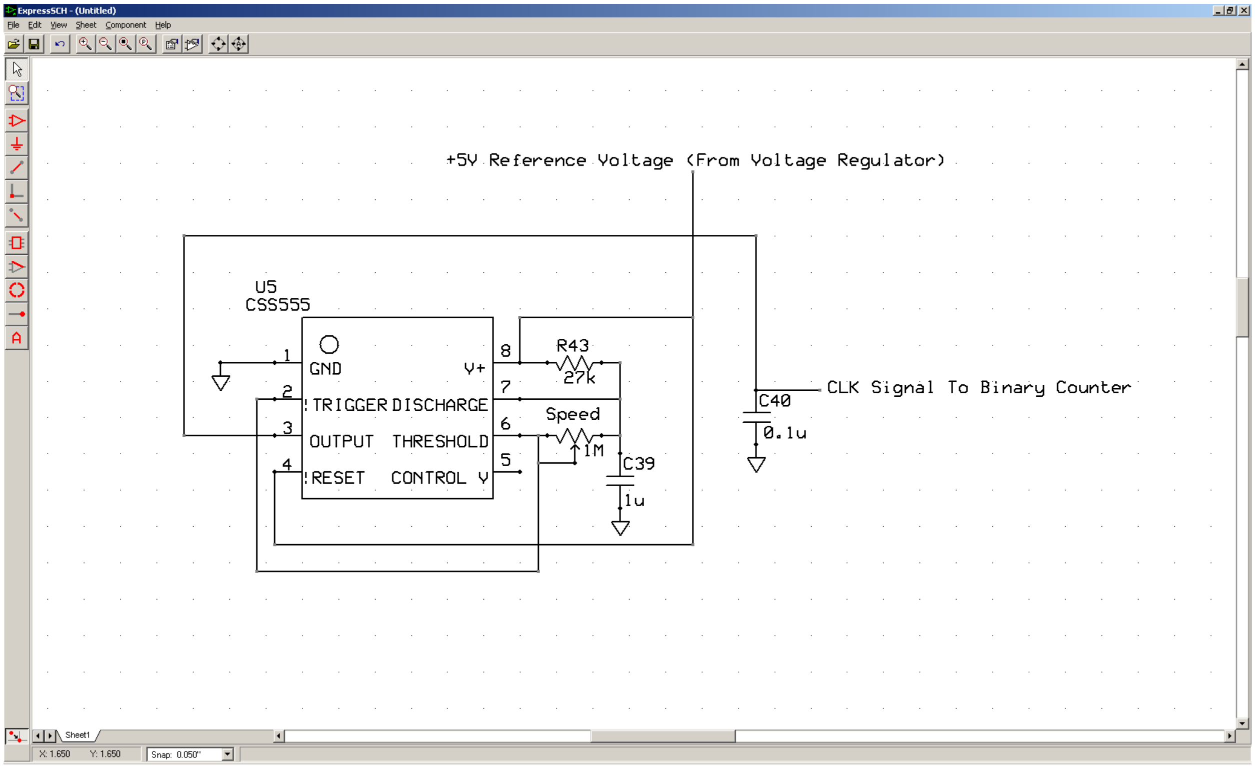


Figure 15 - 555 Timer Circuit

Binary Counter Design

An SN74HC191N binary counter was used for the counter ciruit. Although it is a 4-bit counter, only two of the bits, or outputs, were required by the multiplexer. The least significant bit, or output pin Q_A, is connected to the select input pin A of the multiplexer. The next highest bit, or output Q_B, is connected to the select input pin B of the multiplexer. Implementing these two bits results in two synchronized square wave signals controlled by the clock frequency of the timer. The output frequency of the square wave from Q_A is exactly twice as fast as the output frequency of the square wave from Q_B as shown in Figure 16.

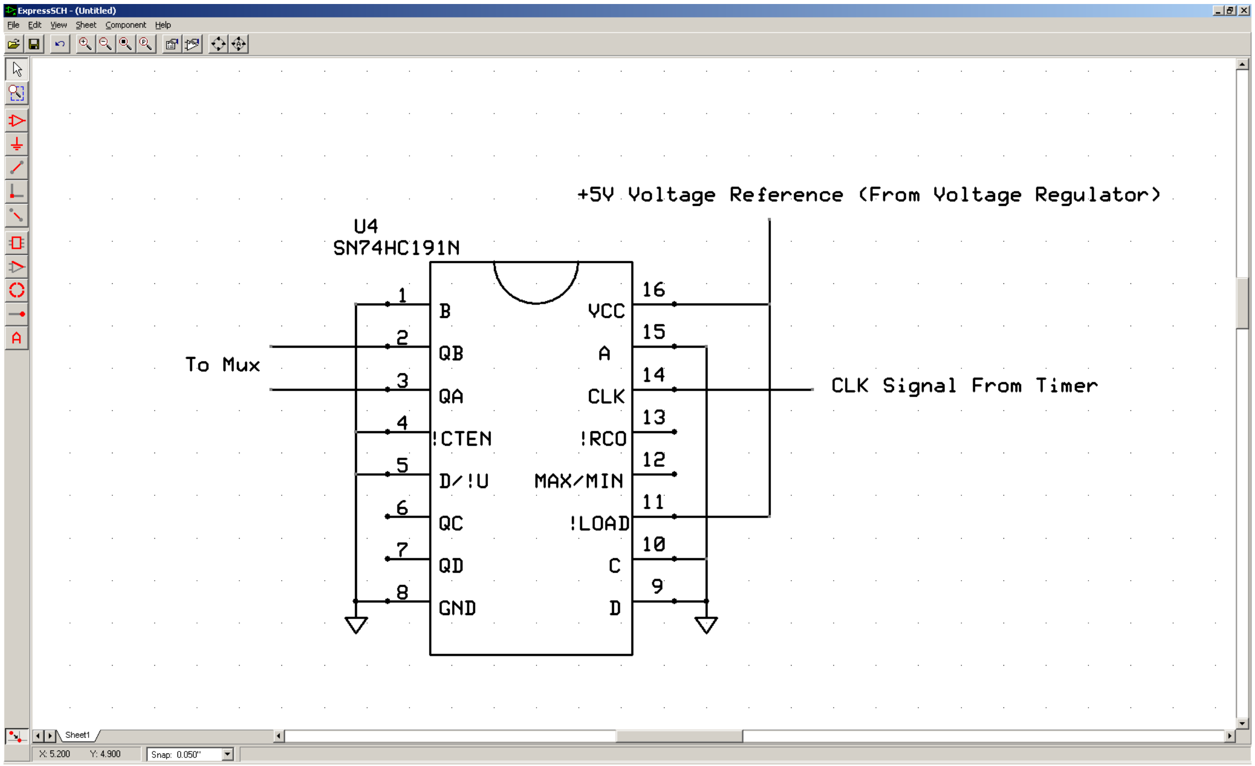


Figure 16 - Binary Counter Output Signals Q_A and Q_B

Multiplexer Design

A CD4052BE multiplexer is used to switch between the outputs of the phase splitter. The multiplexer circuit is shown in Figure 17.

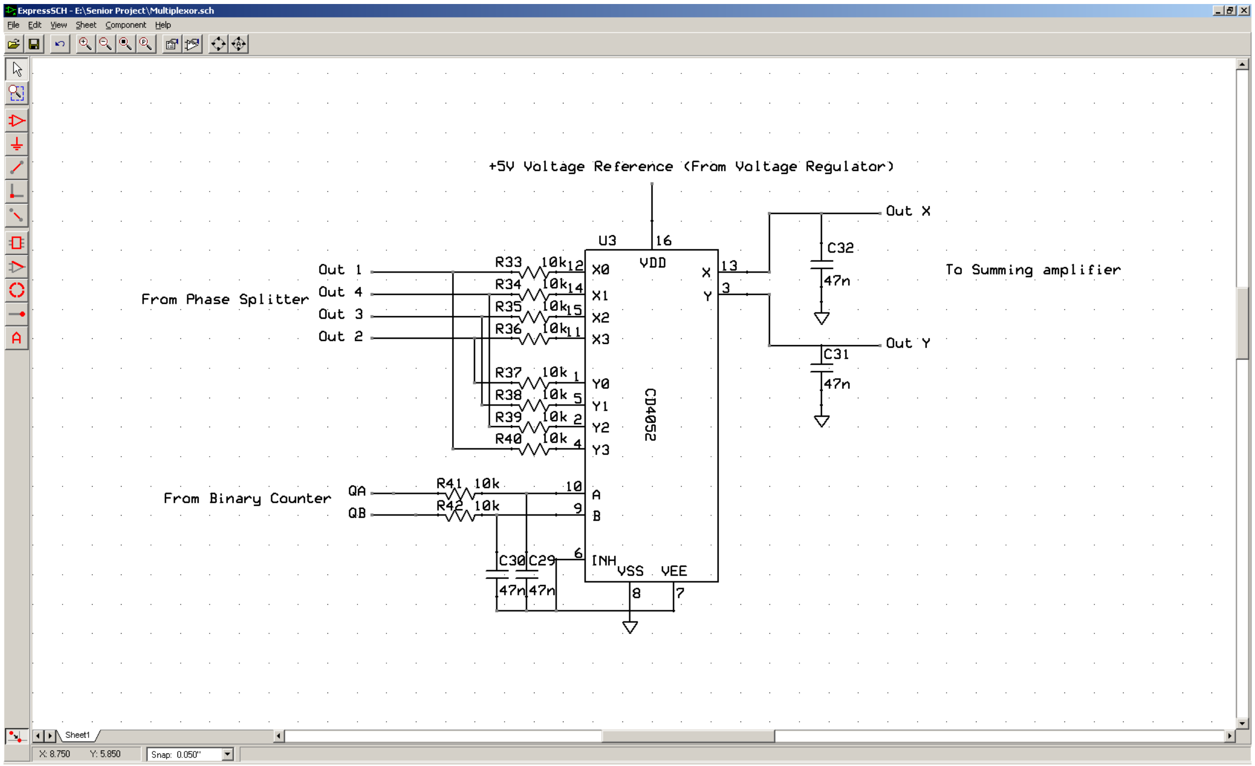


Figure 17 - Multiplexer Circuit

The multiplexer uses the two signals Q_A and Q_B from the binary counter to switch between the outputs. Using these two synchronized signals ensures that the outputs of the phase splitter are sent in order to the output of the multiplexer. Table III below illustrates the cycle of the outputs of the multiplexer based on the logic level of the select inputs[9]. Note that a ‘0’ represents a logic low voltage and a ‘1’ indicates a logic high voltage.

Input B	Input A	Output X	Output Y
0	0	X0	Y0
0	1	X1	Y1
1	0	X2	Y2
1	1	X3	Y3

Table III - Multiplexer Output Selecting Scheme

The input signals of the multiplexer X0 – X3 and Y0 – Y3 are connected to the outputs of the phase splitter. The output signals of the multiplexer Output X and Output Y are connected to a summing amplifier. Although only one set of inputs and outputs (X or Y) of the multiplexer is needed to produce the vibrato and tremolo effects, both sets were implemented. This is accomplished by splitting each of the four outputs of the phase splitter through two 10kΩ resistors to provide eight input signals for the multiplexer. The connections between the phase splitter and multiplexer is illustrated by Table IV below.

Output of Phase Splitter	Input of Multiplexer Connections
Out 1	X0, Y3
Out 2	X3, Y0
Out 3	X2, Y1
Out 4	X1, Y2

Table IV - Multiplexer Input Connections

With this configuration, the Y output will shift forward by 90° at each switch and the X output will shift by 90° in the opposite direction.

Summing Amplifier Design

To produce the tremolo effect, a summing amplifier was implemented. This circuit was constructed using a MC33204P op amp quad package. The inputs of the summing amplifier come from the multiplexer outputs and the original guitar signal. Each of the inputs is connected to the negative terminal of an op amp through a 10kΩ resistor so that three approximately equal magnitude signals are summed together. The summed signals at the output are illustrated by Table V.

Cycle of Output	Signals at Output
1	Guitar Input + Out 1+ Out 2
2	Guitar Input + Out 4 + Out 3
3	Guitar Input + Out 3 + Out 4
4	Guitar Input + Out 2 + Out 1

Table V – Summed Signals of Summing Amplifier

Since the summing amplifier is inverting, the output is fed through another inverting amplifier that also acts as a gain stage. The summing amplifier circuit with the gain stage is shown below in Figure 18.

