Softclipping amplifier, octave-up guitar pedal:

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Introduction:

The objective of this project was to design and build a fuzz pedal with significant distortion control as well as include an octave-up component to enrich the tone with harmonics. The design references the iconic MXR distortion+ pedal ; it also incorporates a frequency multiplier circuit to perform the octave-up function, and a linear regulator circuit to reduce unwanted power-supply noise.The entire circuit was built with components I already had available (apart from the ¼'' audio cable “jacks” at the input/output) which limited some of the design choices but reduced costs overall. The design was simulated in Multisim 14.1 first , then built and tested using a breadboard , DC adjustable power supply, various components and lengths of wire, my guitar, two ¼'' audio cables , and my guitar amplifier. This fuzz-octave pedal was a fun project to undertake and is also a wonderful addition to my growing collection of guitar pedals.

Equipment Used:

- Digital Multimeter
- DC Power Supply :SHNITPWR SNT-0312-60
- Capacitors: ranging from 4.7nF to 100uF
- Resistors: ranging from 47Ω to 680kΩ
- Diodes: 1N4007,1N4232B
- BJTs: 2N3904, 2N5551
- Inductor: 10mH
- Op-amps: TL081CP
- Potentiometers: 10kΩ,100kΩ
- Breadboard

SUMMARY:

The Linear regulator circuit provides stability of the 9V power rail and reduces the high-frequency noise that is an undesirable byproduct of the power supply. U2 is a comparator , and the zener voltage across D6 is the reference voltage . Both U2 and Q2 work together to adjust the line current and thus compensate as the load resistance fluctuates.R13 and R14 act as a voltage divider, biased to the zener voltage of D6. The error voltage of the op-amp comparator U2 is the difference between the zener diode reference voltage and a voltage-divided ,scaled version of the line voltage.This is the sense mechanism for the negative feedback control scheme used to regulate the power supply rail . R1 is a current limiting resistor, ensuring conduction of zener diode D6.

The Fuzz circuit provides the distortion control , as well as some amplitude control of the guitar output signal. R1 and R2 act as a voltage divider to bias the DC operating point of U1's positive input (pin3). Op-amp U1 is configured as a non-inverting amplifier with feedback resistor Rf of 680kΩ and input resistor Ri of 6.8kΩ. C1, C3,and C5 are DC blocking capacitors that remove the DC portion of the signal from the signal chain.C3 brings the DC gain of the amplifier to ~1 (the gain is effectively 1 + Rf/inf which approximates to unity) .The combined impedance of the 6.8kΩ and the 100kΩ potentiometer, in combination with clipping diodes D1 and D2, generate the fuzz control circuitry. R4 and C2 act as a low pass filter with a cutoff of ~16kHz. R4 limits the current supplied to the clipping diodes (D1 and D2).C4 acts as a bypass capacitor to provide stability for the 9V power rail.

The frequency multiplier circuit provides frequency doubling. The guitar input is simulated in multisim as a 400mV, 330Hz sine wave (approximately the amplitude and frequency of the “High E” guitar string; this is the highest string frequency out of the 6 guitar strings of a conventional guitar) . The circuit is specifically tuned as a frequency doubler to provide the desired “octave-up” function. C11,C13, and L1 are tuned as a bandpass filter with center frequency(ie resonant frequency) of 666Hz.Quality factor of the filter is 1.76, which puts the effective bandwidth of the filter at 379Hz.The two cutoff frequencies of fc1, fc2 are approximately [477,855]Hz. Q2 acts as a Common-Emitter amplifier , using the LC “tank” circuit's impedance as the load impedance. R17 and R6 act as a voltage divider , providing Q2 with appropriate biasing for active mode of operation. C10 and C12 act as DC blocking capacitors to remove the DC part of the signal from the signal chain. R18,R19,R20 act as a “**π**” formation resistor attenuator network to reduce the amplitude of the signal back to ~1 before it goes to the fuzz circuit so that the full range of distortion control is preserved.

Experimental Part:

