Audio Amplifier

Bandwidth between [16, 2048] Hz, output between [4, 6] Volts and output resistance 35 ohms

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-Documentation-

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I. Overview

Audio amplifiers come in various types, including preamps, power amps or headphone amps, each with its specific purpose and characteristics. Preamps are designed to amplify weak audio signals from microphones, instruments, or line-level sources to a level that can be processed further by power amps or mixers. Power amps are designed to take the amplified signal from a preamp or mixer and boost it to a level that can drive loudspeakers, with power outputs ranging from a few watts to several thousand watts. It is the final electronic stage in a typical audio playback chain before the signal is sent to the loudspeakers. The choice of audio amplifier will depend on the application, the required power output, the desired sound quality, and other factors such as size, weight, and cost.

Lee de Forest created the triode vacuum tube in 1907, the first useful electrical component for electrical amplification, which allowed him to create the audio amplifier around 1912. With the widespread availability of low-cost transistors in the late 1960s, audio power amplifiers based on transistors became feasible. Since the 1970s, solid-state transistors, particularly the bipolar junction transistor (BJT) and the metal-oxide semiconductor field-effect transistor (MOSFET), have been the foundation of the majority of contemporary audio amplifiers. Compared to tube amplifiers, transistor-based amplifiers are more dependable, lighter, and require less upkeep.

I.1 Requirements

Key design parameters for audio power amplifiers are frequency response, gain, noise, and distortion. These are interdependent; increasing gain often leads to undesirable increases in noise and distortion. Most audio amplifiers are linear amplifiers operating in class AB.

The designed circuit must work on a bandwidth of [16, 2048] Hz with an output between [4, 6] volts while driving an output resistance Ro = 35 ohms considering the amplitude of the input voltage is approximately 700 microvolts.

I.2 Power amplifiers

Power amplifiers, also known as power amps, are electronic devices that take an audio signal and amplify it to a level that can drive loudspeakers or other output devices. They are an essential component in audio systems that require high-power output. To drive a speaker, we must use a power amplifier. These come in different types and topologies, each with its own advantages or disadvantages.

Table 1. Power amplifiers

Class	Description	Conduction angle	Efficiency
A	Full cycle 360° of Conduction	$\Theta = 2\pi$	20-30%
B	Half cycle 180° of Conduction	$\Theta = \pi$	30-40%

AB	Slightly more than 180° of Conduction	$\pi < \Theta < 2\pi$	65%
D	ON-OFF non-linear switching	$\theta = 0$	90-99%

The Class A amplifier provides high linearity and low distortion, but terrible efficiency.

The Class B amplifier uses a “push-pull” arrangement with a pair of complementary amplifier elements (such as N-/P-channel MOSFETs) resulting in an improvement in efficiency (30-40% range), but it suffers from crossover distortion whichmakes it unsuitable for audio applications.

The efficiency of Class C amplifiers can be fairly high, up to about 70-80%, but because the distortion is also high (10 to 30%) the Class C approach cannot be used for audio.

Class D amplifiers use pulse-width modulation (PWM) to produce a digital output signal with a variable duty cycle to approximate the analog input signal. These amps are highly efficient (90% or higher) because the output transistors are either fully turned on or fully turned off during operation. This approach completely eliminates the use of the linear region of the transistor that is responsible for the inefficiency of other amplifier types.