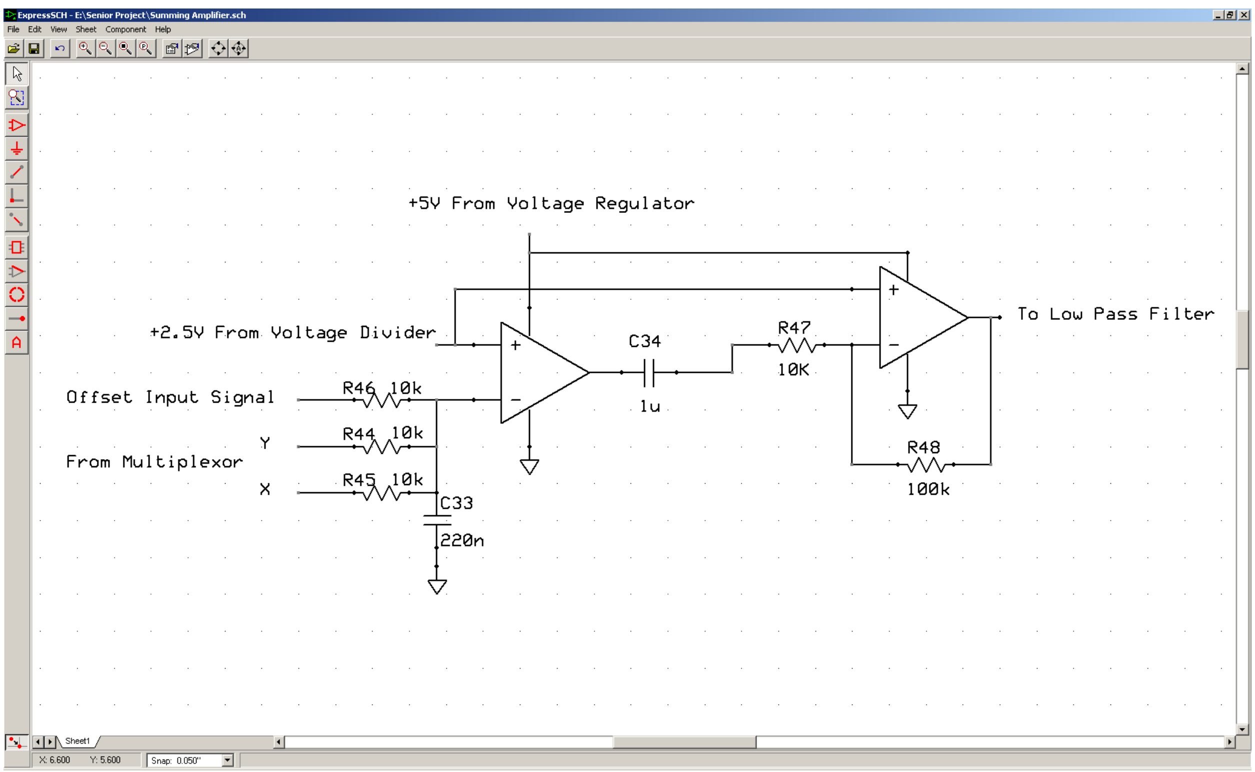


Figure 18 - Summing Amplifier and Gain Stage

Noise Reducing Low Pass Filter Design

To reduce noise caused by the multiplexer switching and smooth out the transition between out of phase signals a low pass filter was implemented. The low pass filter is a simple passive first order filter with the configuration shown in Figure 19.

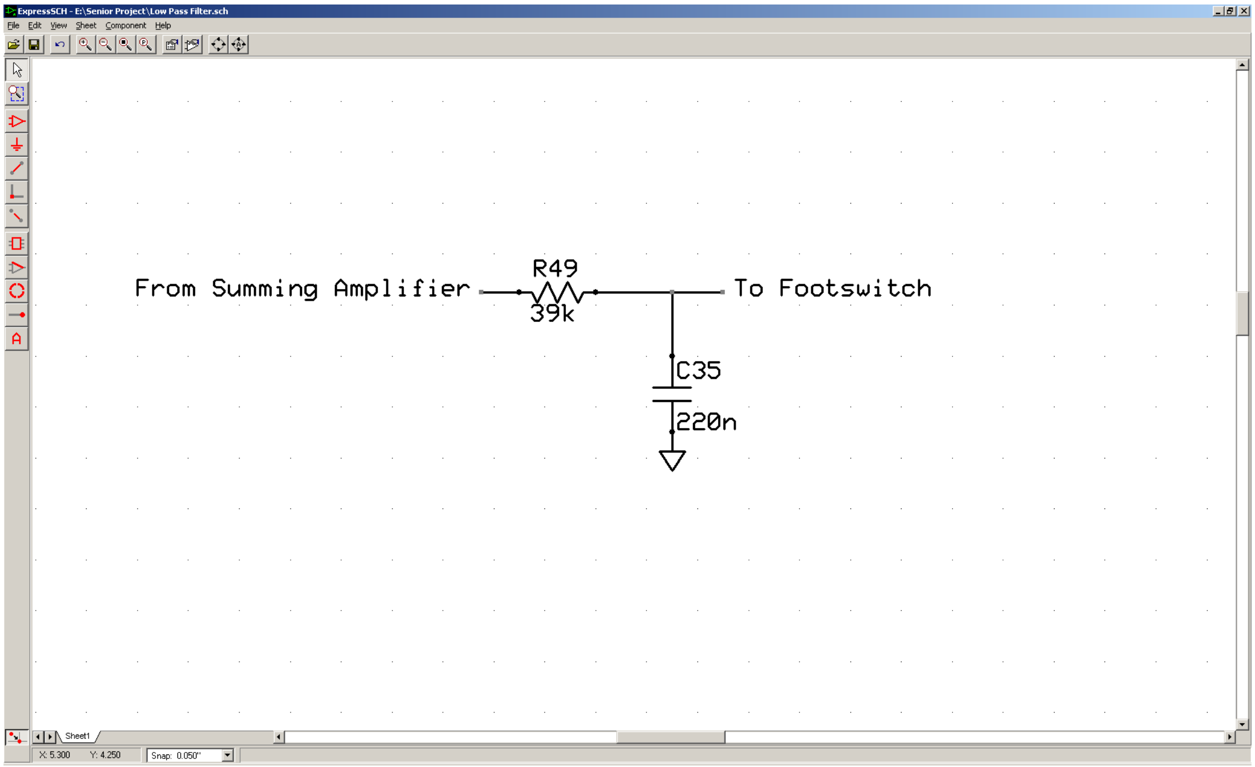


Figure 19 - Noise Reducing Low Pass Filter

The low pass filter receives its input from the output of the summing amplifier and its output is connected to the bypass footswitch. The 39kΩ resistor and 220nF capacitor produce a large time constant to reduce high frequency noise. A calculation of the time constant and cutoff frequency is shown below.

$$\tau = RC = (39k\Omega)(220nF)$$

$$\tau = 8.58ms$$

$$f_c = \frac{1}{2\pi RC} = \frac{1}{2\pi(39k\Omega)(220nF)}$$

$$f_c = 18.55\ Hz$$

An unfortunate side effect of the low pass filter is that the higher frequencies of the input signal are attenuated. This causes higher pitches played on the guitar to sound quieter and also attenuates the harmonics of the guitar signal. This creates a tradeoff between noise reduction and signal loss so the designed filter attempts to reach the best compromise between the two.

Final Circuit Schematic

Once the design phase was completed, the final circuit design of Figure 20 below was constructed.

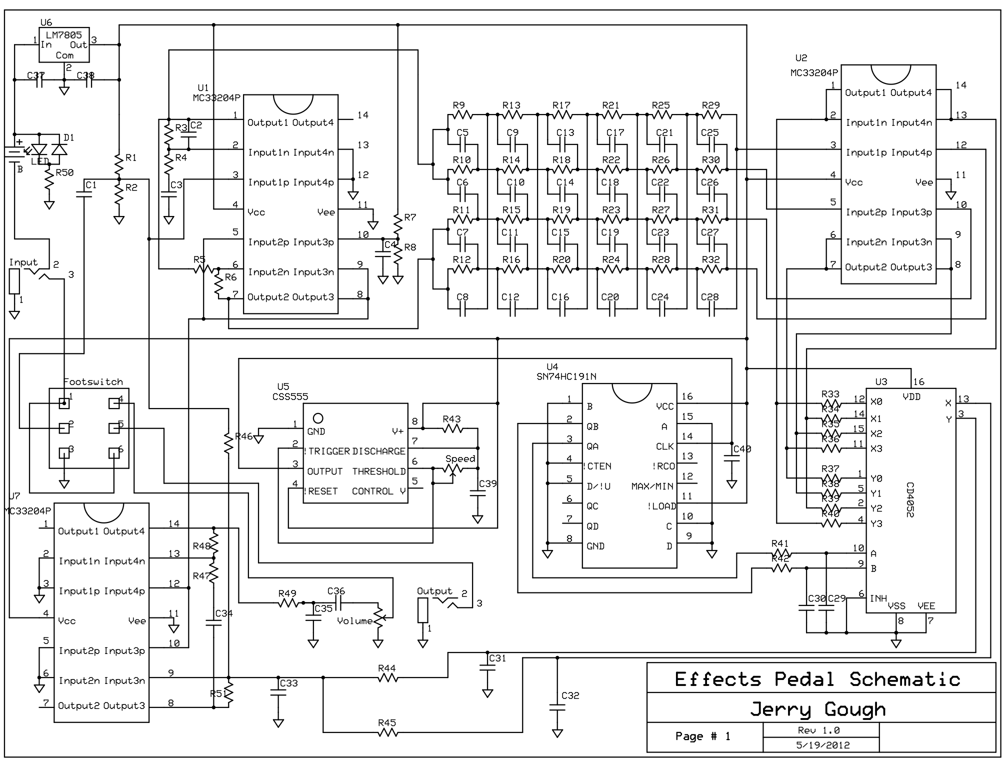


Figure 20 - Final Circuit Design

V. Construction

Breadboard Circuit

Construction of the project began with a breadboard circuit design. Different parts of the circuit were constructed separately on a breadboard, tested, and eventually integrated with the other parts. After the breadboard phase splitter circuit became operational, it was soldered on to a prototype board with copper traces to improve durability and reliability. A picture of the phase splitter circuit on the prototype board is shown in Figure 21 below.

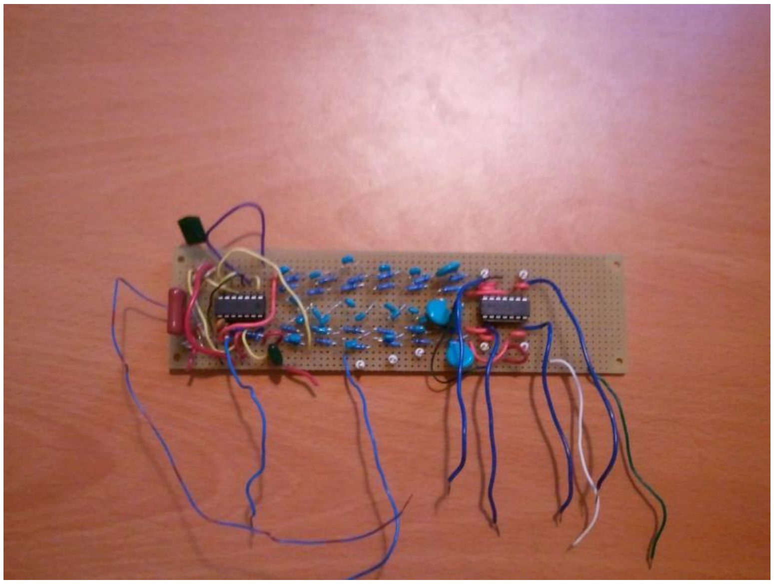


Figure 21 - Phase Splitter Prototype Circuit

The prototype phase splitter was integrated with the rest of the effects pedal breadboard circuit to produce the breadboard circuit of Figure 22.