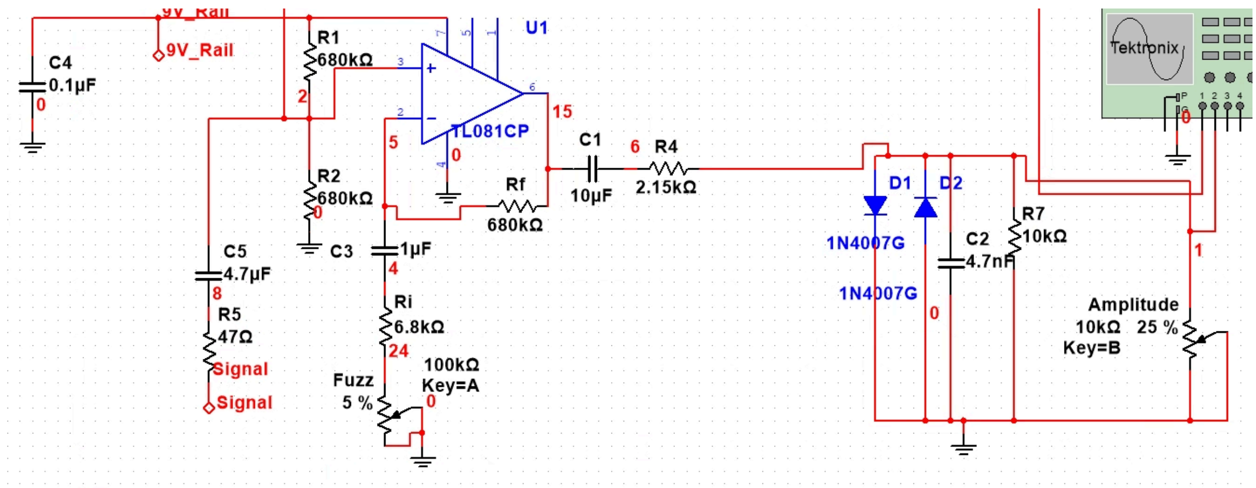

Figure 1: fuzz circuit

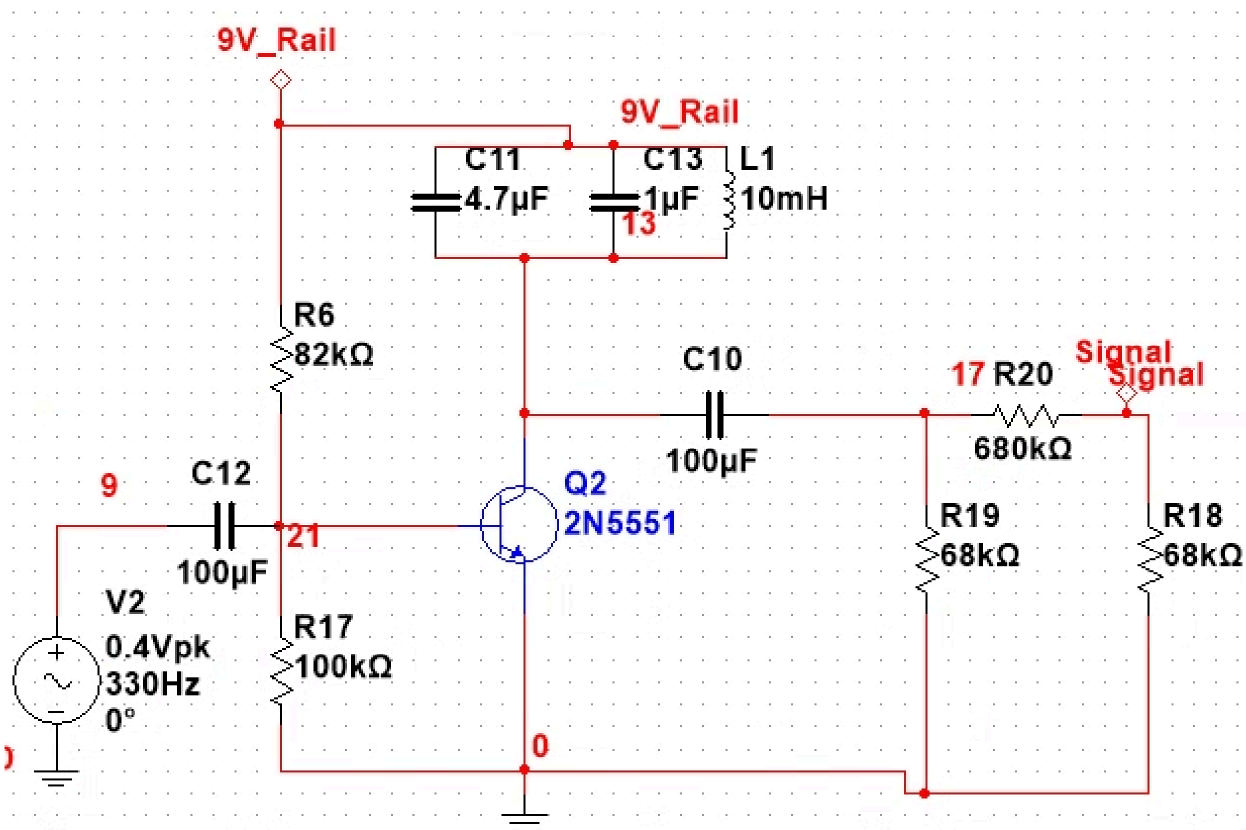

Figure 2: frequency multiplier (doubler) circuit

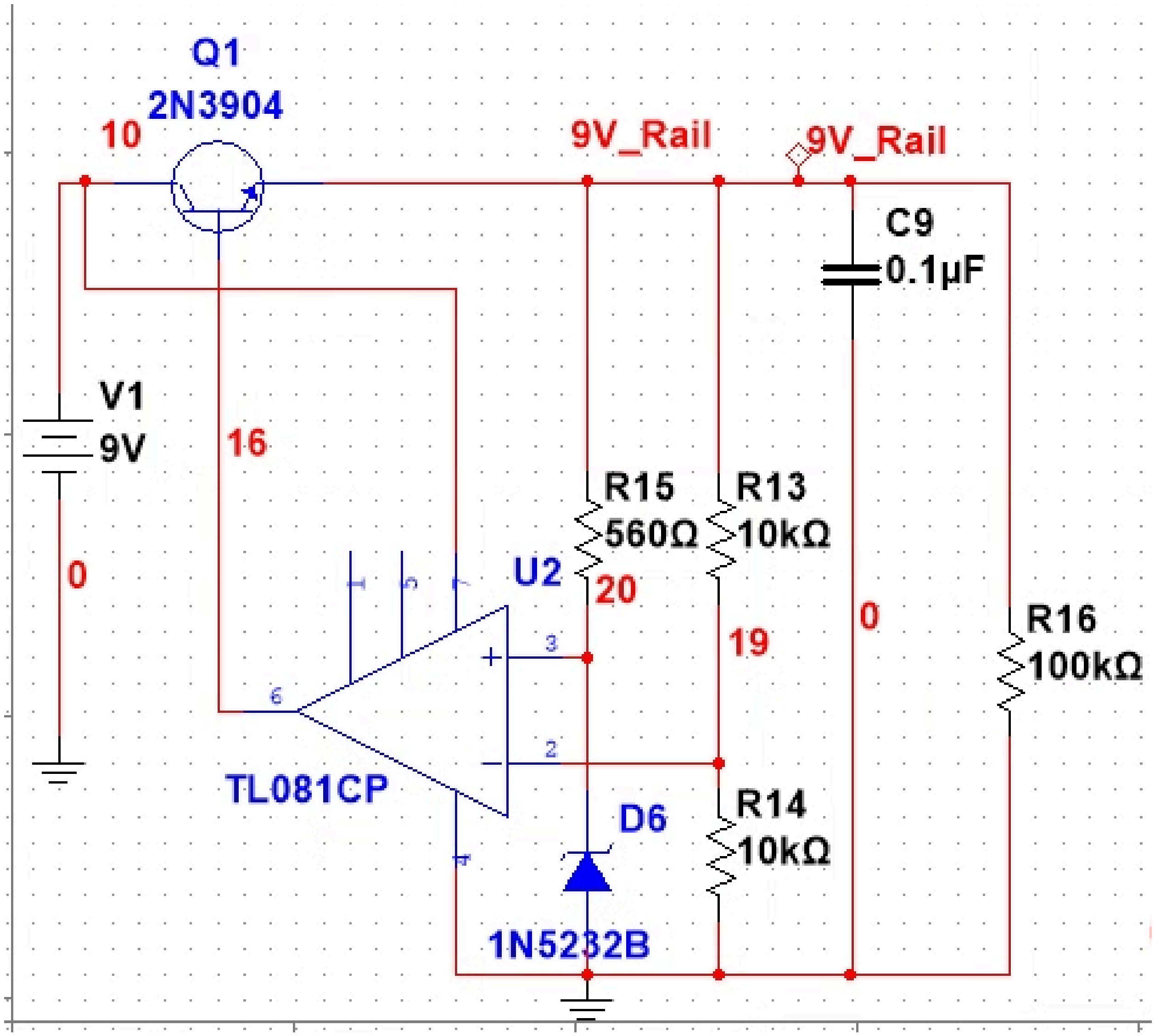

Figure 3: linear regulator circuit

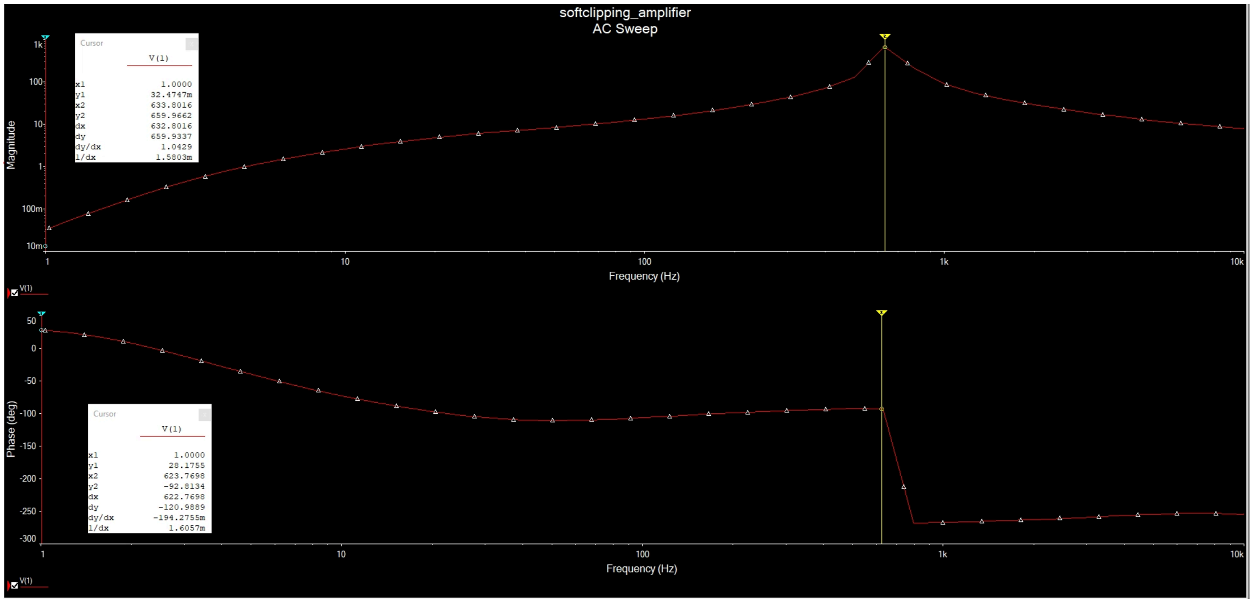

Figure 4: AC sweep of the final stage of fuzz circuit (output to guitar amplifier)

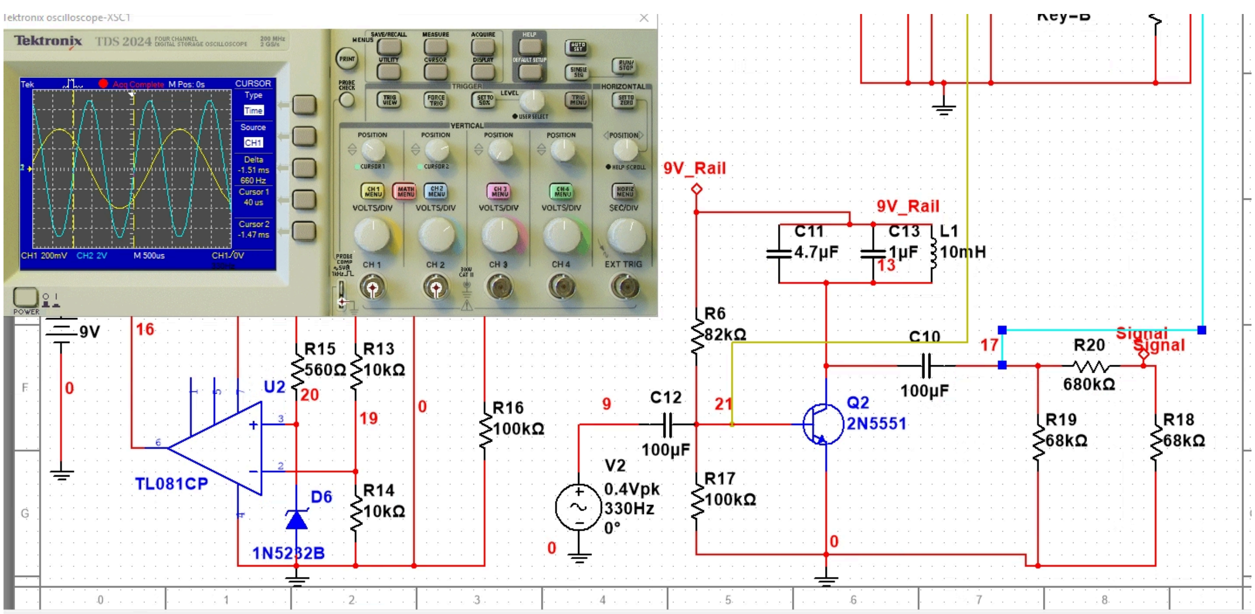

Figure 5: AC gain of the frequency multiplier ~70 [linear] = 18.45 [dB]