I.3 Filtering

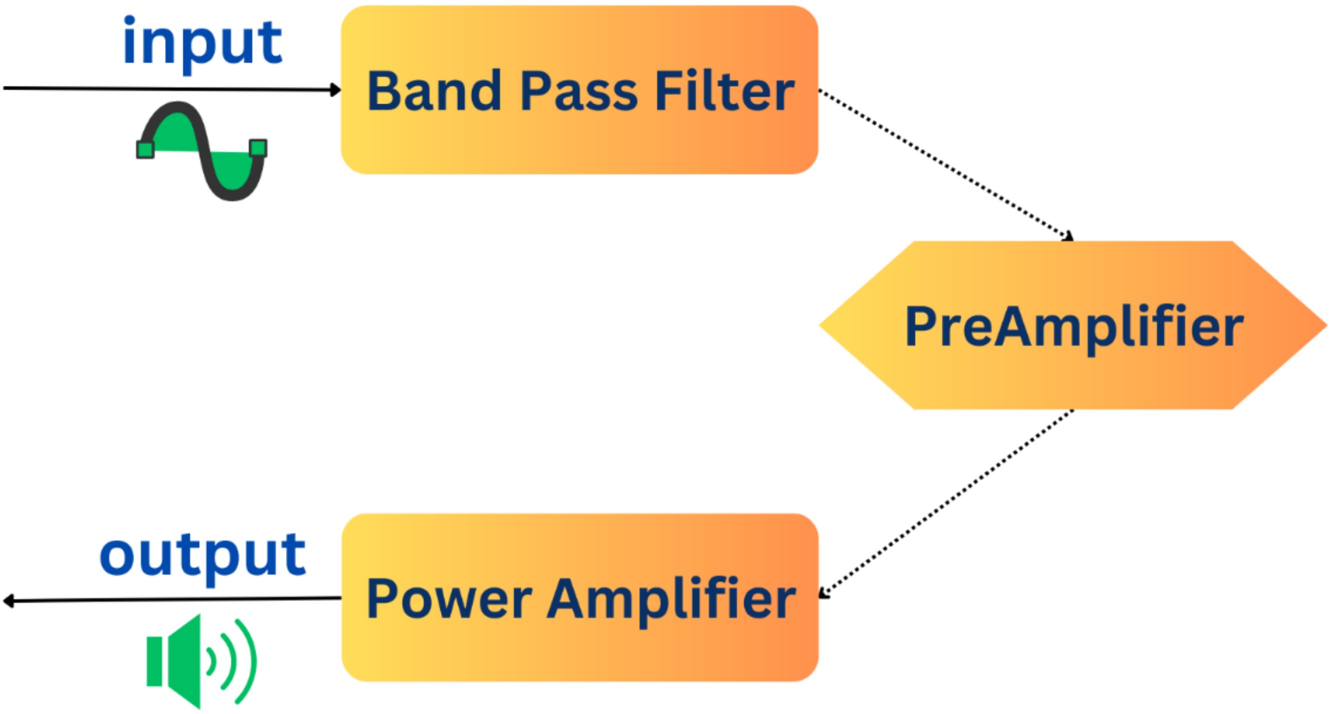
There are several types of filters, including lowpass, highpass, and bandpass filters. A lowpass filter is a circuit that weakens high-frequency signals while letting low-frequency signals pass through. It is frequently applied to eliminate unwanted high-frequency noise or to improve the overall audio quality of a signal. A highpass filter, on the other hand, allows high-frequency signals to pass through while attenuating low-frequency signals. It is frequently applied to an audio signal to reduce unwanted low-frequency noise or to highlight the high-frequency content. A band pass filter is needed to guarantee that the circuit only operates between the desired frequency range of [16, 2048] Hz. This can be easily implemented by first filtering using a lowpass and then a highpass filter or viceversa. The resulting filter achieves it’s purpose with minimal complexity and it is very simple to implement in a real circuit.

I.4 Preamplification

Preamplifiers, also known as preamps, are tools for boosting and enhancing low-level audio signals. When working with extremely low input voltage, a preamplifier stage is necessary to raise the voltage and ensure the power amplifier will function properly. This can be accomplished using a variety of circuits, transistors, and ICs (integrated circuits) chosen in accordance with the objectives of the circuit: maximum gain, minimal noise, adjustability, low or high impedance. The sound quality of an audio signal can be significantly improved by a high quality preamp.

II. Block diagram

Figure 1. Block diagram



II.1 Band-Pass Filter

The input signal of the circuit can have a very large range of frequencies. Amplifying this signal and sending it to a speaker without any filtering will result in distorted audio. A subwoofer can only output low-frequency sounds (bass) and can even be damaged by high-frequency signals. This problem can be resolved by implementing a passive bandpass filter. Passive bandpass filters can be made by connecting a low-pass filter with a high-pass filter. The cut-off frequency, or f_c point, in a simple RC passive filter can be accurately controlled using just a single resistor in series with a non-polarized capacitor.