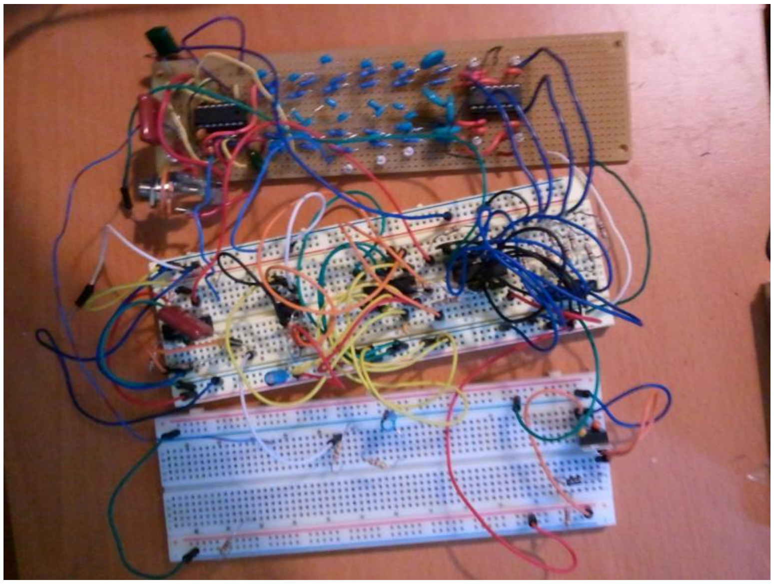


Figure 22 - Breadboard Effects Pedal Circuit

Note: This is a picture of the final breadboard circuit with the potentiometers, audio cable jacks, and footswitch removed.

Once an operational breadboard circuit was completed and finalized, design and construction of the Printed Circuit Board began, as explained by the following section.

PCB Circuit

The printed circuit board was designed using ExpressPCB CAD software. ExpressPCB is also the printed circuit board manufacturing company that was hired to assemble the PCB for this project. Initially a schematic of the effects pedal circuit was created using Express PCB software, which was shown earlier in Figure 20. This step greatly facilitated the actual PCB design because the schematic file could be linked to the PCB layout file. The linking feature shows the connections between components by highlighting all of the components connected to the selected node in the PCB layout software. After all of the components and connections were placed, the PCB layout design was completed, which is shown below in Figure 23.

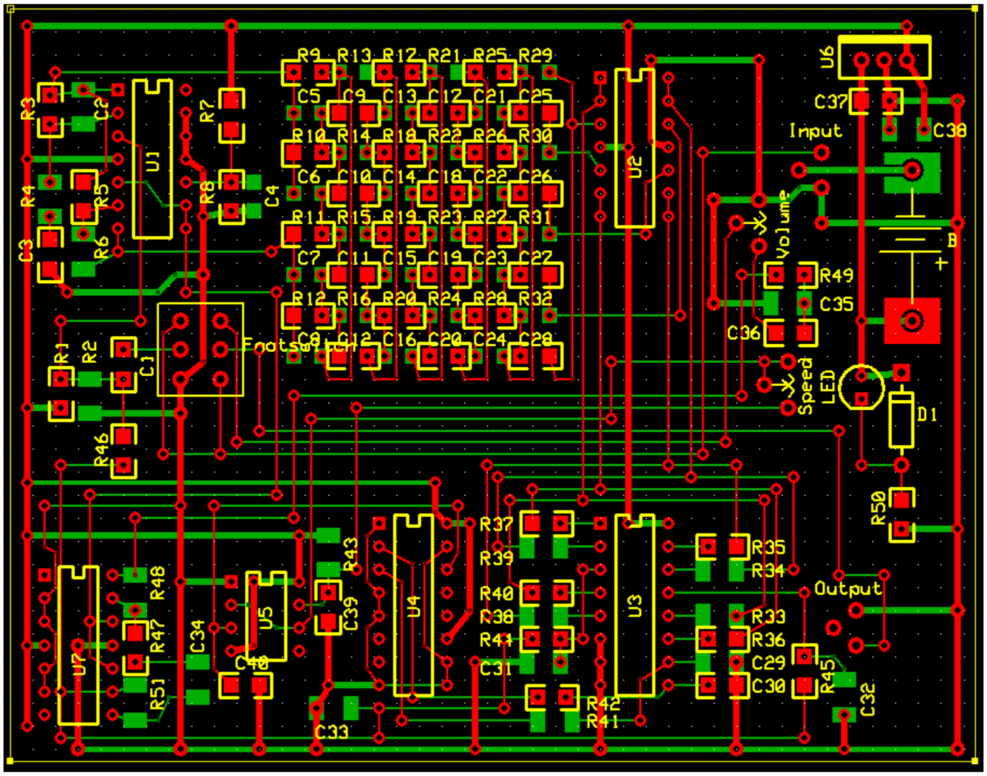


Figure 23 - PCB Layout Design

The PCB layout of Figure 23 was designed using a “Manhattan Style” technique. This technique requires most of the traces to be either perfectly vertical or horizontal depending on what side of the board they are on. The color red in the layout indicates the features of the top side of the board and the color green shows the features of the bottom side of the board. The red circles however are holes or “vias”, which connect to both sides of the board. The color yellow is a silkscreen layer, which was not used to reduce the cost of the boards. The PCB layout was checked for errors and two boards were ordered through ExpressPCB. A picture one of the manufactured boards is shown in Figure 24.

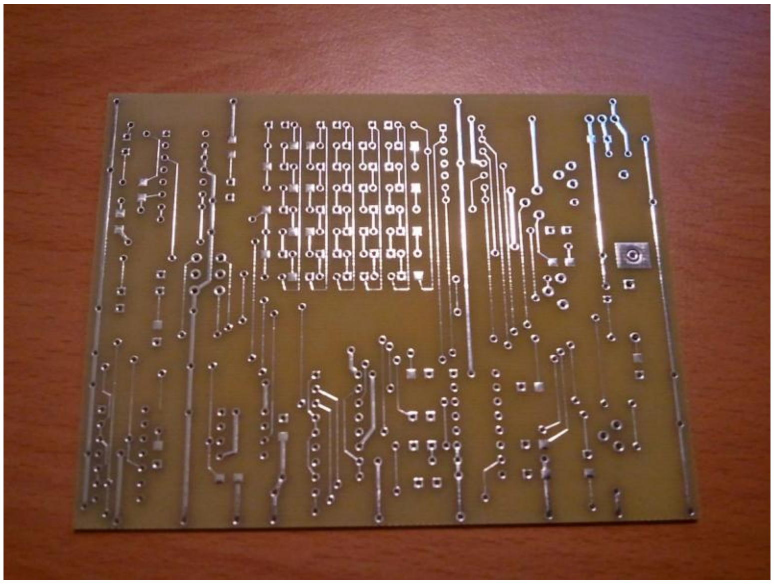


Figure 24 - Manufactured PCB

Assembly and Enclosure

Once all of the parts were acquired, they were soldered to the PCB to produce the circuit of Figure 25. All of the resistors and capacitors of the circuit are SMT 1206 surface mount components.

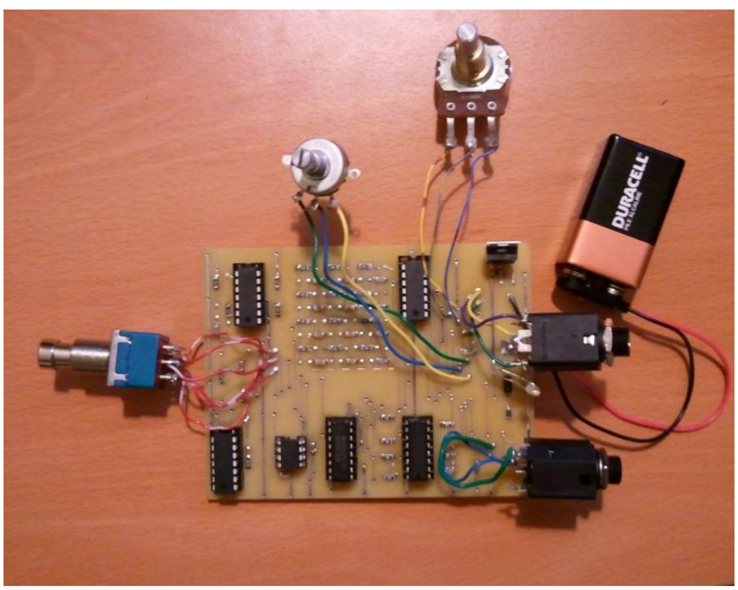


Figure 25 - Assembled PCB Design

To improve durability the assembled PCB Design of Figure 25 was placed in an aluminum enclosure. The enclosure used is a 4 Site 1590 Aluminum Diecast Enclosure and was ordered from a company called Pedal Parts Plus. Holes were drilled in the enclosure for the footswitch, potentiometer, LED, and Audio Cable Jacks. After painting the enclosure, the assembled PCB design was placed in the enclosure to create the finished prototype shown in Figure 26.

Figure 26 - Finished Effects Pedal Prototype

True Bypass Verification

To verify that the bypass was functioning properly, a 240mV$_{p\text{-}p}$ sinusoidal signal with a frequency of 200Hz was applied to the input. By comparing the output signal with the input signal in bypass mode, the true bypass feature could be verified. Figure 27 below shows a scope capture of the input and output signals in bypass mode.

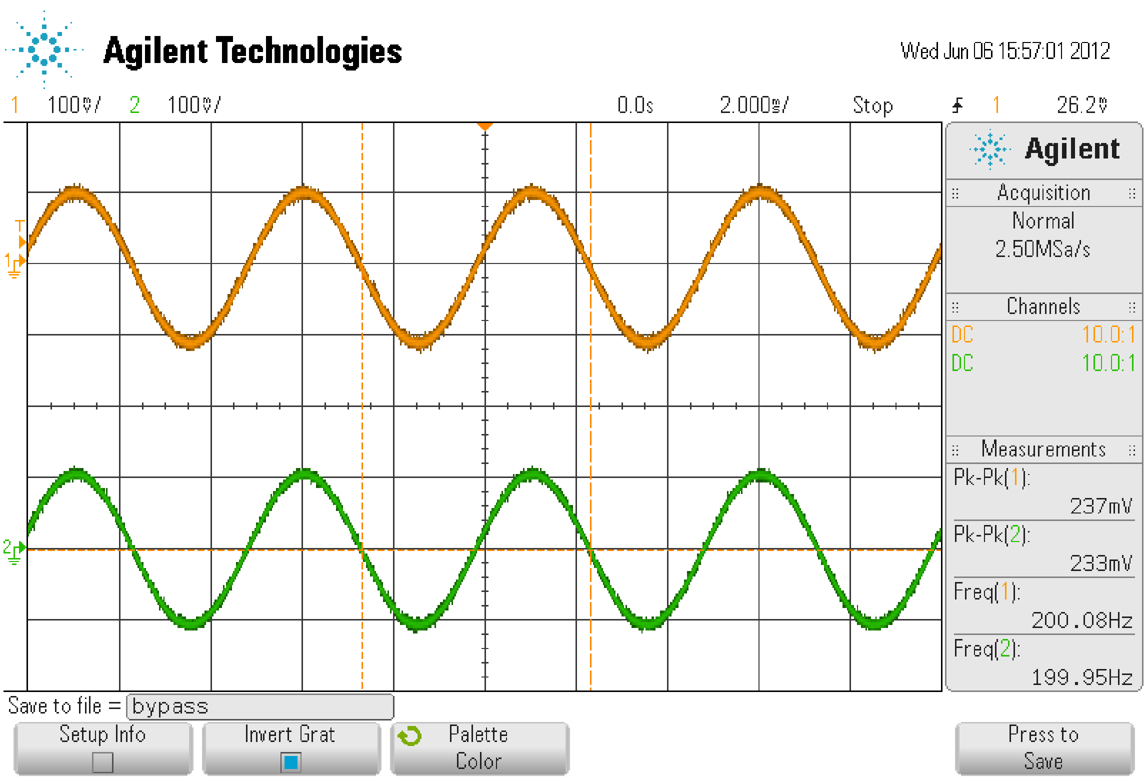


Figure 27 - Input and Output Signal In True Bypass Mode

Figure 27 shows a small 4mV difference in magnitude however the input and output signals appear to be relatively the same. The output was also listened to through headphones via the Roland Micro Cube-R amplifier, but the clicking noise mentioned earlier was audible in bypass mode. It was also discovered that this clicking noise varied with the speed of the timer. An oscilloscope capture of the clicking noise is shown in Figure 28.