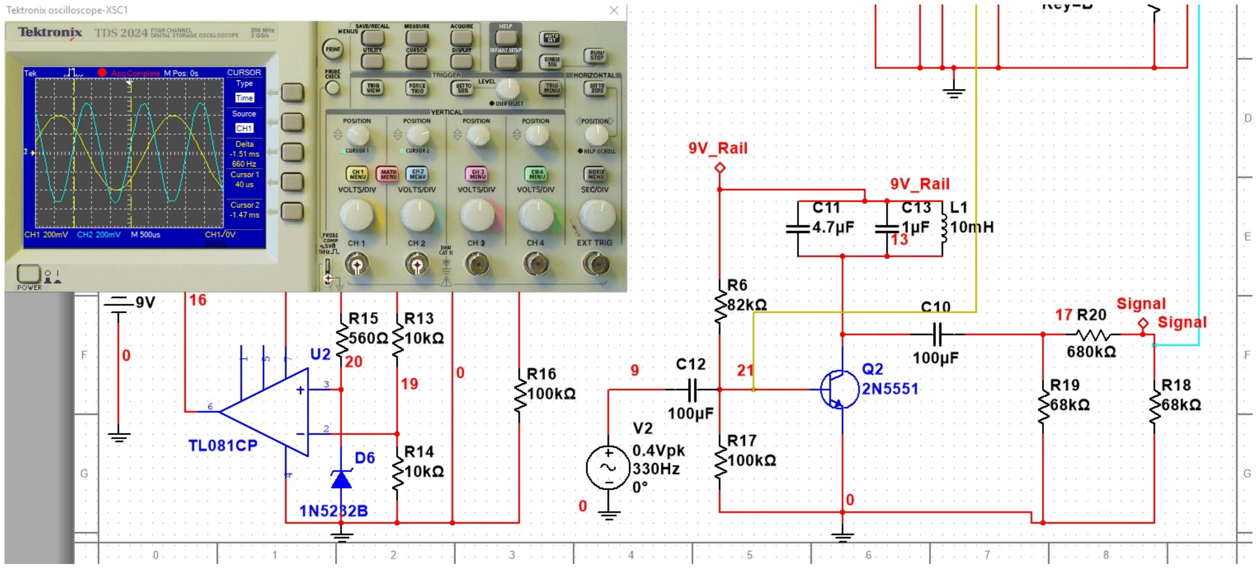

Figure 6: frequency multiplier stage

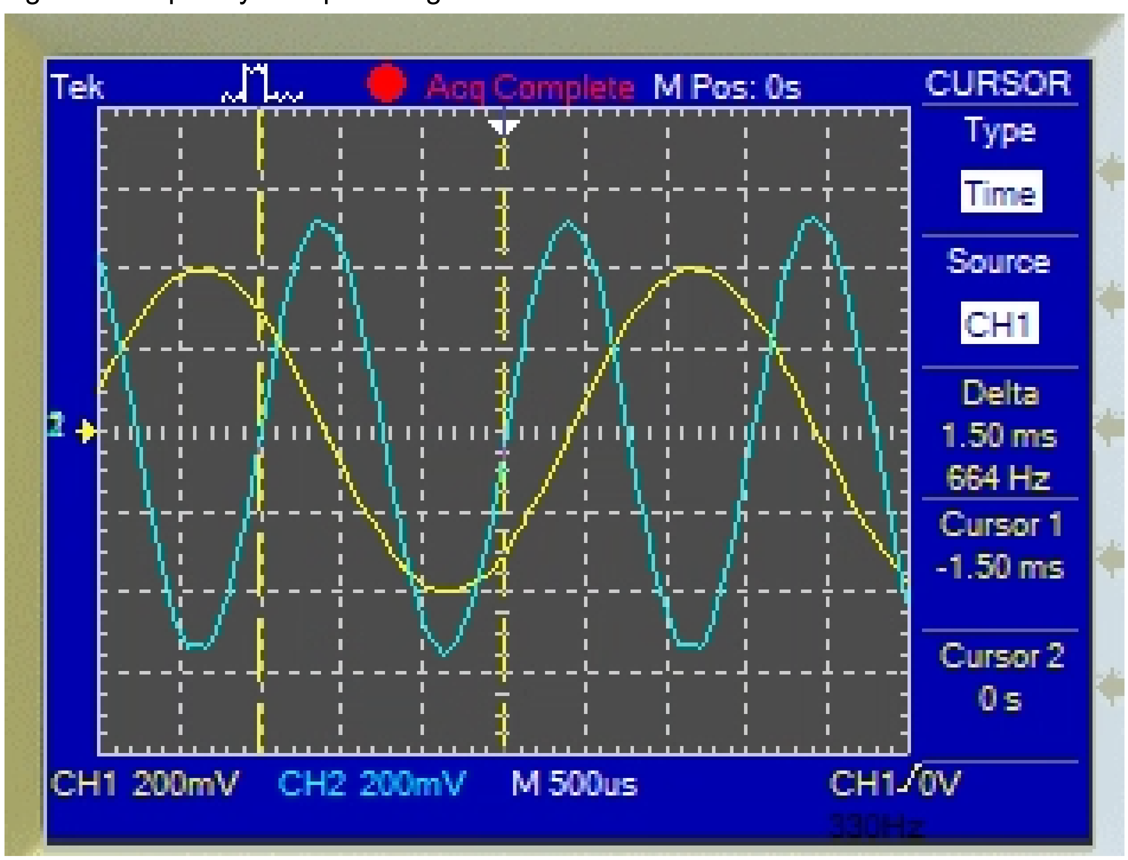

Figure 7 : frequency multiplier stage (zoomed in)