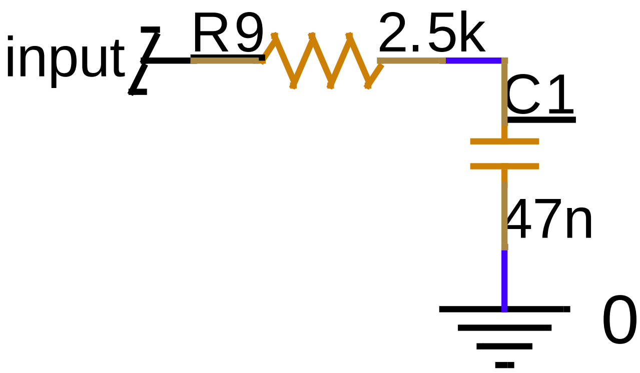
$$f_C = \frac{1}{2\pi RC} \quad (1)$$

II.3.1 Low-Pass Filter

The low-pass filter should have a cutoff frequency of 2048 Hz. Choosing a common 2.5k ohm resistor, the value of the capacitor should be 31nF. In simulations, this results in an f_c=3100Hz, a 51.3% error. A standard 47n capacitor gets the f_c=2058 which is only a 0.48% error.

$$C = \frac{1}{2\pi R f_C} = \frac{1}{2\pi \cdot 2.5 \cdot 10^3 \cdot 2048} = 31nF \qquad (2)$$

Figure 2. Low-pass filter

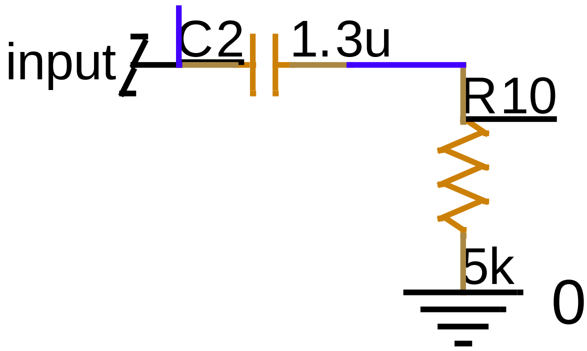


II.3.2 High-Pass Filter

The high-pass filter should have a cutoff frequency of 16 Hz. Using a 5k ohm resistor, the value of the capacitor, according to calculations should be 1.989uF. According to the simulations, this would result in an f_c=10.6Hz, an error of 33.4%. However, using a capacitor with a value of 1.3uF results in a 0.49% error, so it is used instead.

$$C = \frac{1}{2\pi R f_C} = \frac{1}{2\pi \cdot 5 \cdot 10^3 \cdot 16} = 1{,}9894uF \qquad (3)$$

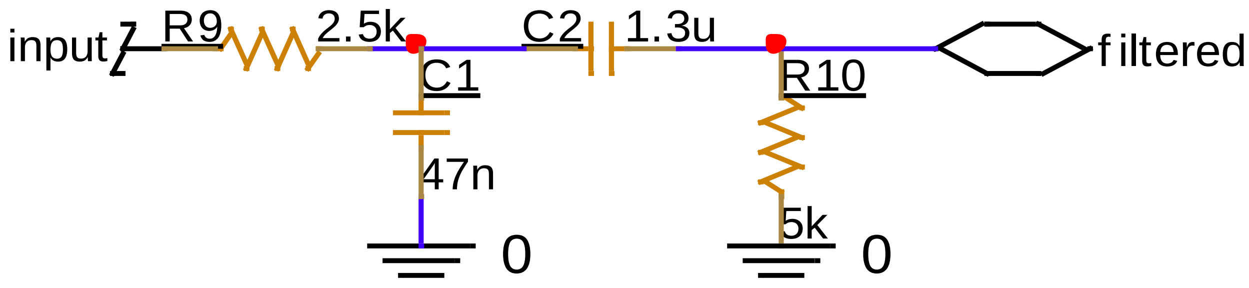
Figure 3. High-pass filter



II.3.3 Complete filter

When combining the two filters together, if the initially calculated values were to be kept, it would result in a very large error. Instead, in the pursuit of accuracy, a 47nF and a 1.3uF capacitor are used, obtaining a bandwidth that is only 0.98% different from the ideal one.