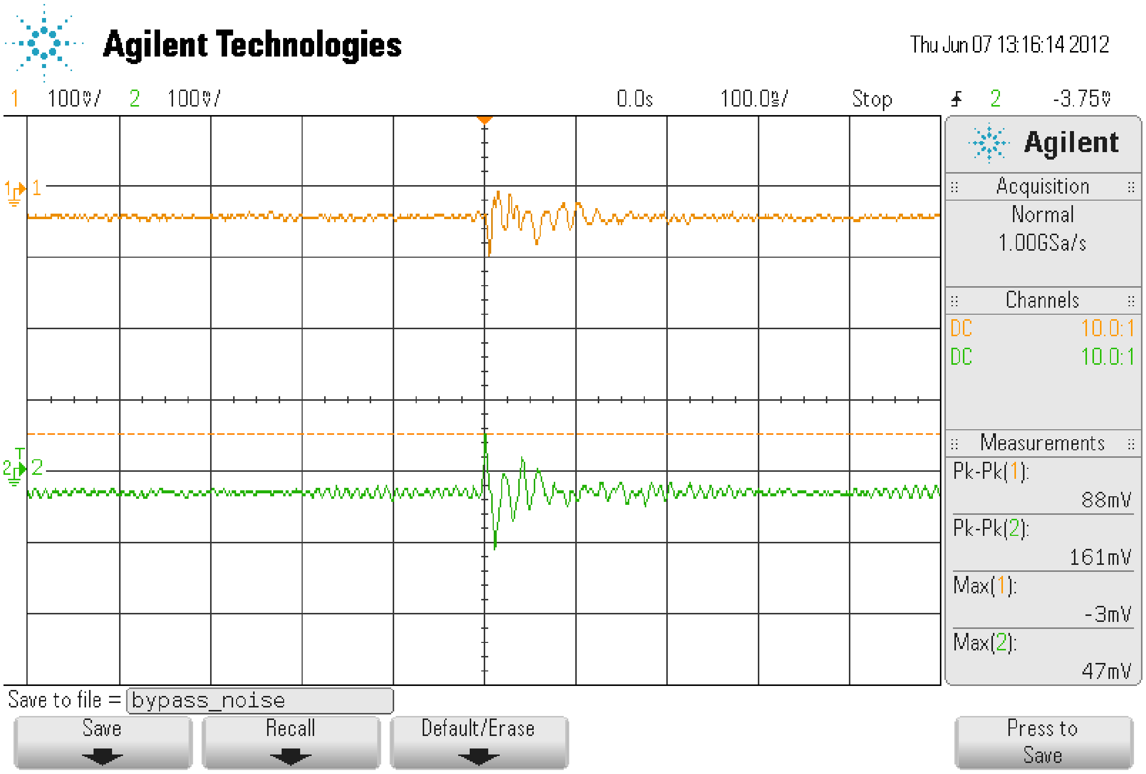


Figure 28 - Bypass Input and Output Noise

Figure 28 shows the bypass clicking noise to be a sharp change in voltage level on both the input and output signal. The output signal showed a noise level of 161mV$_{p\text{-}p}$ and the input level showed a noise level of 88mV$_{p\text{-}p}$.

It was very unexpected to find that the clicking noise had affected the input signal. Since the only connection between the input and the suspected cause of the noise (multiplexer switching) is ground, it is likely that the bypass noise is caused by a grounding issue. A possible solution for this issue is to use a buffer to maintain a constant and stable ground.

Phase Splitter Verification

The frequency response of the phase splitter was measured to ensure that it was functioning correctly. A 1V$_{p\text{-}p}$ sinusoidal signal was used for the input of the circuit. By varying the frequency of the input signal and measuring the peak to peak voltage of the four outputs, the data

of Table VI was collected.

Frequency (Hz)	Input Magnitude (Vp-p)	Out 1 Magnitude (Vp-p)	Out 2 Magnitude (Vp-p)	Out 3 Magnitude (Vp-p)	Out 4 Magnitude (Vp-p)
1	1	1.02	1.01	1.02	1.02
100	1	0.93	0.96	0.92	0.96
200	1	0.98	1	0.97	1
300	1	0.97	0.98	0.95	0.98
400	1	0.95	0.95	0.94	0.96
500	1	0.94	0.94	0.92	0.94
600	1	0.93	0.93	0.91	0.93
700	1	0.92	0.92	0.91	0.93
800	1	0.92	0.91	0.91	0.93
900	1	0.92	0.92	0.91	0.93
1000	1	0.93	0.92	0.91	0.93

Table VI - Phase Splitter Magnitude Response

Table VI shows that the magnitudes of the output signals are nearly the same and do not deviate far from the magnitude of the input signal. This indicates that the magnitude correction part of the circuit is working properly. The data of Table VI was graphed in excel to obtain the Magnitude Response plot of Figure 29 below.

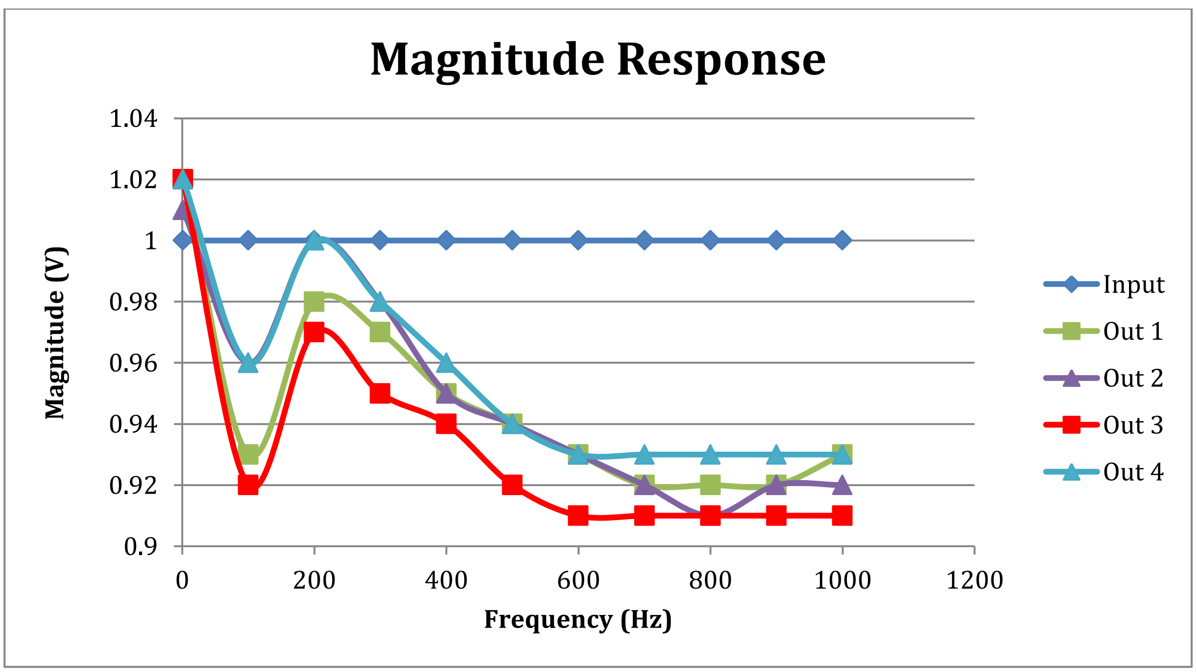


Figure 29 - Phase Splitter Magnitude Response

The plot of Figure 29 shows that the phase splitter has a relatively flat magnitude response as expected. The magnitude response also closely follows the Pspice simulation results shown earlier in Figure 14. Data for the phase response of the phase splitter was also collected and can be seen in Table VII below.

Frequency (Hz)	Input Phase (degrees)	Out 1 Phase (degrees)	Out 2 Phase (degrees)	Out 3 Phase (degrees)	Out 4 Phase (degrees)
1	0	0	1	180	181
100	0	-315	-250	-135	-70
200	0	-275	-189	-93.4	-9
300	0	-240	-152	-59.5	28.7
400	0	-214	-125	-32	55
500	0	-193	-104	-12	76
600	0	-175	-86.2	5.5	94
700	0	-160	-72	20.5	109
800	0	-149	-58	33	122
900	0	-137	-46	45	133
1000	0	-126	-37	55	143

Table VII - Phase Splitter Phase Response Data

The phase values of the outputs in Table VII are relative to phase of the input (0°). The phase response data collected shows that the phase difference between successive outputs is close to the expected value of 90°. The collected phase response data was graphed in excel to produce the plot of Figure 30.

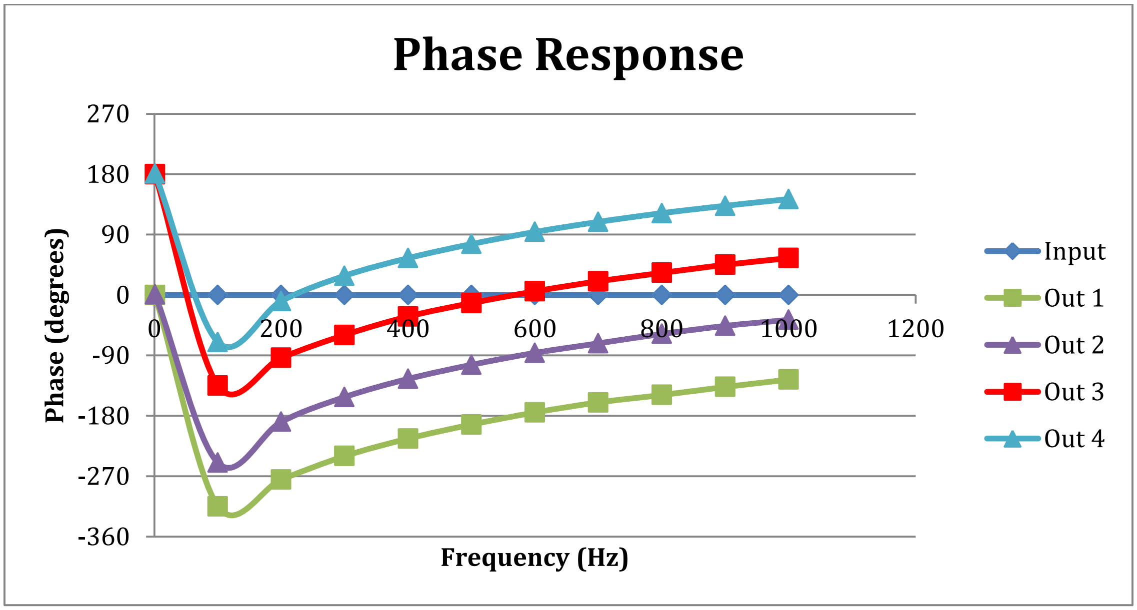


Figure 30 - Phase Splitter Phase Response

Figure 30 shows that the phase difference between successive outputs is approximately 90° for a large range of frequencies. The effectiveness of the phase splitter deteriorates at low frequencies and the phase differences deviate from 90°. The Hilbert transformer pairs (Out 1 & Out 2, Out 3 & Out 4) however maintain a phase difference of approximately 180 degrees between each other at low frequencies.

Timer Verification

To test the operation of the CSS555 timer on the assembled PCB circuit, the output signal CLK was viewed on the oscilloscope. First, the signal was analyzed with the potentiometer at its highest value of 1MΩ, which produced the slowest speed of the CLK signal, which is shown in Figure 31.

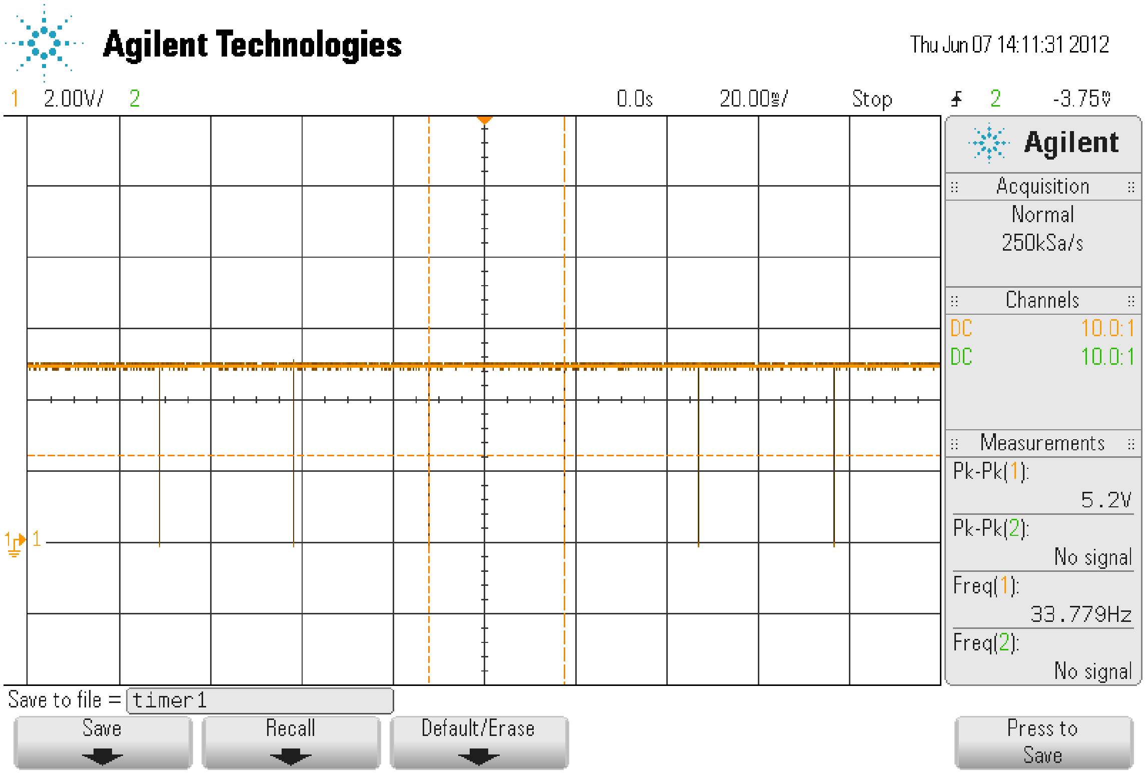


Figure 31 - Timer at Slowest Speed with $f_{CLK} \approx 33.8Hz$

Figure 31 indicates that the slowest speed of the clock is approximately 33.8Hz, which is significantly higher than the expected value of approximately 1Hz. It is unclear what caused this issue because the breadboard circuit was able to achieve the desired low speed, but the assembled PCB design did not. One possible cause of the deviation of the expected clock frequency is that a mistake was made in the PCB design. A malfunctioning timer could also be the cause of the faster clock speed. Another test of the timer was conducted with the potentiometer turned all the way off. The resulting measured clock signal is shown in Figure 32.