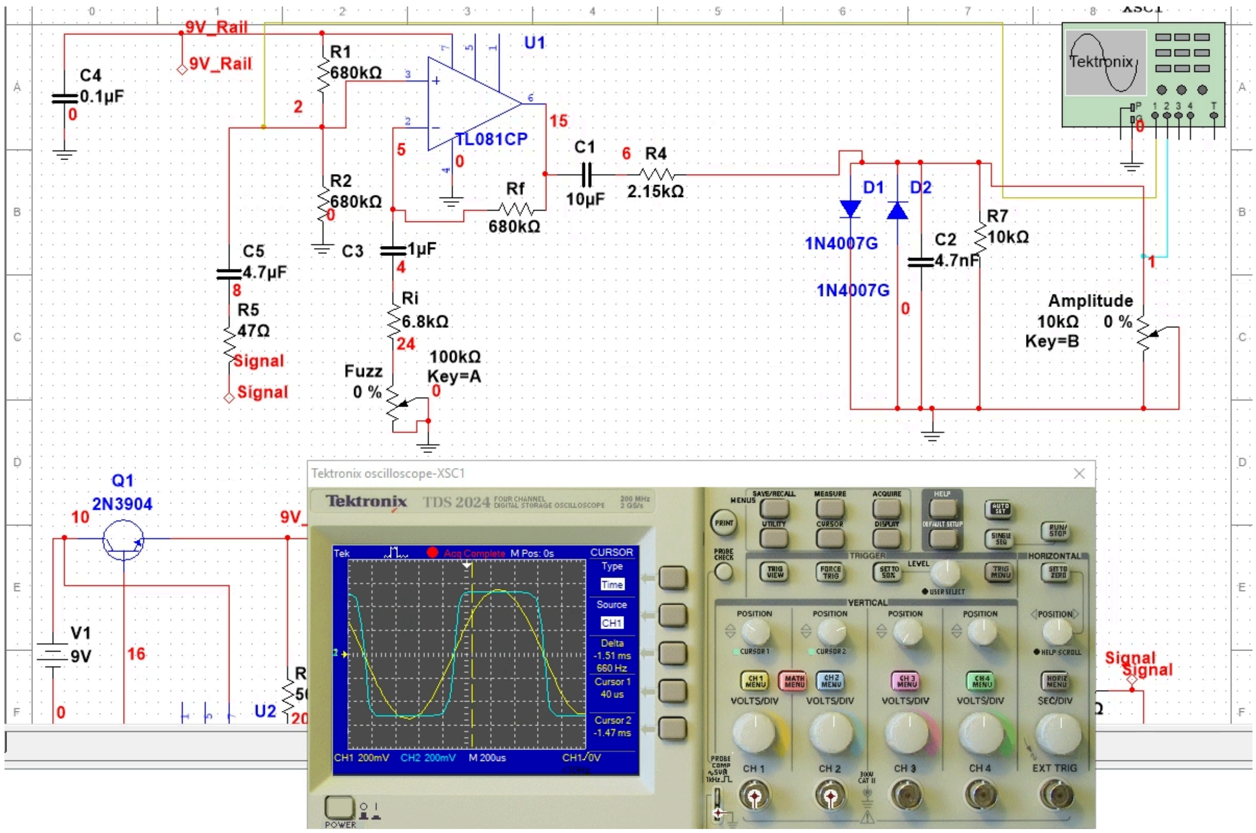

Figure 8 : Fuzz at 0%

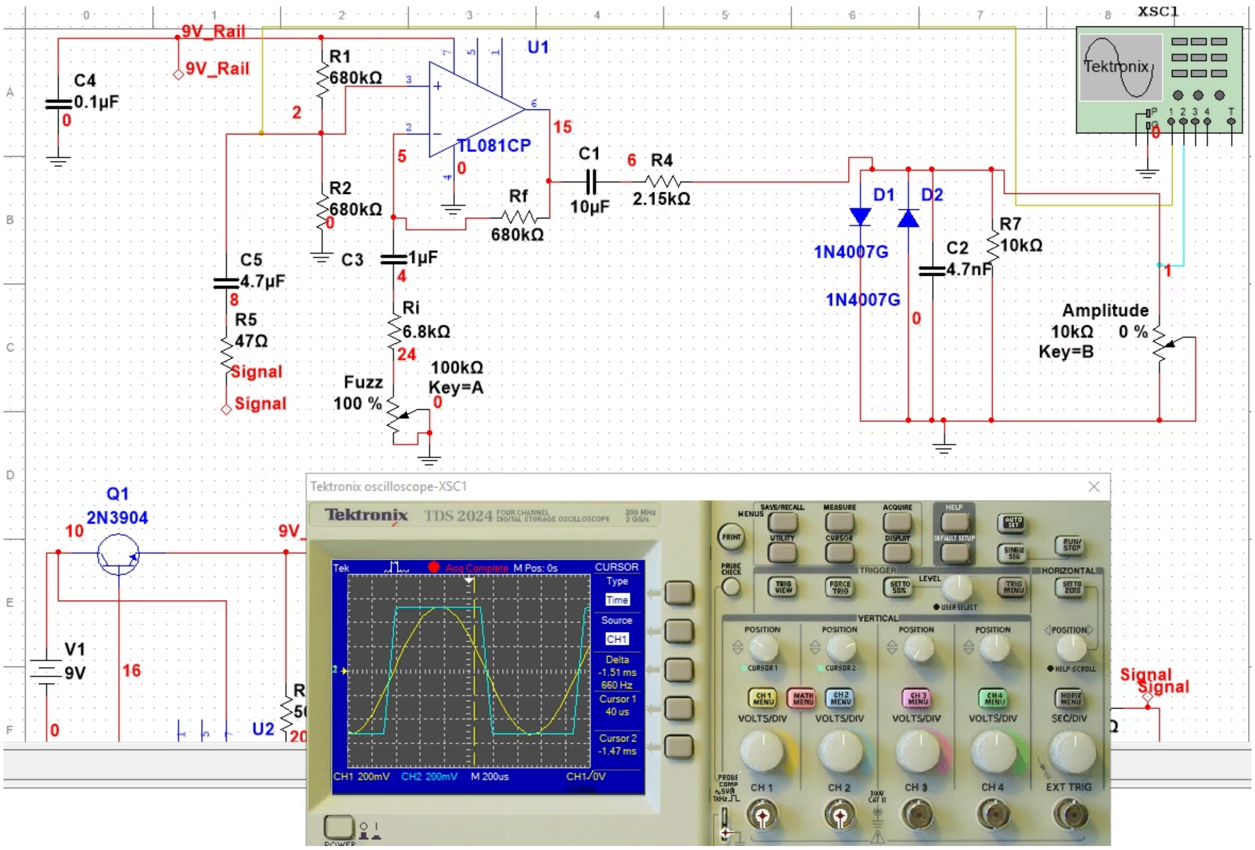

Figure 9 : Fuzz at 100%

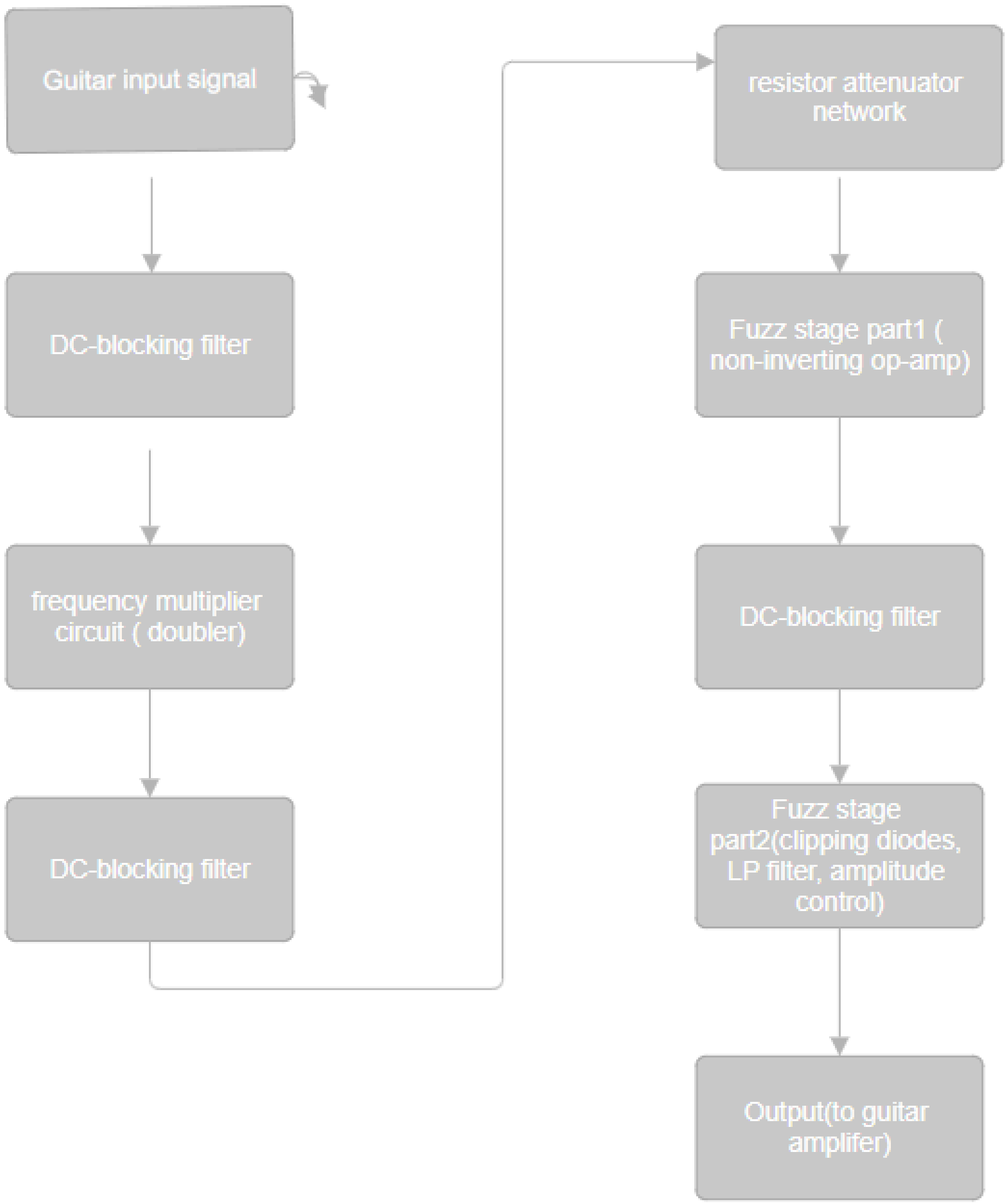

Figure 10: block diagram of the signal chain stages

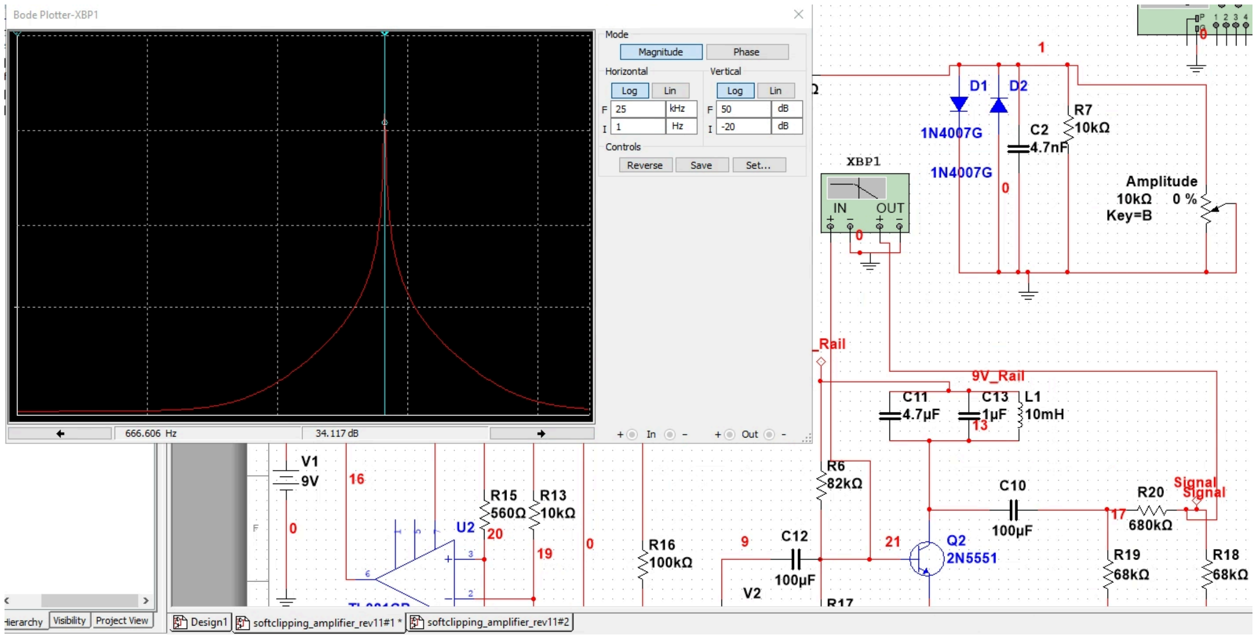

Figure 11: magnitude BODE plot of frequency multiplier circuit

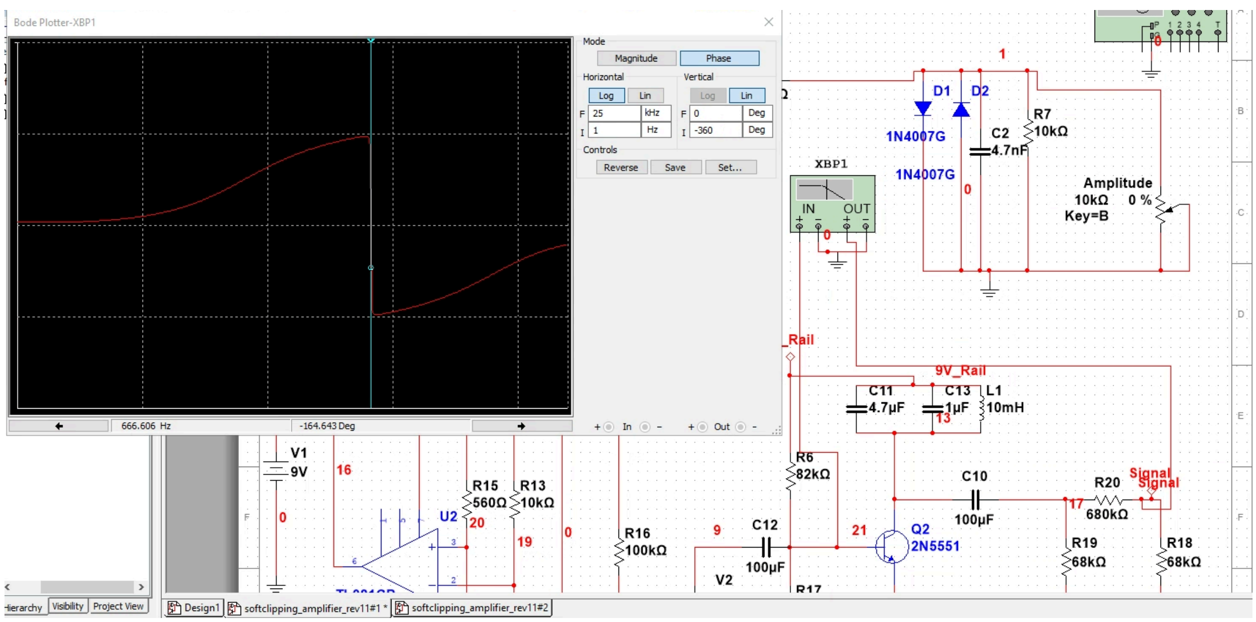

Figure 12: phase BODE plot of frequency multiplier circuit