Figure 4. Band pass filter



II.2 PreAmplifier

Implemented using a cascade of operational amplifiers with negative feedback, this stage of the circuit provides the necessary voltage gain to the input signal so that the power amplifier can function correctly. Given the input signal's extremely low amplitude, a significant amount of amplification is required. The chosen IC is OPA2604 because it has very low distortion, low noise, and a wide bandwidth, which provides superior performance in high-quality audio.

$$A = \frac{v_0}{v_i} = \frac{5}{700u} \approx 7200 \tag{4}$$

Such high gain cannot be achieved with a single operational amplifier, so two units are used. The latter one has a potentiometer with a 450k ohm resistor in parallel with its feedback loop, ensuring the adjustment between 4 and 6 volts at the output. The maximum value of the two is:

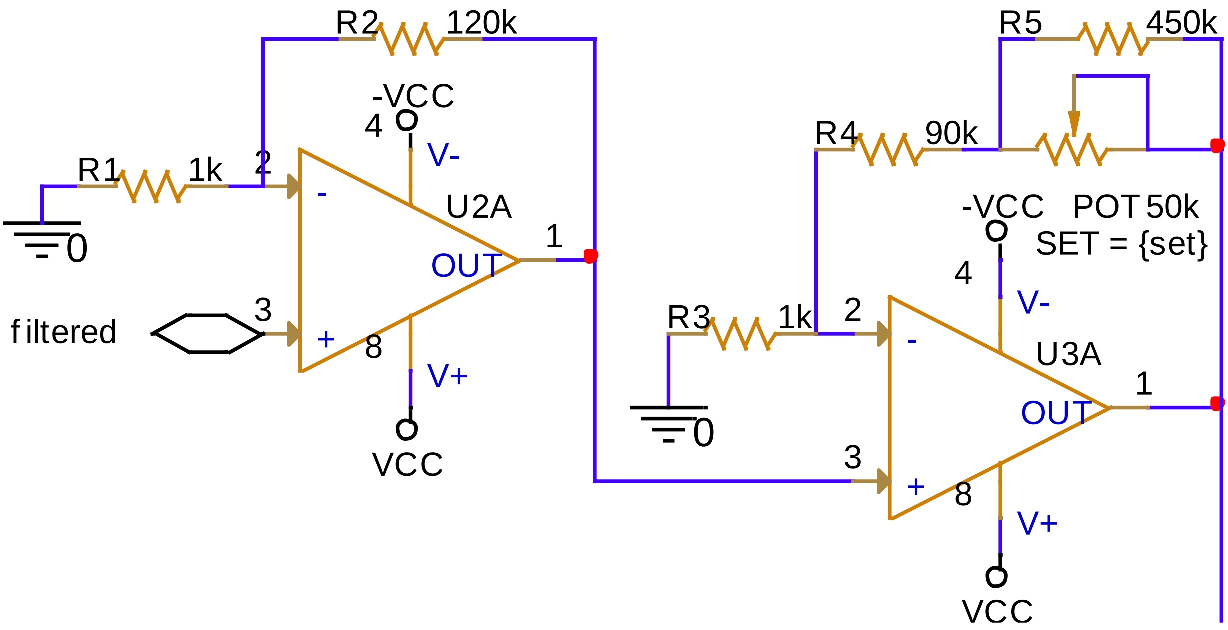
$$R_{eq} = \frac{POT * R5}{POT + R5} = \frac{22500k}{500k} = 45k \tag{5}$$

The first IC in the current configuration has a gain of:

$$A = 1 + \frac{R_{NF}}{R_{-}} = 1 + \frac{120}{1} = 121 \tag{6}$$

Considering SET = 1, the gain of the second amplifier is 136. The ideal calculated gain is a maximum of 121*136≈16500. When SET = 0, the gain is ~10500. Although these numbers initially appear excessive, in simulation they result in an output of minimum 3.97V (0.75% difference) and maximum 6V. The final voltage gain ranges from ~5710 to ~8710.