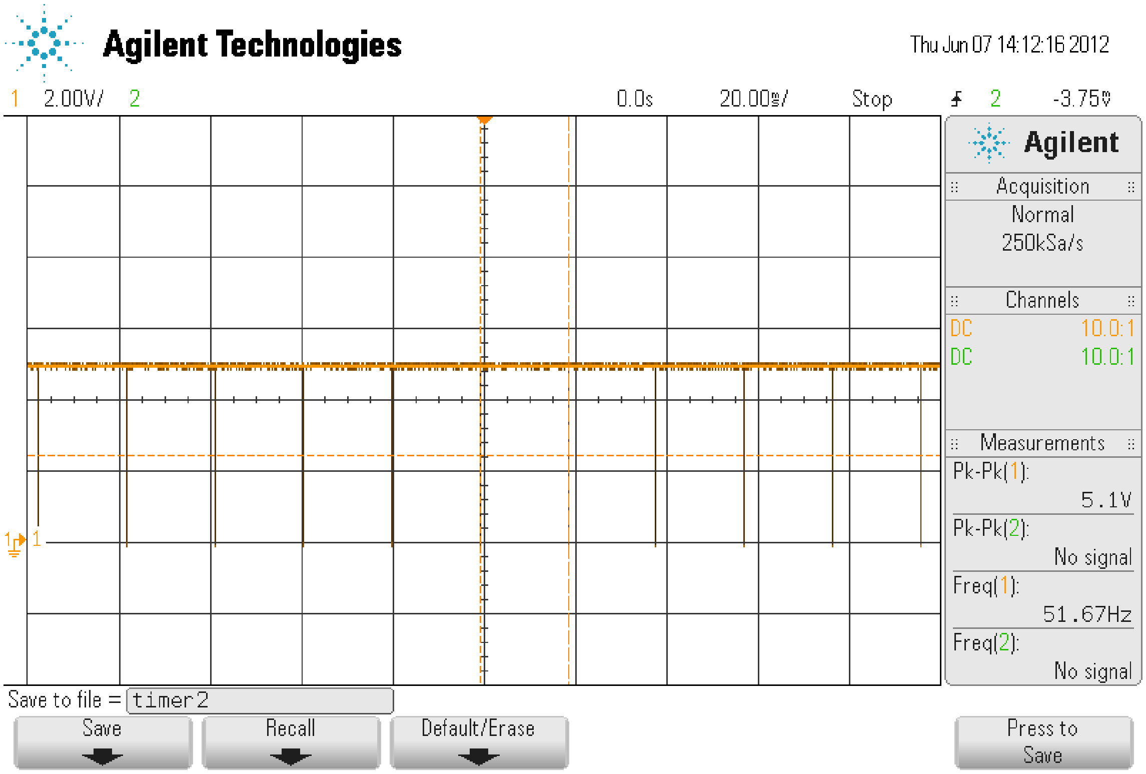


Figure 32 - Timer at Fastest Speed with $f_{CLK} \approx 51.7$Hz

Figure 32 shows that the highest frequency of the clock is approximately 51.7Hz, which is reasonably close to the expected value of 50Hz. This produced an error of approximately 3.4% between measured and expected results. From the test results, the timer circuit did not operate as desired, however the approximate 20Hz range of f_{CLK} provided an acceptable variable speed for the distortion effect.

Counter Verification

To verify the operation of the SN74HC191N binary counter, the output signals Q_A and Q_B were viewed on the oscilloscope. A scope capture of Q_A, Q_B, and CLK, is shown in Figure 33.

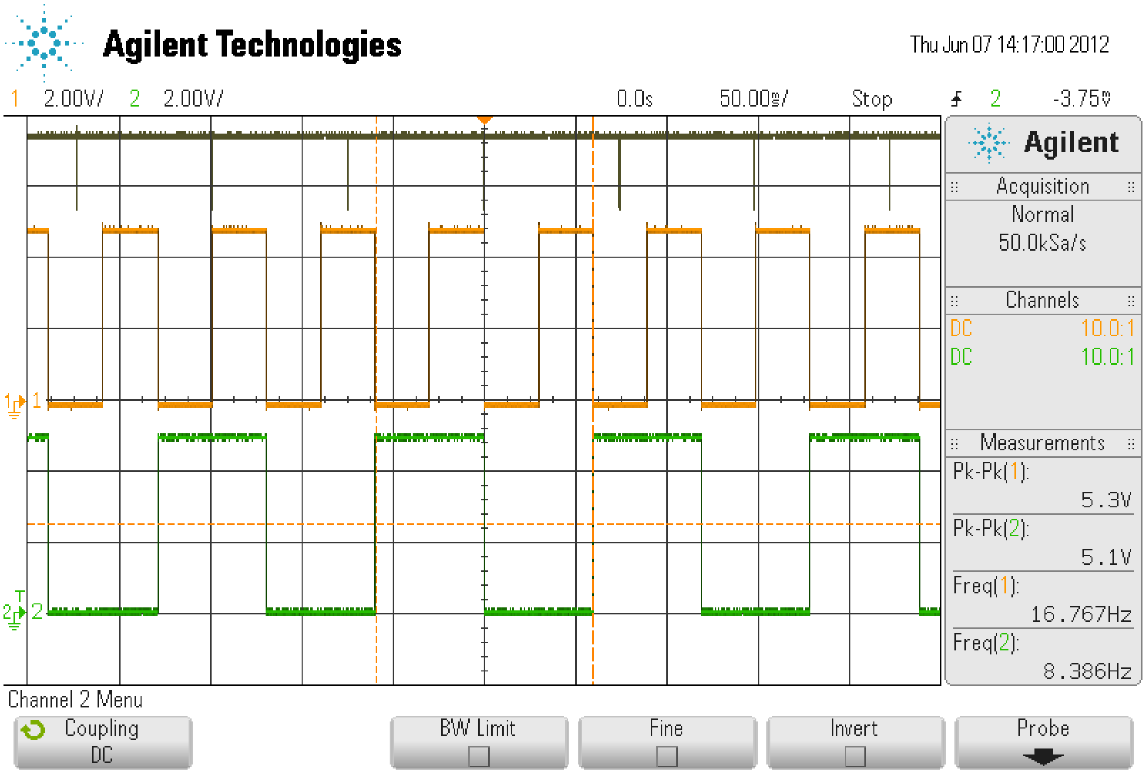


Figure 33 - Binary Counter Signals Q_A, Q_B, and CLK with $f_{CLK} \approx 33.8$Hz

Figure 33 shows that the signals Q_A (orange) and Q_B (green) are synchronized as expected. When the clock (black) is running at its lowest frequency of 33.8Hz, the frequency f_{QA} ($\approx$ 16.8Hz) is twice the frequency f_{QB} ($\approx$ 8.4Hz), as expected. From the scope capture, we can also conclude that the slowest switching speed of the multiplexer will be approximately 16.8Hz since it switches at the rate of signal Q_A. A second scope capture of the binary counter signals was taken with the clock set to its highest speed, which is shown in Figure 34.

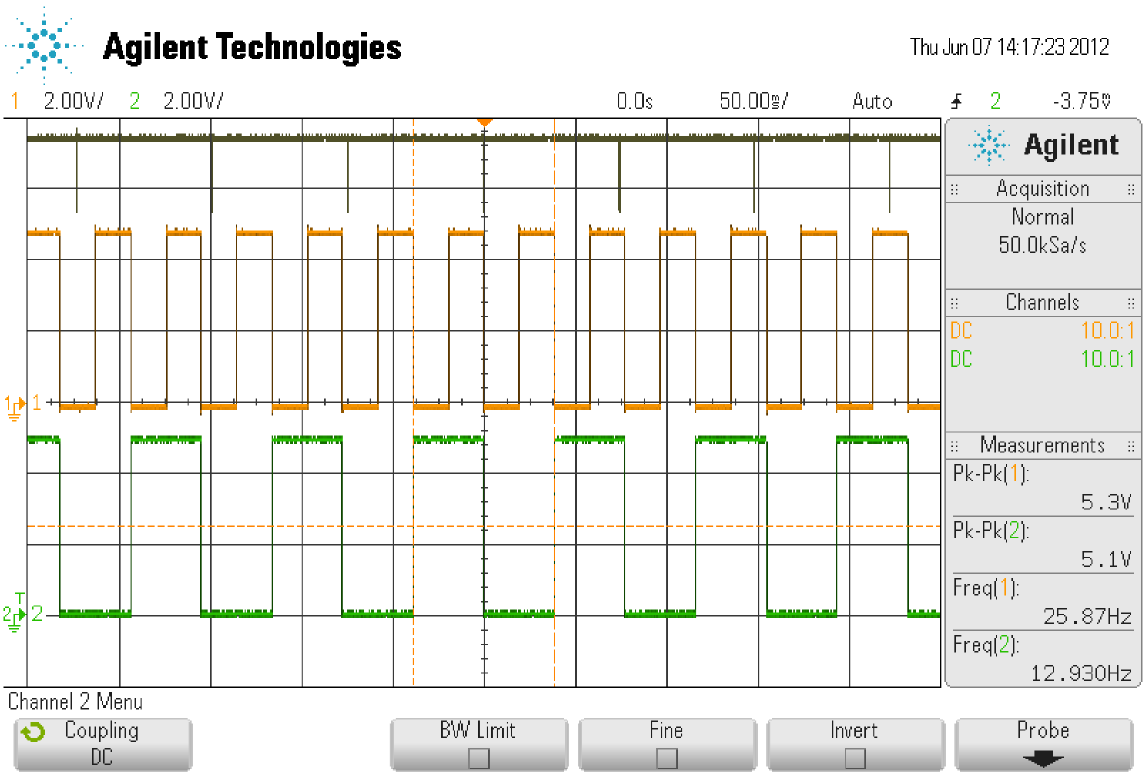


Figure 34 - Binary Counter Signals Q_A, Q_B, and CLK with $f_{CLK} \approx 51.7$Hz

Figure 34 shows that the fastest clock frequency f_{CLK} = 51.7Hz produces a Q_A frequency f_{QA} of approximately 25.9Hz. This indicates that the fastest switching speed of the multiplexer will be 25.9Hz. From the results of the binary counter test, we can verify that the counter is functioning correctly.

Distortion Verification

To verify that the distortion effect was functional, the output of the effects pedal was connected to the Roland Micro Cube-R guitar amplifier and listened to with a pair of headphones. Using a guitar as the input signal, the strings were played and a "wobbly sounding" tremolo and vibrato like distortion was heard. To visually verify the distortion effect, a 110Hz sinusoidal signal was applied to the input and the output was viewed on the oscilloscope. A scope capture of the distortion effect is shown in Figure 35.