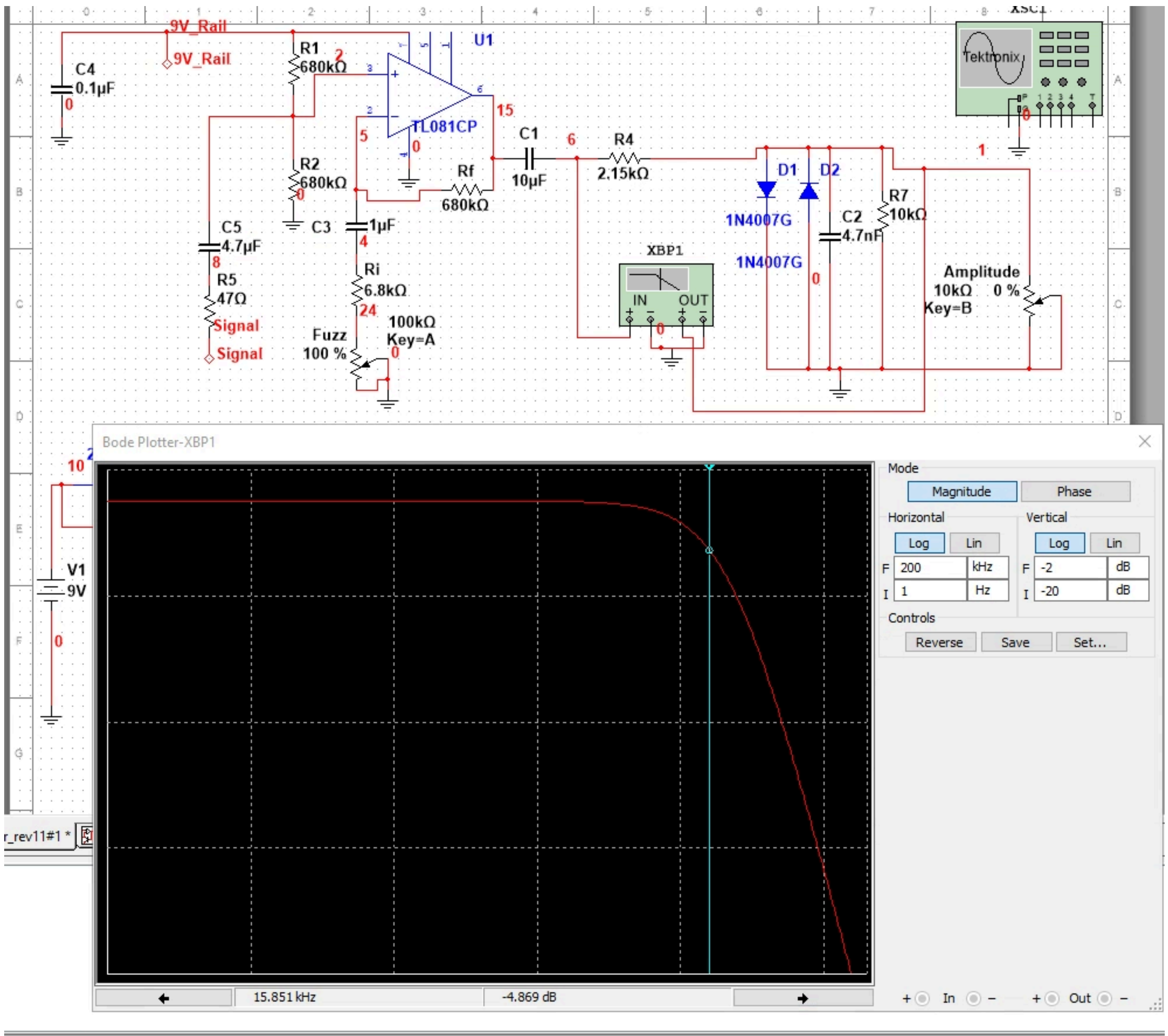

Figure 13: magnitude BODE plot of LP filter on output stage of fuzz circuit

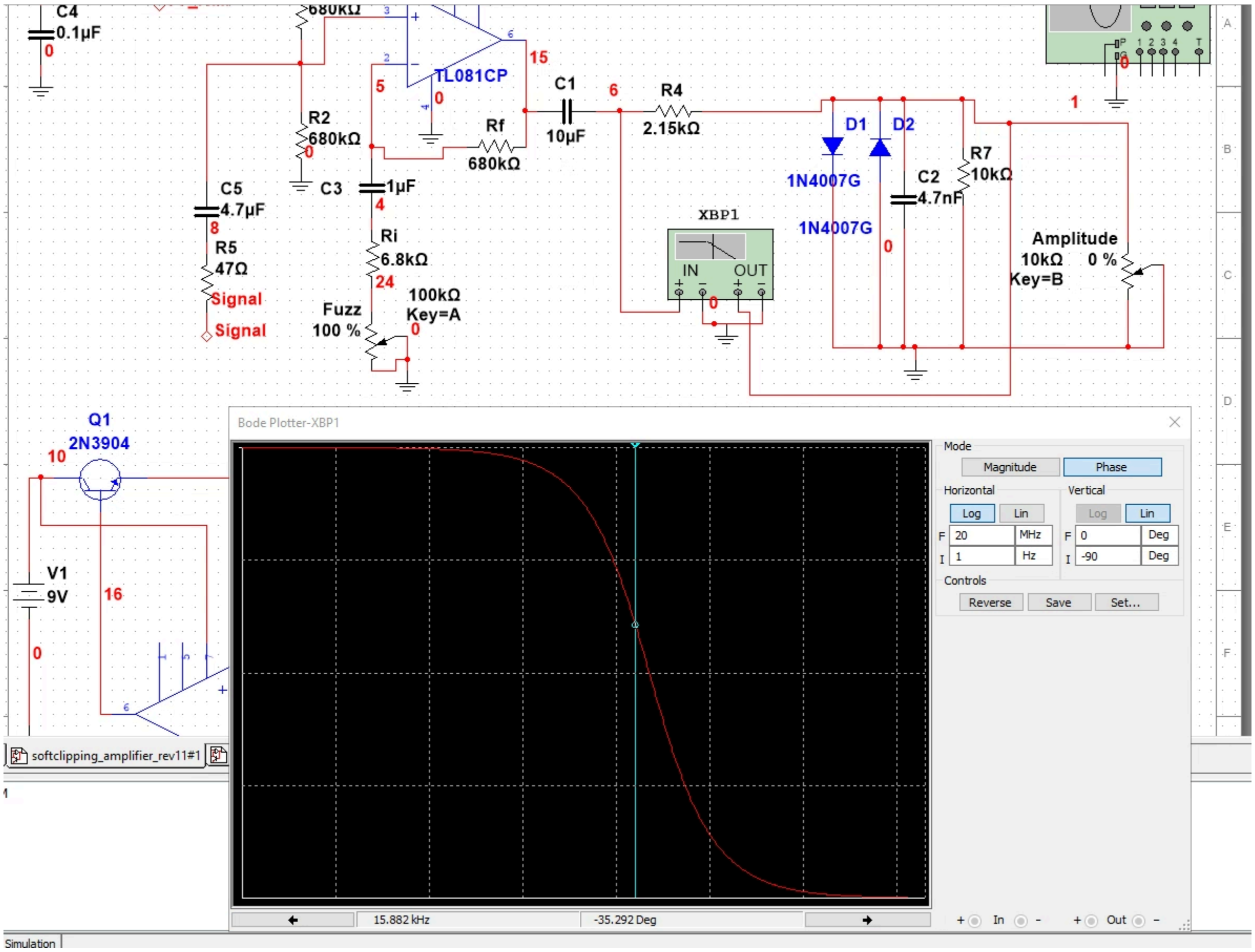

Figure 14: phase BODE plot of LP filter on output stage of fuzz circuit

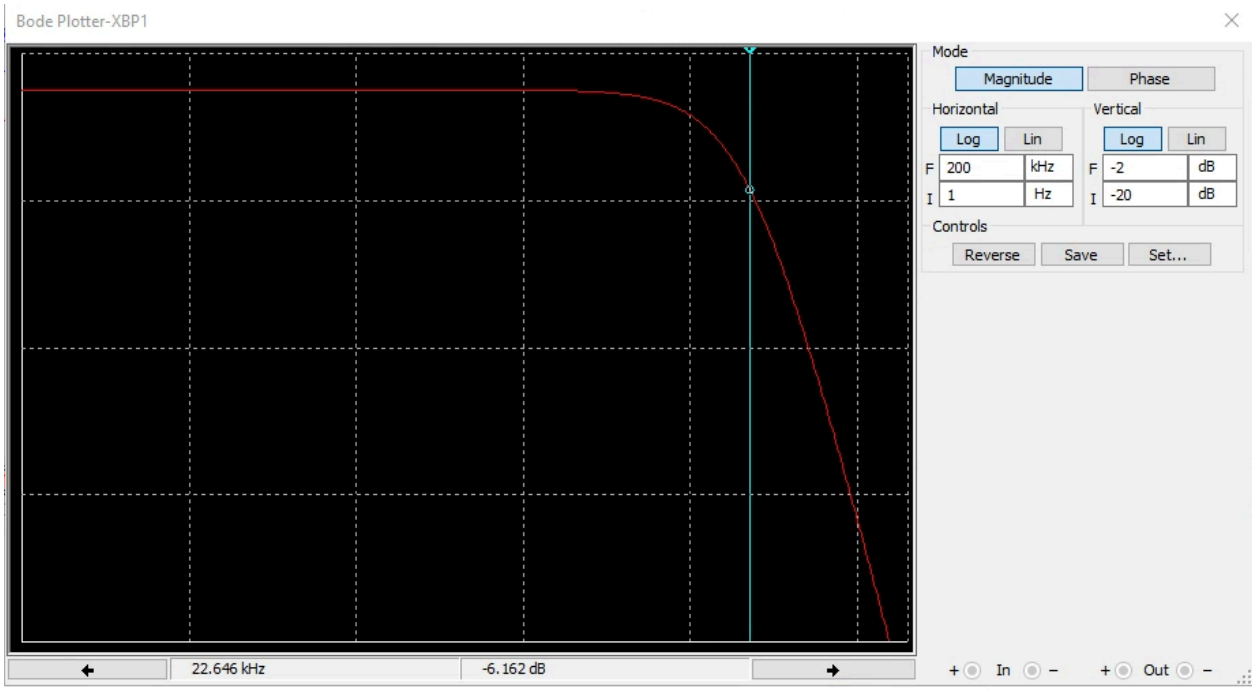

Figure 15: Magnitude of corner frequency for LP filter on output stage of fuzz circuit (-3dB drop from starting magnitude of ~ -3.1dB)