Figure 5. Preamp



II.3 Power Amplifier

The circuit uses a class AB power amplifier for its good efficiency compared to class A, low distortion compared to class C or B, and simplicity compared to class D. This stage boosts the signal's power so that it can drive a speaker or other output device. The transistor Q2 is NPN type, and the transistor Q1 is PNP type, both being relatively high-power transistors. The two forward-biased diodes D1 and D2 are used to bias the transistors, while R6 and R7 limit the current to 15mA. This means that the diodes can generate 0.7V of constant voltage. This property is utilized to provide a 1.4V constant potential between the bases of Q1 and Q2 transistors. The advantage of this method is the self-adjustment of the voltage drop across the diodes D1 and D2 at any temperature change.

The transistors Q3 and Q4 are used to offer short-circuit protection for the amplifier. Should the load ever become damaged, lowering its resistance or even shorting to ground, this structure will limit the current, protecting the circuit from thermal runaway cause by excessive current flow. The resistors R10 and R11 generate 0.7V to turn on the protection transistors when the output current exceeds 300mA.

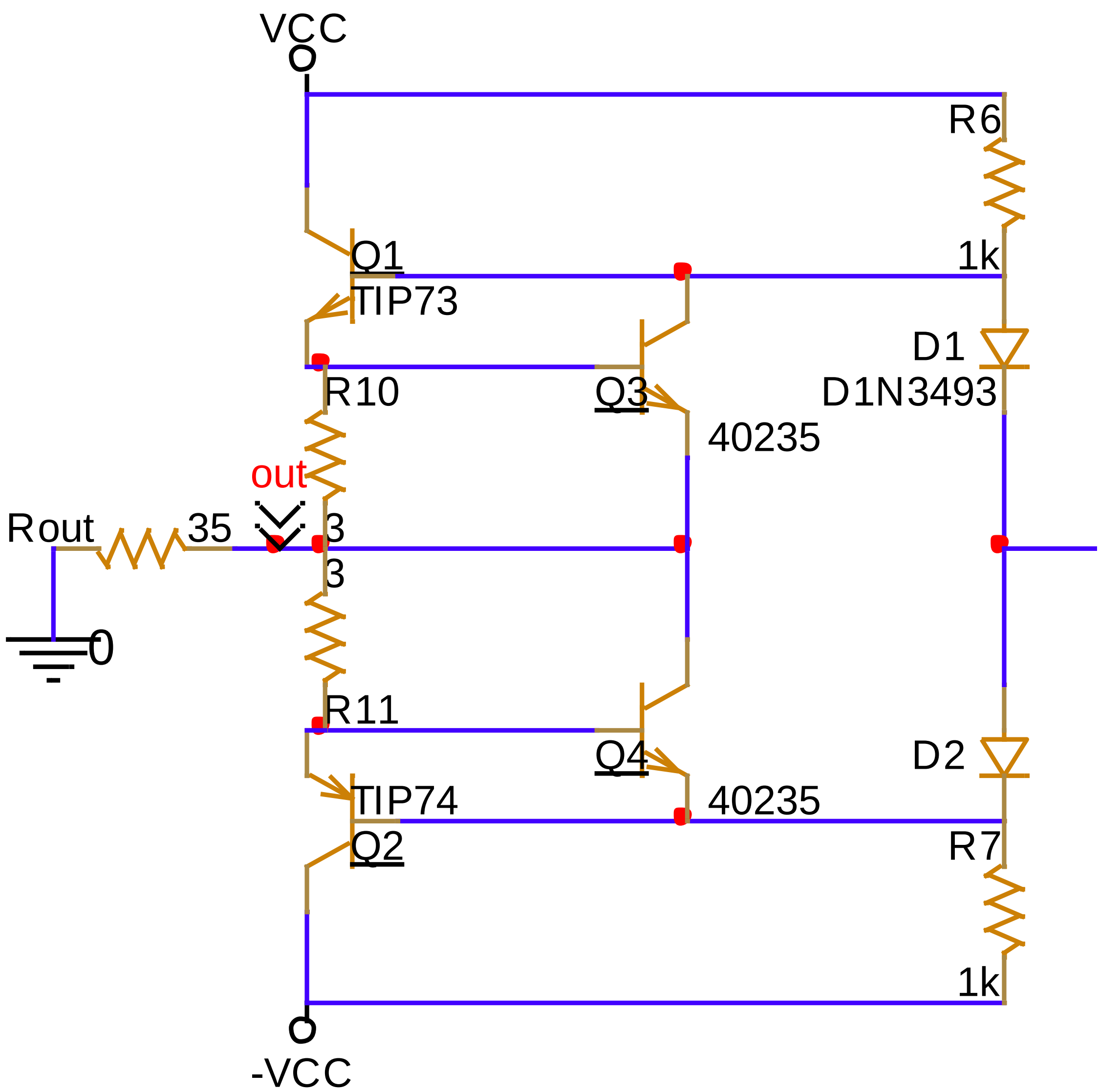
$$R_{protection} = \frac{V_{BEon}}{I_{out}} = \frac{0.9V}{300mA} \approx 3\Omega \quad (7)$$