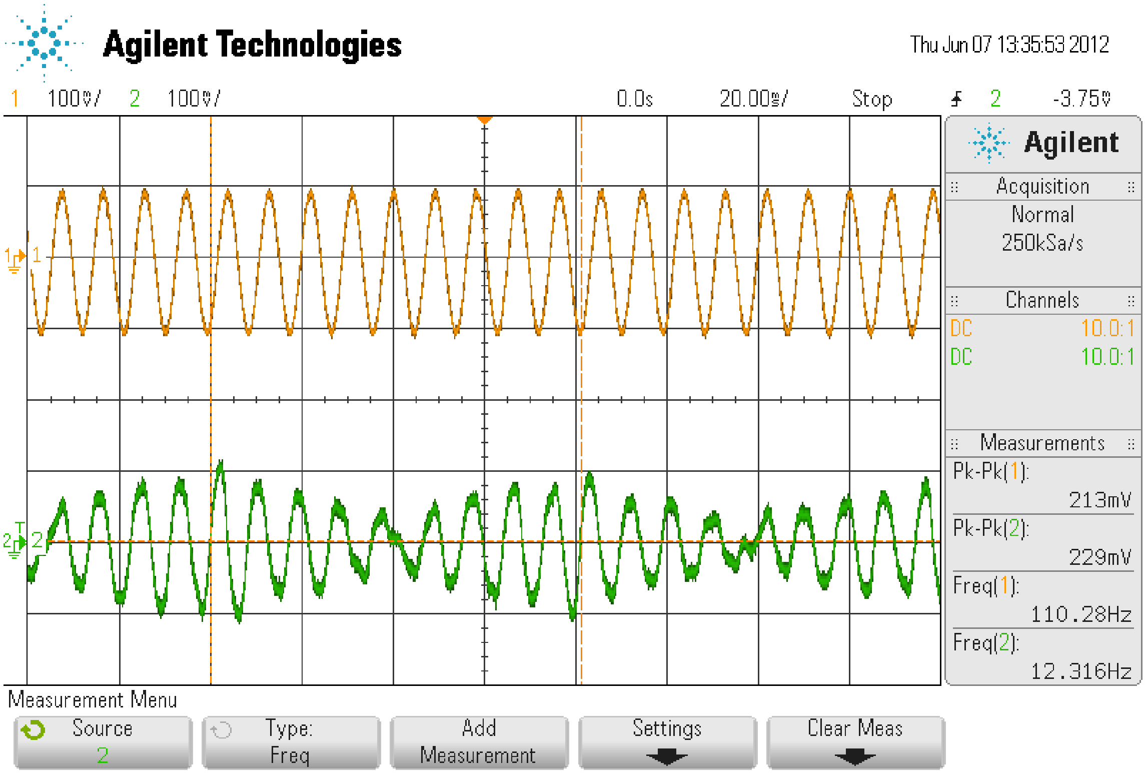


Figure 35 - Phase Splitter Effects Pedal Distortion Effect

Figure 35 clearly indicates that there is a change in the amplitude of the output signal, which is a visual representation of the tremolo effect. By closely looking at the output signal, discontinuities of the sinusoid are visible, which indicate switching between out of phase signals. The switching between the out of phase signals creates the momentary change of frequency that is heard as a vibrato effect. A zoomed out, broader view of the distortion effect is shown in Figure 36.

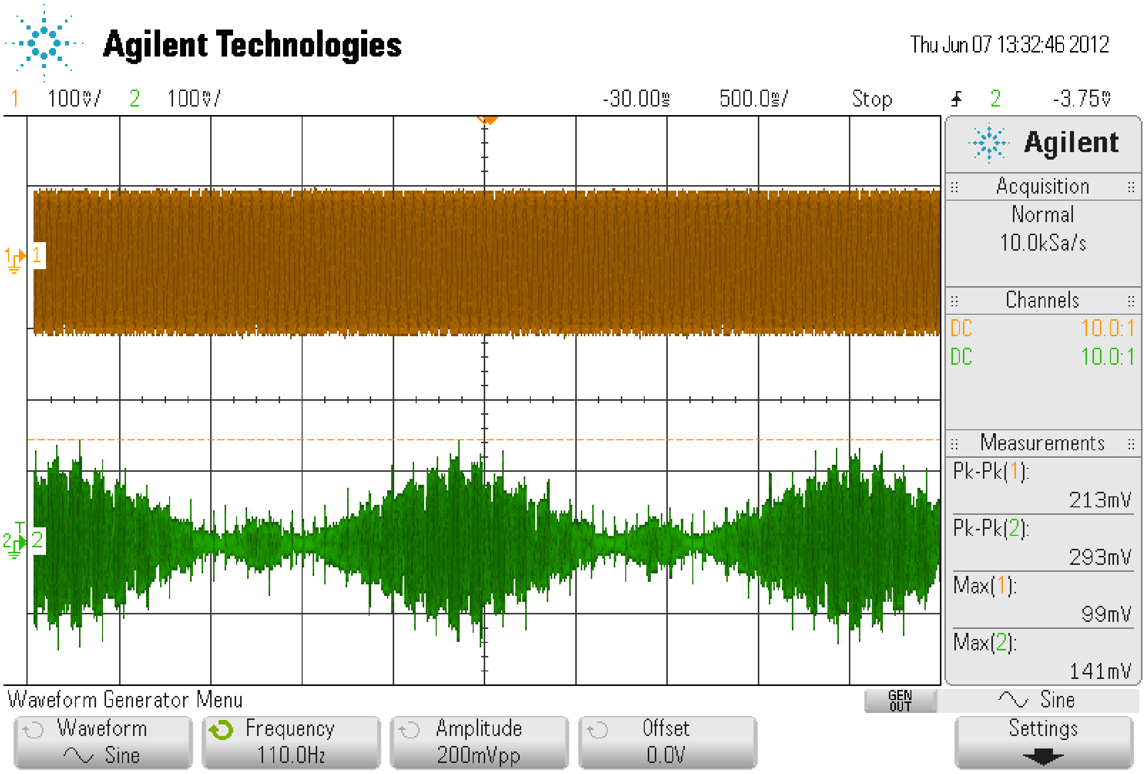


Figure 36 - Zoomed Out View of the Tremolo Effect

The zoomed out view of the tremolo effect in Figure 36 shows that the output signal has two distinct repeating levels of peak amplitude. This effect is heard as a small and fast increase in sound, followed by a larger and slower increase in sound.

The clicking noise was also audible in the distortion mode however the low pass filter was able to reduce the noise and the clicking was almost unnoticeable when the guitar was played. A scope capture was taken of the clipping noise in the distortion mode and can be seen in Figure 37.

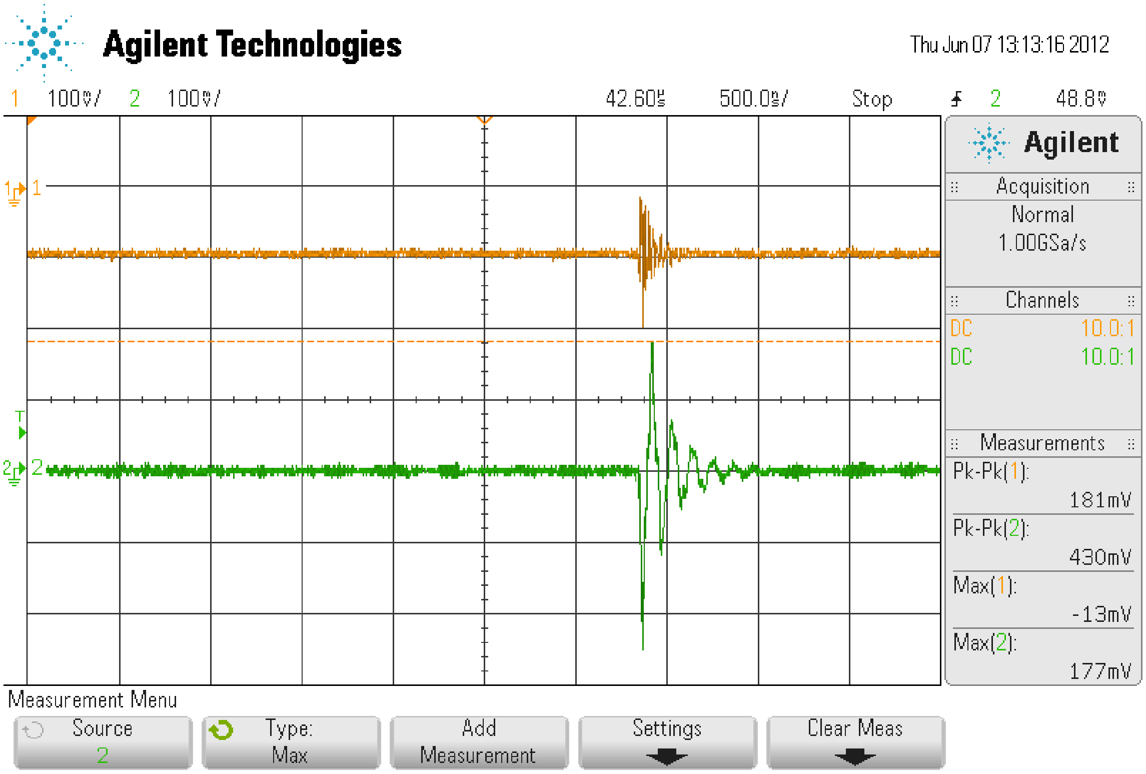


Figure 37 - Distortion Mode Clicking Noise

The distortion noise of Figure 37 was measured at approximately 430m$V_{p\text{-}p}$. This noise is significantly larger than the bypass mode noise that was measured at 161m$V_{p\text{-}p}$. However like the bypass mode, the distortion mode showed noise on the input signal, which may also be caused by an unstable ground connection. Disregarding the clicking noise, the distortion effect operated as expected and worked fairly well.

VII. Conclusion

The phase splitter effects pedal design, construction, and assembly, ultimately turned out to be a successful project. The effects pedal produced a unique combination of tremolo and vibrato distortion that separates it from other effects pedals. As stated in the introduction, the goal of this project was to create a unique type of guitar effects pedal using a phase splitter. After considering the outcome of the final design, it is clear that that goal has been reached. Although a few aspects of the final design did not work as desired (e.g. clicking noise and timer speed), the project was overall a success. The difficulties encountered in this project represent the difficulty of designing audio projects as well as other electronics with similar complexity in a small amount of time. At the design's current state, I would not attempt to manufacture and sell it commercially. I do however plan to use the progress and achievements of this project, improve and revise the design, and eventually sell phase splitter effects pedals if possible.

VIII. Endnotes

[1] Hunter, Dave. *Guitar Effects Pedals: the Practical Handbook*. San Francisco, CA: Backbeat, 2004. Print.

[2] Hunter, Dave. *Guitar Effects Pedals: the Practical Handbook*. San Francisco, CA: Backbeat, 2004. Print.

[3] "Micro-CUBE Owner's Manual." *Roland.com*. Roland Corporation, 2003. Web. 16 May 2012. <http://lib.roland.co.jp/support/en/manuals/res/1811450/M-CUBE_e1.pdf>.

[4] Carter, Bruce. "A Single Supply Op Amp Circuit Collection." *Ti.com*. Texas Instruments, Nov. 2000. Web. 14 Mar. 2012. <http://www.ti.com/lit/an/sloa058/sloa058.pdf>.

[5] Orman, Jack. "Guitar Stompbox & Effects Projects." *Muzique.com*. N.p., 1995-2000. Web. 03 Feb. 2012. <http://www.muzique.com/schem/projects.htm>.

[6] Prodanov, Vladimir. *Buffered 90-degree Phase Splitter*. 11 Jan. 2012. Design Overview.

[7] Prodanov, Vladimir. *Magnitude Correction*. 30 Jan. 2012. Design Overview.

[8] "CSS555 Micropower Timer Datasheet." *CustomSiliconSolutions.com*. N.p., May 2009. Web. 02 May 2012. <http://www.customsiliconsolutions.com/products-for-ASIC-solutions/standard-IC-products.aspx>.

[9] "CD4051B, CD4052B, CD4053B Datasheet." *Ti.com*. Texas Instruments, Oct. 2003. Web. 02 Feb. 2012. <http://www.ti.com/lit/ds/symlink/cd4052b.pdf>.

IX. Bibliography

Hunter, Dave. *Guitar Effects Pedals: the Practical Handbook*. San Francisco, CA: Backbeat, 2004. Print.

Orman, Jack. "Guitar Pickup Signal." *Guitar Effects Pedals, Schematics, Stompboxes & Electronic Projects*. Web. Accessed: 23 Nov. 2011. <http://www.muzique.com/lab/pick.htm>.

Jenkins, Michael A. *Analog Electric Guitar Distortion Effects and Headphone Amplification*. 2010. Senior Project--Electrical Engineering. Cal Poly Kennedy Library, San Luis Obispo, CA.