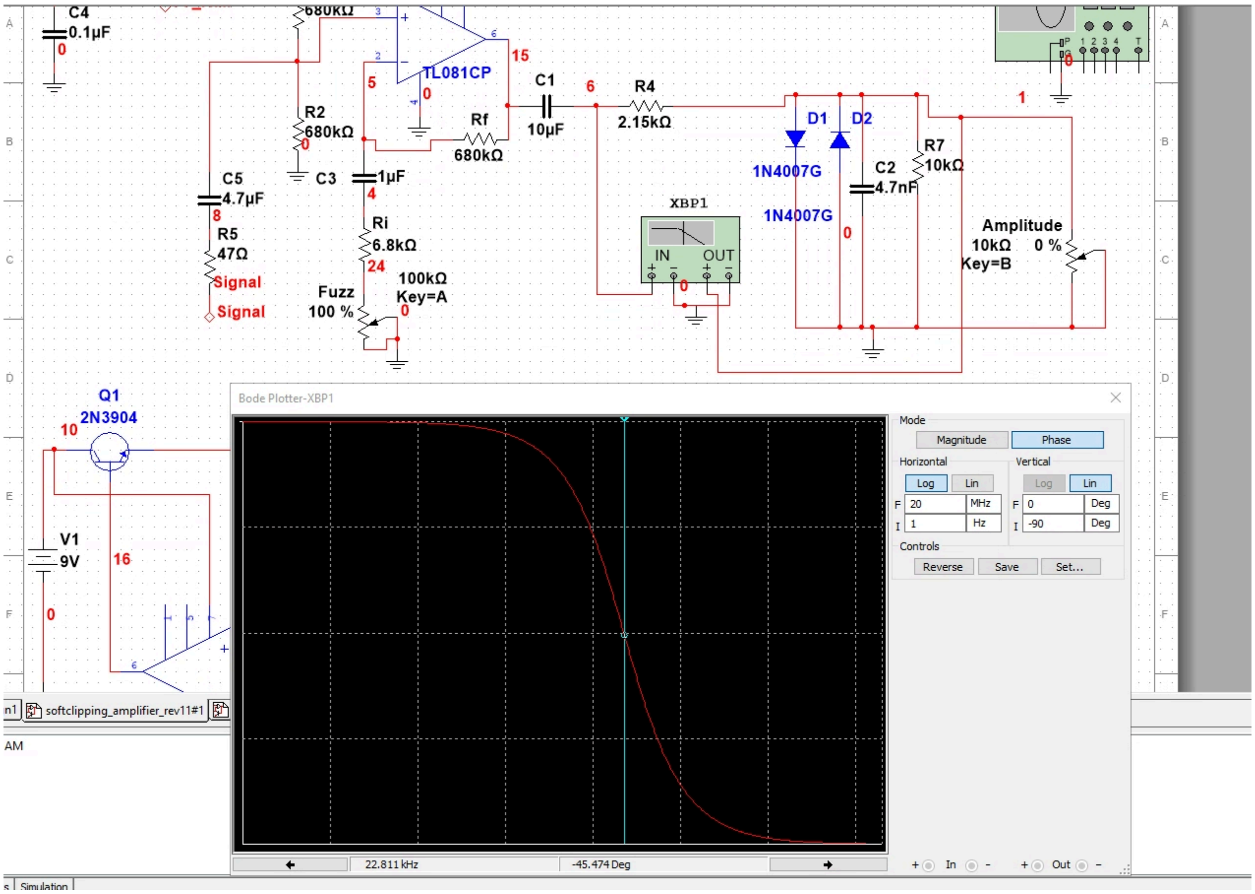

Figure 16: phase of corner frequency for LP filter on output stage of fuzz circuit

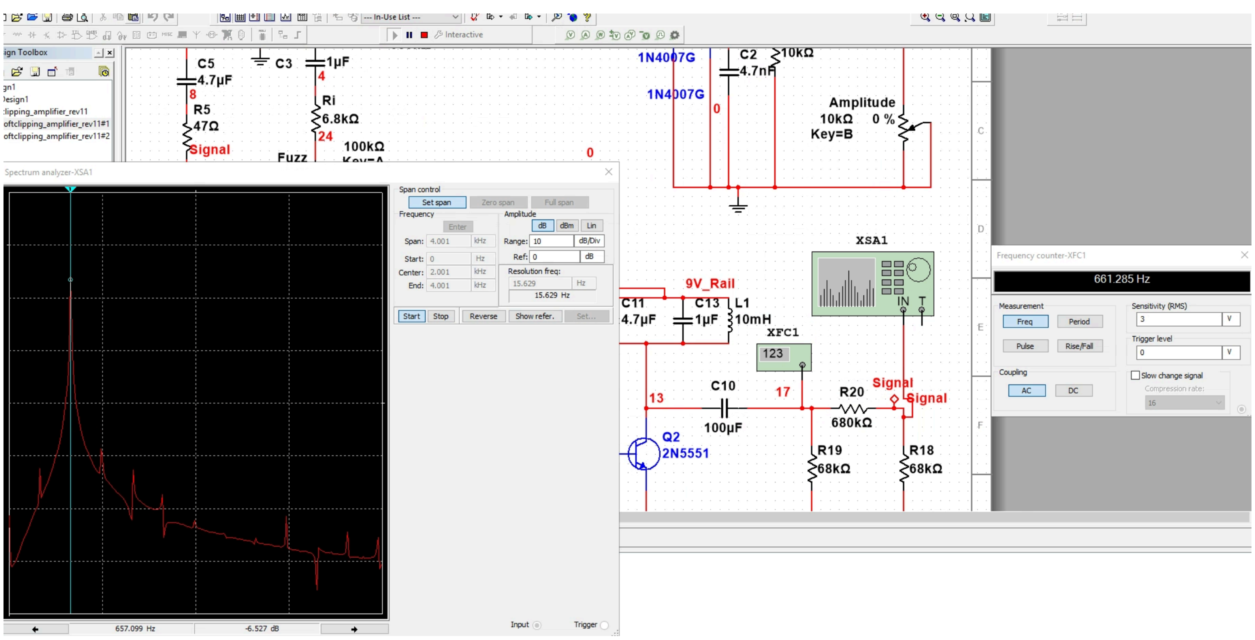

Figure 17: spectrum analyzer plot and frequency counter measurement for output of frequency multiplier (doubler) circuit.

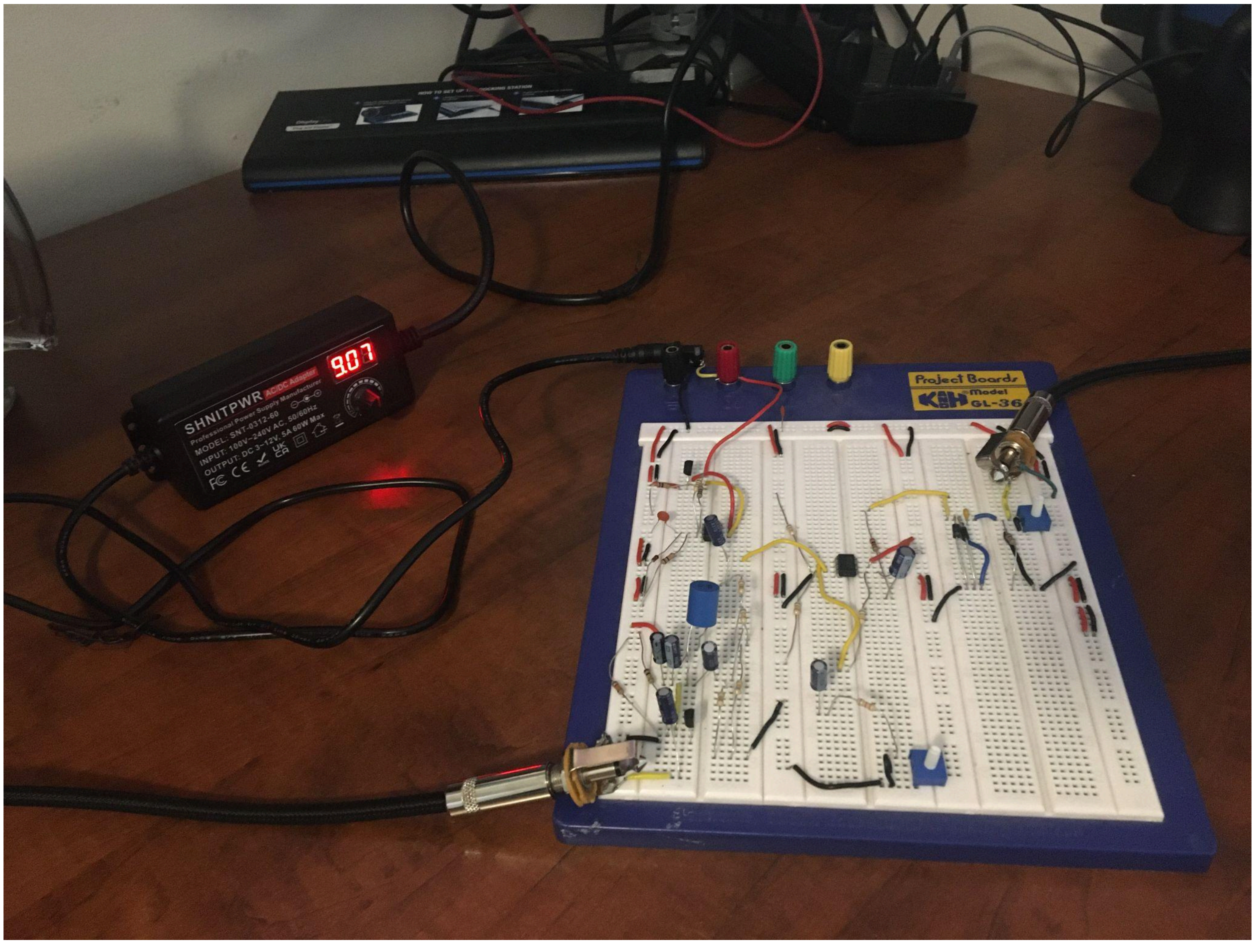

Figure 18: real world testing

Discussion:

Part 1 - Fuzz circuit:

R1 and R2 act as a voltage divider to bias the positive input pin U1 at ~4.5v so that we can operate the Op-amp off a single, positive, power supply and thus ground the Vcc- pin 4 (instead of supplying it with another power supply) . Op-amp U1 is configured as a non-inverting amplifier with feedback resistor Rf of 680kΩ and input resistor Ri of 6.8kΩ.The DC gain of the op-amp , "K", is (1 + Rf/Ri) which approximates to 101. However, C3 acts as an open circuit under DC conditions; thus, the actual gain of U1 is (1 + Rf/inf) which approximates to unity. C1, C3,and C5 are DC blocking capacitors which ensure that only the AC part of the signal is transferred from the guitar input of the fuzz circuit to the guitar amplifier on the output .The combined AC impedance of the Ri, C3 ,and the 100kΩ potentiometer, in combination with clipping diodes D1 and D2, generate the fuzz control circuitry.Solving the frequency domain representation of U1 for the transfer function gives the following expression:

$\frac{V_{pin6}}{V_{signal}} = (\frac{R_D}{R_D+R_5+\frac{1}{j\omega C_5}})(1 + \frac{R_F}{R_{potentiometer}+R_i+\frac{1}{j\omega C_2}})$,where R_D is $R_1//R_2$. As the resistance of the 100kΩ pot ($R_{potentiometer}$) is decreased, the AC gain of the noninverting amplifier configuration increases. The clipping diodes limit the of the op-amp AC peak voltage output to ±500mV . As the AC gain increases beyond the ±500mV limit, more of the op-amp output signal becomes clipped and the resulting wave becomes more distorted (ie square shaped). For low AC gain, the signal is still slightly clipped which in turn provides the desired “soft-clipped” or rounded edges of the waveform. This is where the “soft-clipping amplifier” part of the circuit name comes from. From the Bode plot, we can see that the corner frequency is ~660Hz as expected (due to the frequency doubling of the previous frequency multiplier stage in the signal chain) . R4 and C2 act as a low pass filter with cutoff of ~16kHz; this is satisfactorily high to retain most of the audible frequency spectrum and filter out high frequency noise. R4 limits the current supplied to the clipping diodes (D1 and D2) to prevent overdriving the diodes.C4 acts as a bypass capacitor which provides stability for the 9V power rail by shunting high frequency noise from the rail to ground.