$$V_{cc} = V_{peak} * 2 + 2 = 14V \quad (8)$$

$$I_{peak} = \frac{V_{peak}}{R_{out}} = \frac{6}{35} = 0.171A \quad (9)$$

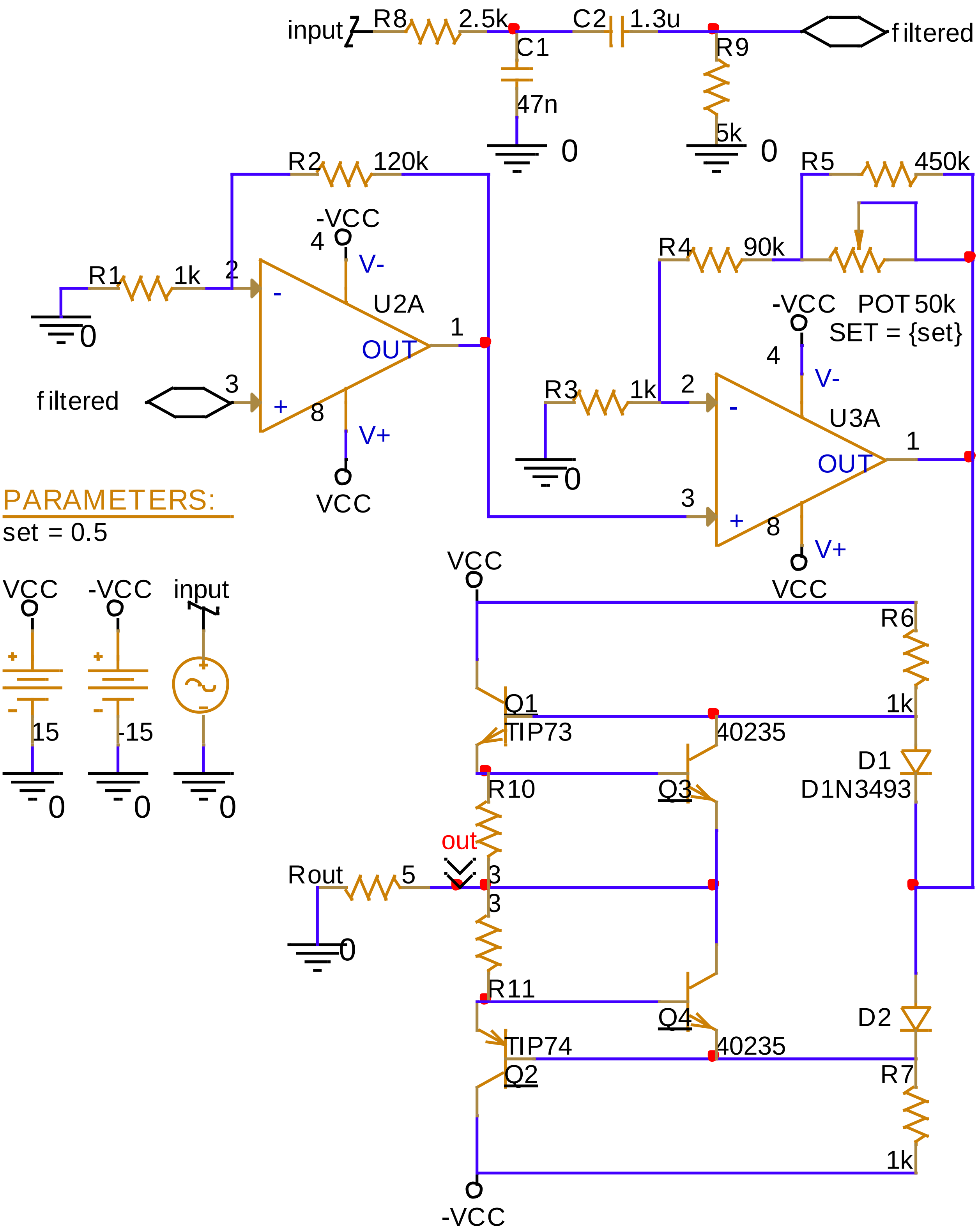
$$P_{out} = I_{rms} * V_{rms} = 0.12 * 4.24 \approx 0.51W \quad (10)$$