Franco, Sergio. *Design with Operational Amplifiers and Analog Integrated Circuits*. New York: McGraw-Hill, 2002. Print.

Alexander, Charles K., and Matthew N. O. Sadiku. *Fundamentals of Electric Circuits*. Boston: McGraw-Hill, 2009. Print.

Jaeger, Richard C., and Travis N. Blalock. *Microelectronic Circuit Design*. New York: McGraw-Hill, 2011. Print.

Appendix A

Analysis of Senior Project Design

The phase splitter guitar effects pedal creates tremolo and vibrato distortion effects. It features a speed control for the distortion effects and a volume control. The system also has a footswitch that enables true bypass. A single 9V battery is used for the power supply and an LED illuminates when the device is on. The system is turned on when a guitar cable is plugged in to the input jack.

Converting the power supply from a dual supply to single supply caused considerable difficulty, but fortunately this issue was eventually resolved. Integration of the different parts of the circuit was also somewhat difficult. Each IC had a different maximum value for the voltage supply, which required either multiple voltage regulators or a single voltage regulator that would supply 5V.

The most significant difficulty encountered on the project was a switching noise created by the multiplexer. When the multiplexer switched outputs, a sharp ringing would occur at the output, which resulted in a clicking sound. A low pass filter was implemented to reduce the noise, however this significantly reduced the output signal level and made many of the higher harmonics of the signal inaudible. This created a tradeoff between the amount of audible noise and the severity of the signal attenuation. The loss of the higher harmonics also had significant negative impacts on the tonal quality.

A possible human capital economic impact that results from using the phase splitter effects pedal is the creation of music. This can have cultural as well as financial impact as music is sold as a product. Financial capital impacts include the purchase of electronic components and other miscellaneous components used in the manufacture of the design. Manufacturing the device could also have natural capital impacts because it uses limited resources from the earth.

The costs of the project's lifecycle accrue with the procurement of the devices components and assembly costs. Benefits accrue when finished device units are sold and also when the device is used to make music.

The experiment requires an electric guitar input signal, which creates an additional cost if an electric guitar is not already possessed. The project cost an estimated $300 for parts. This includes the parts acquired for the breadboard circuit, replaced parts and other miscellaneous expenditures. The cost for one device is approximately $80. The cost of course would be significantly lower per unit if parts were ordered in bulk. I originally paid for most of the parts less some of the ICs and other miscellaneous parts supplied by Professor Prodanov. The Cal Poly Electrical Engineering Department will also reimburse me for $150 for project costs.

The original estimated cost of component parts at the start of the project was $70-155 (for 1 device). The actual final cost of component parts at the end of the project was ($90 for 1 device). For a final bill of materials for the components please see attatched. All other equipment used for the project (e.g. headphones, guitar amplifier, lab equipment) was borrowed. Financially the project does not earn anything because it will not be sold in its current state. I do however intend to improve the design and attempt to sell it in the future. For now, I profit by having a new one of a kind guitar effects pedal. Products emerge upon the completion of the PCB and enclosure assembly. The finished product is very durable and will exist for a long time if handled with care. Unless circuit components malfunction and need to be replaced, the only foreseeable operation cost will be the cost of a 9V battery.

The development time of the project (both estimated and actual) is illustrated by the two attatched Gantt charts. After the project is finished I will graduate and use available time to improve the project design to eventually create a sellable product.

If manufactured on a commercial basis the estimate number of devices sold per year is

$250 units. The estimated manufacturing cost for each device is $50 or less if the parts are bought in bulk. The estimated purchase price for each device is $100, which would yield an estimated $12,500 in profit per year. The estimated cost for a user to operate the device is $5 per year for battery replacement.

Use of the product results in the consumption of 9V batteries. If disposed of improperly, the battery can release chemicals and materials harmful to animals and the environment. Natural resources that the project uses includes resources used for the components and enclosure like aluminum. The project does not improve any natural resources or ecosystem services. The project could harm the environment if parts of the device were disposed of improperly (e.g. the battery). The project itself does not significantly impact other species for reasons other than mentioned before. Other species could be harmed if the came into contact with the harmful chemicals or materials used in the project like battery acid or lead.

The most significant challenge of manufacturing is the production of the PCB. Although only a few easily correctible mistakes were made on the PCB design, modifying the PCB traces would require new boards to be ordered, which are very expensive. The PCB also requires surface mount components that are difficult to solder. If the assembled PCB circuit is not functional, it is also very difficult to troubleshoot and fix.

One challenge encountered for maintaining the device was that the paint of the enclosure peeled. This is only an aesthetic aspect of the device, but it had to be repainted a few times. The project uses limited resources for the components of the device. The battery of the device must also be replaced every so often to power the device.

Reducing the clicking noise would be the most significant improvement on the design of the project. This is the first improvement that I will attempt to make on the project. Removing the clicking noise would also improve the frequency response of the circuit as it would reduce

the need for the noise reducing low pass filter. Another improvement would be to add extra controls for the distortion effects. One considered upgrade is to add a depth control to the tremolo effect.

Upgrading the design would require additional breadboard circuit design and testing. I attempted to remove the clicking noise for weeks however I was unsuccessful so it will be a difficult problem to solve. I think the issue might be resolved by using a buffer to create a more stable ground. If that idea works it will not be very complicated to implement the upgrade.

Ethical implications include ensuring that the design is manufactured safely. Manufacturing one device for the project was fairly safe, but more safety measures would have to be taken if the device is manufactured on a large scale. Ethical implications also include financial ethics, and the device should be sold to make a profit, however it should be sold at a price that is reasonable and affordable to consumers.

Safety concerns associated with the manufacture of the design include the use of a soldering iron. If mishandled, the soldering iron can cause severe burns to the operator. Another safety concern associated with the design is the use of power tools to drill holes in the enclosure. If these tools are not handled properly and treated with respect they can also seriously injure the user.

There are not many social or political issues associated with the project, however the device could have cultural impacts if it is used to make music. The project will not really impact anyone else until the design is improved and upgraded and possibly sold in the future. Professor Prodanov and I are the stakeholders of the project. The project benefits me because I have learned invaluable engineering experience and I created something original that I am proud of. The project also benefits Professor Prodanov because he was able to see his idea for the phase splitter effects pedal become realized. Professor Prodanov and I will both benefited from this

project. At the completion of the project I have a guitar effects pedal to show for all of my hard work. Professor Prodanov will also have the other PCB, or if time permits an assembled phase splitter effects pedal prototype.

The main new technique I learned from this project was how to design printed circuit boards. I used the CAD software from a company called ExpressPCB to create the design. ExpressPCB was also the company hired to fabricate the PCB. From the PCB assembly, I also learned how to solder surface mount components.

Bill of Materials

Parts List and Costs

Resistor	Value	Package	Cost (USD)	Capacitor	Value	Package	Cost (USD)
R1	220k (0.1%)	SMT 1206	0.67	C1	1u (10%)	SMT 1206	0.47
R2	220k (0.1%)	SMT 1206	0.67	C2	1.2n (5%)	SMT 1206	0.39
R3	22k (0.1%)	SMT 1206	0.67	C3	120n (10%)	SMT 1206	0.13
R4	10k (5%)	SMT 1206	0.026	C4	120n (10%)	SMT 1206	0.13
R5	22k (0.1%)	SMT 1206	0.67	C5	47n (5%)	SMT 1206	0.11
R6	22k (0.1%)	SMT 1206	0.67	C6	47n (5%)	SMT 1206	0.11
R7	220k (0.1%)	SMT 1206	0.67	C7	47n (5%)	SMT 1206	0.11
R8	220k (0.1%)	SMT 1206	0.67	C8	47n (5%)	SMT 1206	0.11
R9	10k (5%)	SMT 1206	0.026	C9	33n (10%)	SMT 1206	0.32
R10	10k (5%)	SMT 1206	0.026	C10	33n (10%)	SMT 1206	0.32
R11	10k (5%)	SMT 1206	0.026	C11	33n (10%)	SMT 1206	0.32
R12	10k (5%)	SMT 1206	0.026	C12	33n (10%)	SMT 1206	0.32
R13	10k (5%)	SMT 1206	0.026	C13	22n (10%)	SMT 1206	0.1
R14	10k (5%)	SMT 1206	0.026	C14	22n (10%)	SMT 1206	0.1
R15	10k (5%)	SMT 1206	0.026	C15	22n (10%)	SMT 1206	0.1
R16	10k (5%)	SMT 1206	0.026	C16	22n (10%)	SMT 1206	0.1
R17	10k (5%)	SMT 1206	0.026	C17	15n (10%)	SMT 1206	0.26
R18	10k (5%)	SMT 1206	0.026	C18	15n (10%)	SMT 1206	0.26
R19	10k (5%)	SMT 1206	0.026	C19	15n (10%)	SMT 1206	0.26
R20	10k (5%)	SMT 1206	0.026	C20	15n (10%)	SMT 1206	0.26
R21	10k (5%)	SMT 1206	0.026	C21	10n (10%)	SMT 1206	0.13
R22	10k (5%)	SMT 1206	0.026	C22	10n (10%)	SMT 1206	0.13
R23	10k (5%)	SMT 1206	0.026	C23	10n (10%)	SMT 1206	0.13
R24	10k (5%)	SMT 1206	0.026	C24	10n (10%)	SMT 1206	0.13
R25	10k (5%)	SMT 1206	0.026	C25	6.8n (5%)	SMT 1206	0.19
R26	10k (5%)	SMT 1206	0.026	C26	6.8n (5%)	SMT 1206	0.19
R27	10k (5%)	SMT 1206	0.026	C27	6.8n (5%)	SMT 1206	0.19
R28	10k (5%)	SMT 1206	0.026	C28	6.8n (5%)	SMT 1206	0.19
R29	10k (5%)	SMT 1206	0.026	C29	47n (5%)	SMT 1206	0.11
R30	10k (5%)	SMT 1206	0.026	C30	47n (5%)	SMT 1206	0.11
R31	10k (5%)	SMT 1206	0.026	C31	47n (5%)	SMT 1206	0.11
R32	10k (5%)	SMT 1206	0.026	C32	47n (5%)	SMT 1206	0.11
R33	10k (5%)	SMT 1206	0.026	C33	220n (10%)	SMT 1206	0.43
R34	10k (5%)	SMT 1206	0.026	C34	1u (10%)	SMT 1206	0.47
R35	10k (5%)	SMT 1206	0.026	C35	220n (10%)	SMT 1206	0.43
R36	10k (5%)	SMT 1206	0.026	C36	120n (20%)	SMT 1206	0.13
R37	10k (5%)	SMT 1206	0.026	C37	0.33u (10%)	SMT 1206	0.19
R38	10k (5%)	SMT 1206	0.026	C38	0.1u (5%)	SMT 1206	0.67
R39	10k (5%)	SMT 1206	0.026	C39	1u (10%)	SMT 1206	0.47
R40	10k (5%)	SMT 1206	0.026	C40	0.1u (5%)	SMT 1206	0.67
R41	10k (5%)	SMT 1206	0.026				
R42	10k (5%)	SMT 1206	0.026				
R43	27k	SMT 1206	0.1				
R44	10k (5%)	SMT 1206	0.026				
R45	10k (5%)	SMT 1206	0.026				
R46	10k (5%)	SMT 1206	0.026				
R47	10k (5%)	SMT 1206	0.026				
R48	100k	SMT 1206	0.1				
R49	39k	SMT 1206	0.1				
R50	1k	SMT 1206	0.1				
R51	47k	SMT 1206	0.05				

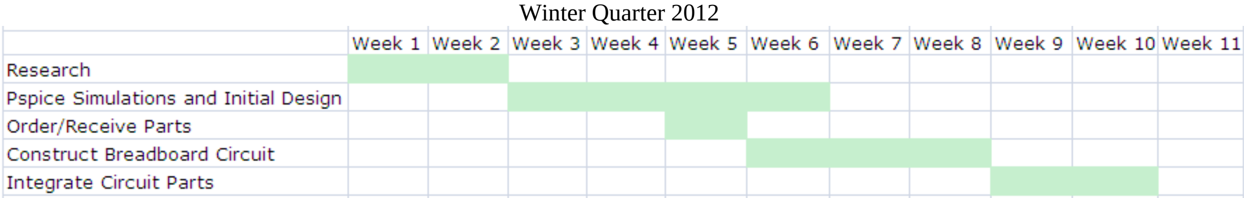
IC #	Name	Package	Cost (USD)
MC33204PG	Op Amps 1.8-12V Quad Rail to Rail	14-pin DIP	1.58
CD4052BE	Multiplexer Switch ICs 4-Ch. Analog	16-pin DIP	0.45
SN74HC191N	4-Bit Up/Dn Binary Counter	16-pin DIP	0.63
CSS555	Programmable 555 Timer	8-pin DIP	2.35
LM 7805CT	Standard 1A Positive Voltage Regulator	TO-220	0.54