Part 2 - frequency multiplier circuit:

This circuit is specifically tuned as a frequency doubler , which provides the desirable “octave-up” function by doubling the frequency of the input.The octave-up function enriches the tone of the signal by adding upper harmonics to frequency spectrum. C11,C13, and L1 are tuned as a bandpass filter with center frequency(ie resonant frequency) of $f_0 = \frac{1}{2\pi\sqrt{LC}} =$ 666Hz.The circuit effectively doubles the input frequency by amplifying frequencies near the resonant frequency and severely attenuating frequencies outside the narrow bandwidth of the bandpass filter.This results in the filter passing only the 2nd harmonic of the input signal.Measuements for the resistance of the inductor yeild R_L = 26.2Ω, and calculations for X_L yeild $X_L = \omega L = 46.1\Omega$. Cutoff frequencies for the edges of the BP filter are fc1, fc2 = $f_0 \pm \frac{BW_{eff}}{2}$ = [477,855]Hz, and the effective Bandwidth of the BP filter BW_{eff} is $\frac{f_0}{Q}$ =379Hz . Quality factor of the BP filter is $\frac{X_L}{R_L}$= 1.76 .BJT transistor Q2 acts as a Common-Emitter amplifier, and R17 and R6 act as a voltage divider to provide Q2 with appropriate biasing in the active mode of operation. C10 and C12 act as DC-blocking capacitors to filter out the DC portion of the signal and ensure that only the AC part of the signal is passed onto the output.The LC “tank” circuit acts both a bandpass filter centered around the resonant frequency and a high impedance load. Since the AC gain of the common-emitter configuration for the BJT depends considerably on the load impedance (this is approximately the impedance seen on the collector of the BJT, ie the combined impedance of the tank circuit) , and since the load impedance is quite high, then the AC gain of the signal is significantly high.AC analysis of the frequency multiplier(before DC blocking capacitor C10 and the attenuation network) gives the AC gain as follows:

$\frac{V_{out}}{V_2} = (\frac{R_6//R_{17}}{\frac{1}{j\omega C_{12}}+R_6//R_{17}})(\frac{g_m L_1}{(C_{11}+C_{13})(1-\omega^2 L_1(C_{11}+C_{13}))})$.A high-valued AC gain is not a desired outcome in this design, and thus the output signal of the common-emitter BJT amplifier must be attenuated before continuing onto the fuzz circuit. R18,R19,R20 act as a "π" formation, resistor attenuator-network to reduce the amplitude of the signal back to ~1 before it continues to the input of the fuzz circuit.The values for these resistors in the attenuator network were determined through trial and error and simulation testing with multisim until unity gain was achieved.

Part 3 - Linear regulator circuit:

Op-amp U2 compares the voltage value of the voltage divider of R13 and R14 to the zener voltage across D6 (ie the reference voltage of ~4.5V). U2 will attempt to reduce the difference in voltage between pins 2 and 3 (ie the error voltage) by driving more current to its output (pin 6) and thus supplying the base of Q1 with higher current. With Q1 biased in saturation mode, the voltage drop between collector and emitter , Vcesat, is very small, and Ic $= \beta_{sat} IE \simeq IE$. In this way, Q1 adjusts the line current to compensate as the load resistance fluctuates,effectively regulating the power supply rail and minimizing power supply noise caused by the load. R1 is a current limiting resistor for D6, ensuring that the zener diode is conducting at all times and keeping the error voltage low.

Conclusion:

Although validation of the circuit was heavily dependant on simulation due to the lack of real-world test equipment available to me, the breadboard circuit exceeded expectations during real-world testing with my guitar setup. Overall , the circuit behaves as intended and produces the desired fuzz -octave-up effect on the signal. From the BODE plots of the fuzz circuit, we can see that the LP filter cutoff frequency is at the upper end of the audible frequency spectrum (~ 22.6kHz). This is quite far from the calculated value of ~15.75kHz for the LP filter but is sufficiently low to filter out high frequencies as intended. The spectrum analyzer plot, frequency counter measurement, and BODE plots of the frequency multiplier show that the LC BP filter has been tuned correctly. Further, the AC sweep of the fuzz circuit shows that only the 2nd harmonic of the frequency multiplier circuit (ie the fundamental frequency of the LC BP filter) is permitted through all stages to the output and confirms that the LC BP filter is tuned correctly. Oscilloscope captures of the fuzz circuit output show that the desired octave-up (frequency doubling) and soft-clipped square-wave distortion (ie fuzz) has been achieved.

Next steps for the design include soldering a pcb and moving the circuit into an actual enclosure(instead of the current breadboard setup). As well,a further next step of including a highpass filter to U1 positive input , along with a noise gate, to further reduce power supply noise could be implemented. At this current iteration of the design, there is still some power supply noise getting through but it is not significant enough to warrant the immediate need for these noise rejection methods. Additionally, implementing a buffer to prevent loading, then shifting the frequency multiplier circuit to the end of the signal chain could be a worthwhile next step in future iterations of the design if it is later determined that having the octave-up function at the end of the signal chain is more desirable than its current position in the signal chain.

Lessons learned during the design cycle include power supply noise reduction control,importance of the order of circuit blocks in the signal chain and impact on the output to guitar amplifier, and importance of resonance and resonant frequency in the filter design. Consumer power supplies are typically quite noisy, and for an effects pedal to amplify the guitar input signal appropriately without being drowned out in power supply noise, the power supply noise must be sufficiently reduced , if not removed entirely. Luckily, power supply noise reduction circuits such as the linear regulator circuit implemented in this design, are easy and affordable means of mitigating this issue. Additionally, the placement of circuit stages in the signal chain plays an important role on the output signal of the final circuit stage.In typical octave-up pedals, the octave-up circuit is placed at the end of the signal chain to introduce upper harmonics to the signal after it has been satisfactorily distorted or manipulated. However, this is more of a preference than a requirement. In the current design , I was forced to place the octave-up function via the frequency multiplier circuit near the start of the signal chain. Placing the frequency multiplier at the end of the signal chain in the current design iteration, after the fuzz circuit, removed the distortion effect, and produced instability of amplitude control of the signal during simulations.The resulting output of the frequency multiplier was a sine wave with doubled frequency but unstable amplitude(see figure 19). The cause of this has not yet been determined. At the current time, I believe that the frequency multiplier circuit is only intended to multiply the frequency of a sine wave and not the distorted wave of the fuzz circuit. This would explain the loss of the distortion effect on the signal. The frequency multiplier circuit's output amplitude is dependant on the nth harmonic of the signal;as higher order harmonics pass through the tank circuit filter, the amplitude of the output signal will change accordingly(Couch,273). This is likely the reason for the fluctuation in amplitude of the sine wave output. The current iteration of the design, with the frequency multiplier circuit preceding the fuzz circuit, has produced both the intended effects on the signal(fuzz and octave-up) while retaining stable control of both the signal's distortion and amplitude.At this current time, I see no reason to change the frequency multiplier circuits position in the signal chain.

The majority of the components chosen in the design were chosen because of immediate availability in my personal inventory. I chose the TL081CP op-amps over the UA741CP and LM358P op-amps that were also available in my inventory because the TL081CP is a low noise op-amp which is desirable for audio applications.Basic components such as resistors, potentiometers,capacitors, and diodes were chosen based solely on availability in my inventory , biasing requirements for various other components, DC blocking requirements, and filtering requirements (for R_5,C_5,C_1,R_4,and C_2). R_7 was chosen as an amplitude limiting resistor, which limits the maximum amplitude value for the amplitude control potentiometer. The resistors of the attenuator network were chosen to appropriately attenuate the amplified signal back to unity before proceeding to the fuzz circuit, minimizing the effects of loading on the fuzz circuit by increasing the input resistance on op-amp U1. The BJT's were chosen based on availability in my inventory, as well as voltage and current requirements of related circuitry involving the BJT.The 2N3904 was chosen due to its sufficient voltage and current ratings to meet demand of the linear regulator. The 2N5551 was chosen for the same reasons as mentioned previously for the 2N3904 , along with its preference in audio amplification circuitry.These design choices meet the initial requirement of the project budget (ie don't buy any new components unless strictly necessary) as well as the overall demands of the project and its various subcircuit requirements.

Real-world testing with my guitar setup resulted in the desired distortion, tone , and amplitude control of the input signal (guitar) , and confirms that the design met intended requirements and that the project was successful.

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Appendix:

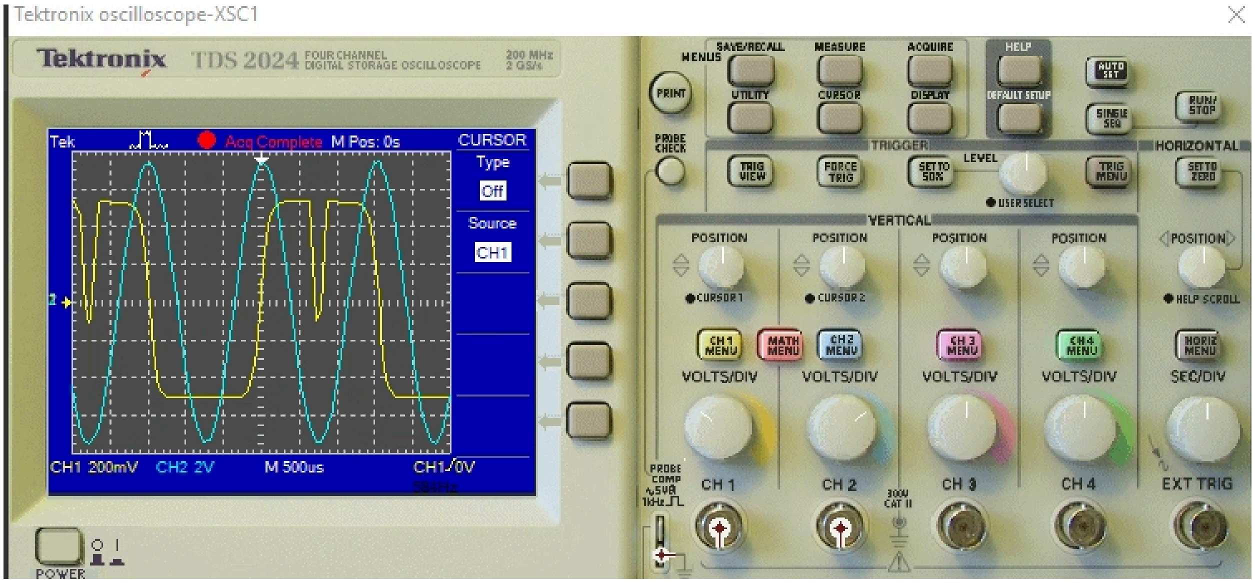
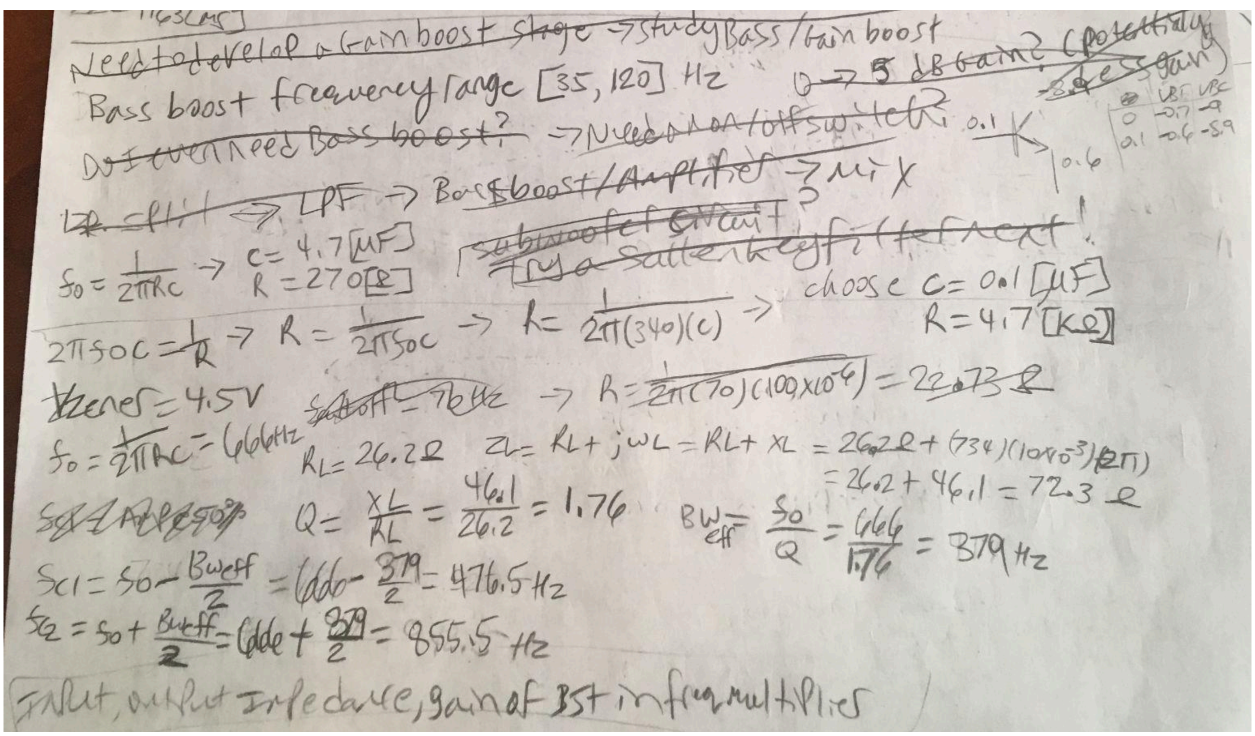


Figure 19 : improper order of signal chain stages and impact on output signal

This screenshot above shows a) loss of square wave distortion on output signal(blue, ch.2) b) phase distortion of the input signal (yellow,ch.1) when the frequency multiplier is placed at the end of the signal chain.

Miscellaneous calculations:


~~Need to develop a Gain boost stage~~ → study Bass/Gain boost

Bass boost frequency range [35, 120] Hz 0 → 5 dB Gain? ~~(potentially less gain)~~

~~Do I even need Bass boost?~~ → ~~Need a on/off switch?~~

~~LR split~~ → LPF → Bass ~~boost/Amplifier~~ → mix

~~subwoofer circuit~~ ~~try a Sallen key filter next~~

$f_0 = \frac{1}{2\pi RC}$ → $C = 4.7$ [μF], $R = 270$ [Ω]

$2\pi f_0 C = \frac{1}{R}$ → $R = \frac{1}{2\pi f_0 C}$ → $R = \frac{1}{2\pi(340)(C)}$ → choose $C = 0.1$ [μF], $R = 4.7$ [kΩ]

~~Vzener~~ = 4.5V ~~f cutoff~~ = 70 Hz → $R = \frac{1}{2\pi(70)(100\times10^{-6})} = 22.73\ \Omega$

$f_0 = \frac{1}{2\pi RC} = 666$ Hz $R_L = 26.2\ \Omega$ $Z_L = R_L + j\omega L = R_L + X_L = 26.2\ \Omega + (734)(10\times10^{-3})(2\pi) = 26.2 + 46.1 = 72.3\ \Omega$

$Q = \frac{X_L}{R_L} = \frac{46.1}{26.2} = 1.76$ $BW_{eff} = \frac{f_0}{Q} = \frac{666}{1.76} = 379$ Hz

$f_{c1} = f_0 - \frac{BW_{eff}}{2} = 666 - \frac{379}{2} = 476.5$ Hz

$f_{c2} = f_0 + \frac{BW_{eff}}{2} = 666 + \frac{379}{2} = 855.5$ Hz

Input, output impedance, gain of 1st in freq multiplier

	VBE	VBC
0	-0.7	-9
0.1	-0.6	-5.9

(where V_{Bias} can
s a voltage divider?
or a voltage
headroom to
d indirectly
the transistor
istor
which
stant

$GBW = 5.25\,[MHz] = A_o\omega_1$

$\omega_b = \text{corner freq} = \frac{A_o\omega_1}{K}$

$A_o = \frac{200V}{1mV} = 200{,}000$

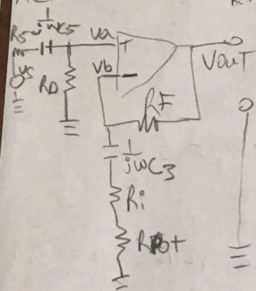
$DC\,gain = A_c \approx K = 1 + \frac{680k}{6.8k} \approx 101$

$A_2 = \frac{A_o}{K} = \frac{200{,}000}{101} \approx 1980$

$$\frac{V_o}{V_s} = \frac{K}{1 + \frac{j\omega}{A_o\omega_1}} = \frac{K}{1 + \frac{j\omega}{\frac{A_o}{K}\left(\frac{K\omega_o}{A_o}\right)}} \approx \frac{K}{1 + j\frac{\omega}{\omega_o}} = \frac{101}{1 + \frac{j\omega}{1320\pi}} = A_c\,gain$$

$$\omega_o = \frac{2\pi(5.25\times10^6)}{101} = 326\,\left[\frac{k\,rad}{s}\right]$$

AC model



$$V_a = \left(\frac{R_D}{R_D + R_5 + \frac{1}{j\omega C_5}}\right)V_s$$

$R_D = R1 // R2 = 340k\Omega$

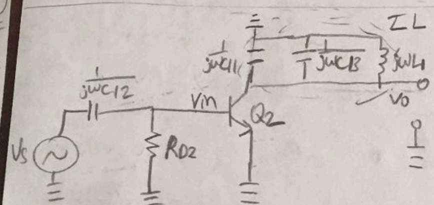
$$\frac{V_o}{V_s} = \frac{V_a}{V_s}\left(\frac{V_b}{V_a}\right)\left(\frac{V_o}{V_b}\right)$$

$$(-)\frac{(V_{out} - V_b)}{R_F} + \frac{V_b}{\frac{1}{j\omega C_3} + R_i + R_{POT}} = 0 \qquad \boxed{V_a = V_b}$$

$$V_{out} - V_b = \frac{R_F V_b}{\frac{1}{j\omega C_3} + R_i + R_{POT}} \rightarrow V_{out} = \left[1 + \left(\frac{R_F}{\frac{1}{j\omega C_3} + R_i + R_{POT}}\right)\right]V_b$$

$$\frac{V_O}{V_S} = \left(\frac{R_D}{R_D + R_5 + \frac{1}{j\omega C_5}}\right)\left(1 + \frac{R_F}{\frac{1}{j\omega C_3} + R_i + R_{POT}}\right)$$

pass clearly
~~n? (potentially~~
~~-design gain~~



$$Z_L = \frac{\frac{1}{j\omega(C11+C13)}(j\omega L1)}{\frac{1}{j\omega(C11+C13)} + j\omega L1} = \frac{\frac{L1}{C11+C13}}{1 - \omega^2 L1(C11+C13)}$$

$$V_{in} = \left(\frac{R_{D2}}{\frac{1}{j\omega C12} + R_{D2}}\right)V_s = \left(\frac{R6//R17}{\frac{1}{j\omega C12} + R6//R17}\right)V_s$$

$$V_{out} = (-g_m Z_L)V_{in} = \left(\frac{-g_m L1}{(C11+C13)(1 - \omega^2 L1(C11+C13))}\right)V_{in} \rightarrow \frac{V_{out}}{V_S} = \frac{V_{in}}{V_S}\left(\frac{V_{out}}{V_{in}}\right)$$

$$\frac{V_{out}}{V_S} = \left(\frac{-R6//R17}{\frac{1}{j\omega C12} + R6//R17}\right)\left(\frac{g_m L1}{(C11+C13)(1 - \omega^2 L1(C11+C13))}\right)$$

~~$$Z_0 = \frac{\frac{L1}{C11+C13+C10}}{1 - \omega^2 L1(C11+C13+C10)} = \frac{\frac{10\times10^{-3}}{105.7\times10^{-6}}}{1 - (1320\pi)^2(1\ldots}$$~~

~~$$Z_0 = \frac{94.61}{1 - 18.177} = -5.508\,\Omega$$~~

~~$$K = \frac{V_{in}}{V_{out}} = 10^{\frac{(18.45)}{20}} = 8.365$$~~

~~$$R20 = Z_0\left(\frac{K^2 - 1}{2K}\right) = (-5.508)\left(\frac{8.37^2 - 1}{2(8.37)}\right) = (-22.72)\,\Omega$$~~

~~$$R18,19 = Z_0\left(\frac{K+1}{K-1}\right) = (-5.508)\left(\frac{8.37+1}{8.37-1}\right) = -7.003\,\Omega$$~~