Figure 6. AB power amp



III. Circuit Diagram

Figure 7. Complete audio amp



III.1 Components and cost

Tabel 2. Resistors

Resistor	Value[Ohms]	Price/unit	Tolerance	Link
R1, 3, 6, 7	1k	0.06$	±1%	https://shorturl.at/vAE29
R2	120k	0.055$	±1%	https://shorturl.at/fhnDE
R4	90k	0.21$	±0.1%	https://shorturl.at/pxENW
R5	450k	0.02$	±1%	https://shorturl.at/hmQWX
R8	2.5k	0.055$	±1%	https://shorturl.at/tzIJT
R9	5k	0.055$	±1%	https://shorturl.at/qEKO2
R10, 11	3	0.055$	±1%	https://shorturl.at/fhmBS
POT	50k	0.5$	±10%	https://shorturl.at/htBKS

Total cost of resistors: 1.245$

Tabel 3. Capacitance

Capacitor	Value[Farad]	Price/unit	Tolerance	Link
C1	47n	0.35$	±5%	https://shorturl.at/efiD8
C2	1.3u	0.033$	±10%	https://shorturl.at/afgtv

Total cost of capacitors: 0.383$

Tabel 4. Diodes

Diode	Model	Price/unit	Link
D1, D2	1N3493	0.28$	https://shorturl.at/ntvBW

Total cost of diodes: 0.56$

Tabel 5. Transistors

Transistor	Model	Price/unit	Link
Q1, Q2	TIP73, TIP74	0.33$	https://shorturl.at/AGHLV
Q3, Q4	40235	0.07$	https://shorturl.at/owzKY

Total cost of transistors: 0.8$

Tabel 6. OPAMPs

OPAMP	Model	Price/unit	Characteristic	Link
U2A, U3A	OA2604	2.4$	Low distortion	https://shorturl.at/cglmF

Total cost of operational amplifiers: 4.8$

Total cost for the audio amplifier is 7.788$. Most of the cost is represented by the high performance operational amplifier OPA2604 (61.6% of the total value).