MISC	Cost (USD)
PCB Board	56.785
Enclosure	7
1MΩ Pot	2.47
100kΩ Pot	2.36
Knobs	1
LED	0.25
Diode	0.25

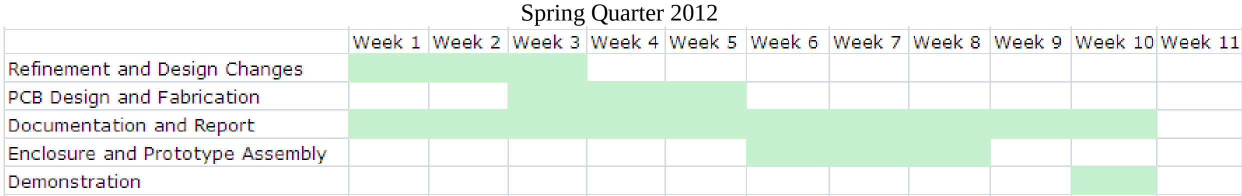
Total Cost for One Phase Splitter Effects Pedal: ≈ $90

Gantt Chart of Original Estimated Development Time (at of the start of the project)

Winter Quarter 2012

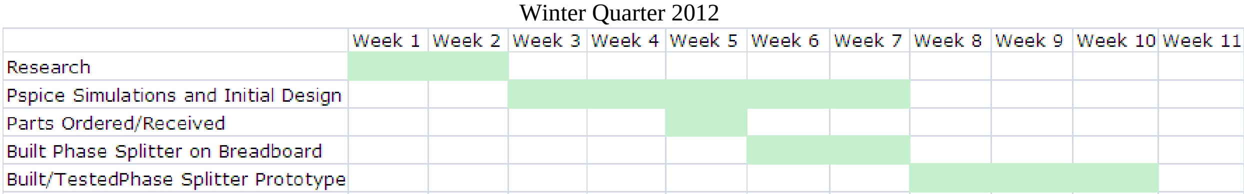


Spring Quarter 2012

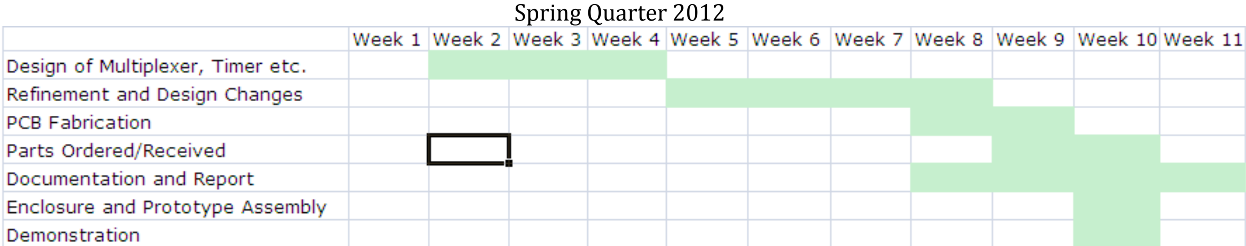


Gantt Chart of Actual Development Time (at the end of the project)

Winter Quarter 2012



Spring Quarter 2012



Appendix B

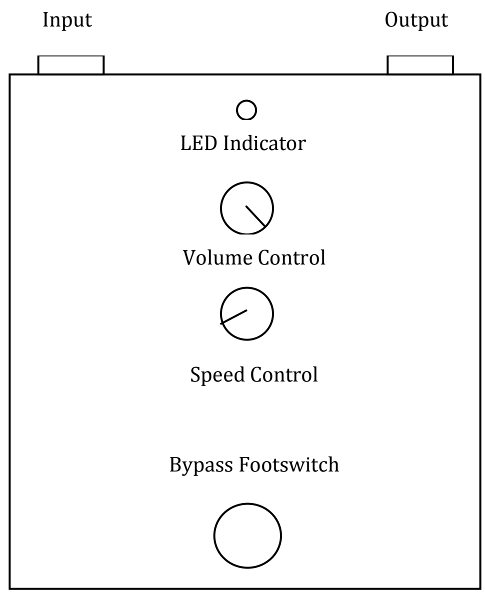
Specifications

Modes of Operation

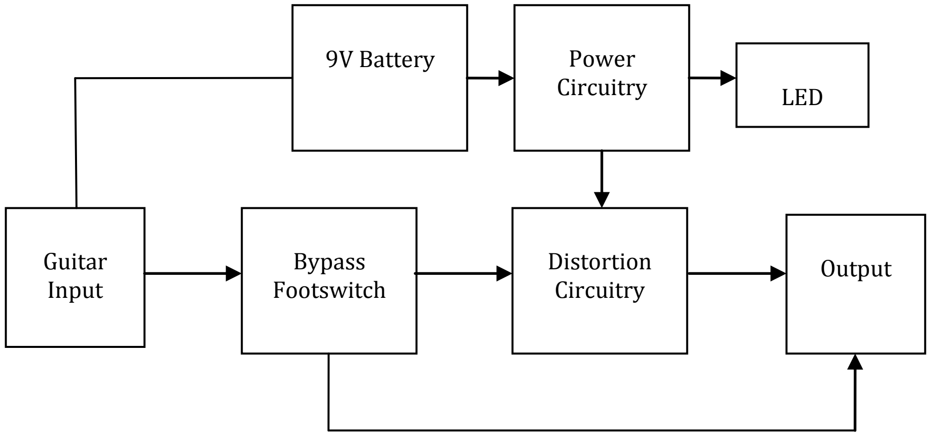
- True Bypass Mode
- Distortion Mode
-

Features of Design

- Tremolo Distortion
- Vibrato Distortion
- True Bypass
- LED Power Indicator
- Power On with Insertion of Input
- Single Supply via 9V Battery



User Interface



Signal Flow Diagram

Appendix C

Parts List and Costs

Resistor	Value	Package	Cost (USD)	Capacitor	Value	Package	Cost (USD)
R1	220k (0.1%)	SMT 1206	0.67	C1	1u (10%)	SMT 1206	0.47
R2	220k (0.1%)	SMT 1206	0.67	C2	1.2n (5%)	SMT 1206	0.39
R3	22k (0.1%)	SMT 1206	0.67	C3	120n (10%)	SMT 1206	0.13
R4	10k (5%)	SMT 1206	0.026	C4	120n (10%)	SMT 1206	0.13
R5	22k (0.1%)	SMT 1206	0.67	C5	47n (5%)	SMT 1206	0.11
R6	22k (0.1%)	SMT 1206	0.67	C6	47n (5%)	SMT 1206	0.11
R7	220k (0.1%)	SMT 1206	0.67	C7	47n (5%)	SMT 1206	0.11
R8	220k (0.1%)	SMT 1206	0.67	C8	47n (5%)	SMT 1206	0.11
R9	10k (5%)	SMT 1206	0.026	C9	33n (10%)	SMT 1206	0.32
R10	10k (5%)	SMT 1206	0.026	C10	33n (10%)	SMT 1206	0.32
R11	10k (5%)	SMT 1206	0.026	C11	33n (10%)	SMT 1206	0.32
R12	10k (5%)	SMT 1206	0.026	C12	33n (10%)	SMT 1206	0.32
R13	10k (5%)	SMT 1206	0.026	C13	22n (10%)	SMT 1206	0.1
R14	10k (5%)	SMT 1206	0.026	C14	22n (10%)	SMT 1206	0.1
R15	10k (5%)	SMT 1206	0.026	C15	22n (10%)	SMT 1206	0.1
R16	10k (5%)	SMT 1206	0.026	C16	22n (10%)	SMT 1206	0.1
R17	10k (5%)	SMT 1206	0.026	C17	15n (10%)	SMT 1206	0.26
R18	10k (5%)	SMT 1206	0.026	C18	15n (10%)	SMT 1206	0.26
R19	10k (5%)	SMT 1206	0.026	C19	15n (10%)	SMT 1206	0.26
R20	10k (5%)	SMT 1206	0.026	C20	15n (10%)	SMT 1206	0.26
R21	10k (5%)	SMT 1206	0.026	C21	10n (10%)	SMT 1206	0.13
R22	10k (5%)	SMT 1206	0.026	C22	10n (10%)	SMT 1206	0.13
R23	10k (5%)	SMT 1206	0.026	C23	10n (10%)	SMT 1206	0.13
R24	10k (5%)	SMT 1206	0.026	C24	10n (10%)	SMT 1206	0.13
R25	10k (5%)	SMT 1206	0.026	C25	6.8n (5%)	SMT 1206	0.19
R26	10k (5%)	SMT 1206	0.026	C26	6.8n (5%)	SMT 1206	0.19
R27	10k (5%)	SMT 1206	0.026	C27	6.8n (5%)	SMT 1206	0.19
R28	10k (5%)	SMT 1206	0.026	C28	6.8n (5%)	SMT 1206	0.19
R29	10k (5%)	SMT 1206	0.026	C29	47n (5%)	SMT 1206	0.11
R30	10k (5%)	SMT 1206	0.026	C30	47n (5%)	SMT 1206	0.11
R31	10k (5%)	SMT 1206	0.026	C31	47n (5%)	SMT 1206	0.11
R32	10k (5%)	SMT 1206	0.026	C32	47n (5%)	SMT 1206	0.11
R33	10k (5%)	SMT 1206	0.026	C33	220n (10%)	SMT 1206	0.43
R34	10k (5%)	SMT 1206	0.026	C34	1u (10%)	SMT 1206	0.47
R35	10k (5%)	SMT 1206	0.026	C35	220n (10%)	SMT 1206	0.43
R36	10k (5%)	SMT 1206	0.026	C36	120n (20%)	SMT 1206	0.13
R37	10k (5%)	SMT 1206	0.026	C37	0.33u (10%)	SMT 1206	0.19
R38	10k (5%)	SMT 1206	0.026	C38	0.1u (5%)	SMT 1206	0.67
R39	10k (5%)	SMT 1206	0.026	C39	1u (10%)	SMT 1206	0.47
R40	10k (5%)	SMT 1206	0.026	C40	0.1u (5%)	SMT 1206	0.67
R41	10k (5%)	SMT 1206	0.026				
R42	10k (5%)	SMT 1206	0.026				
R43	27k	SMT 1206	0.1				
R44	10k (5%)	SMT 1206	0.026				
R45	10k (5%)	SMT 1206	0.026				
R46	10k (5%)	SMT 1206	0.026				
R47	10k (5%)	SMT 1206	0.026				
R48	100k	SMT 1206	0.1				
R49	39k	SMT 1206	0.1				
R50	1k	SMT 1206	0.1				
R51	47k	SMT 1206	0.05				

IC #	Name	Package	Cost (USD)
MC33204PG	Op Amps 1.8-12V Quad Rail to Rail	14-pin DIP	1.58
CD4052BE	Multiplexer Switch ICs 4-Ch. Analog	16-pin DIP	0.45
SN74HC191N	4-Bit Up/Dn Binary Counter	16-pin DIP	0.63
CSS555	Programmable 555 Timer	8-pin DIP	2.35
LM 7805CT	Standard 1A Positive Voltage Regulator	TO-220	0.54

MISC	Cost (USD)
PCB Board	56.785
Enclosure	7
1MΩ Pot	2.47
100kΩ Pot	2.36
Knobs	1
LED	0.25
Diode	0.25

Total Cost for One Phase Splitter Effects Pedal: ≈ $90

Appendix D

Schedule

Winter Quarter 2012

1. Research of Effects Pedals and Phase Splitter	(Weeks 1-2)
2. Pspice Simulation and Initial Design	(Weeks 3-7)
3. Parts Received	(Week 5)
4. Built Phase splitter on Breadboard	(Week 6-7)
5. Phase Splitter Prototype Testing	(Week 8-10)

Spring Quarter 2012

5. Design of Multiplexer, Timer and Counter Circuits (Weeks 2-4)	
6. Refinement and modification of Design	(Weeks 5-8)
7. PCB Design and Fabrication	(Weeks 8-9)
8. Documentation and Report	(Weeks 8-11)
9. Enclosure and Prototype Assembly	(Week 10)
10. Demonstration	(Week 10)

Note: See Appendix A for a Gantt Chart of the project schedule

Appendix E

PCB Layout