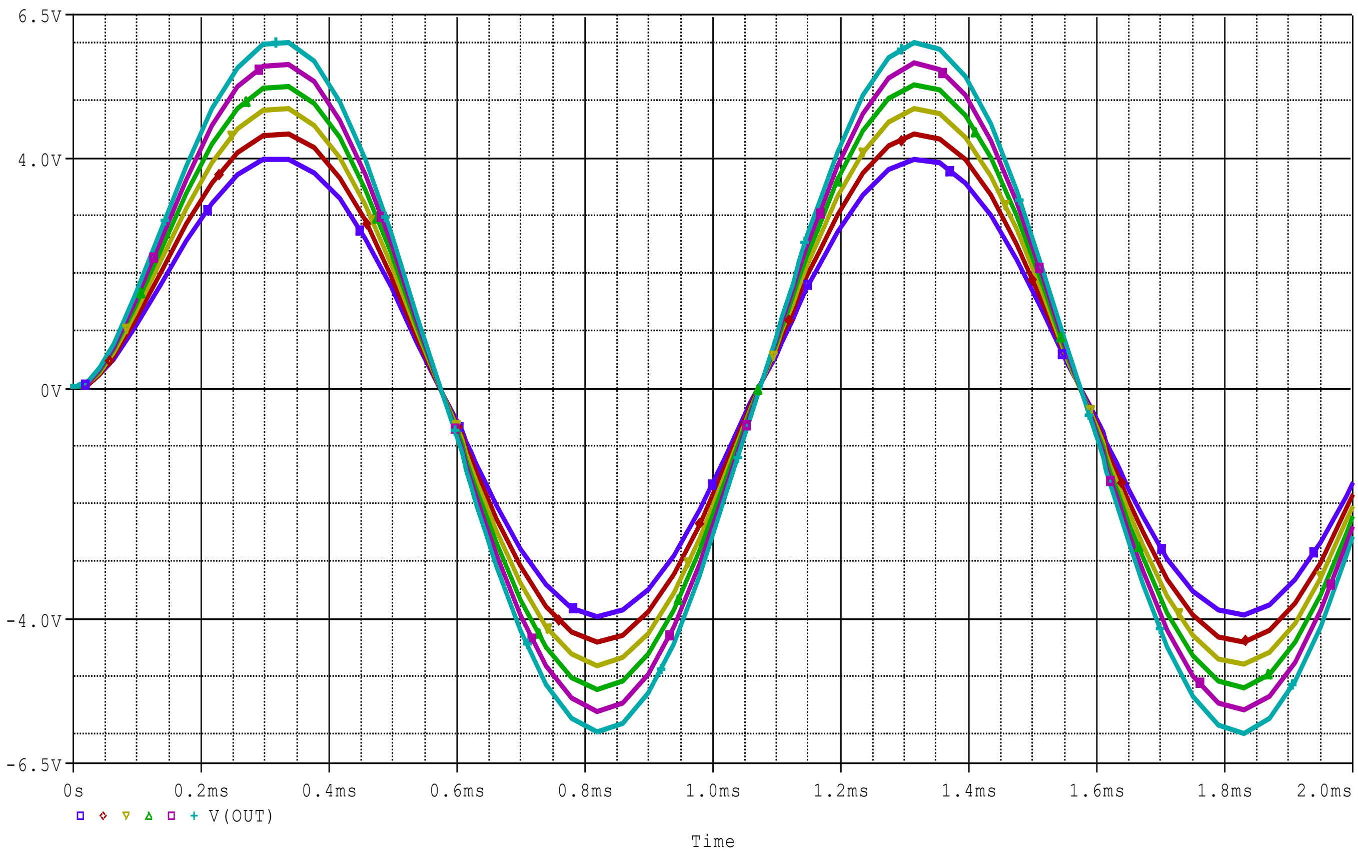
IV. Simulation and Results

IV.1 Parametric sweep

IV.1.1 Transient analysis

Using a transient analysis with a run time of 2ms, we check the „parametric sweep” checkbox and sweep the „SET” parameter of the potentiometer „POT” between 0 and 1 with a step of 0.2 to appreciate the range of voltage that can be generated at the output.

Figure 8. SET sweep in time



In order to better understand the output voltage's maximum values, let's perform a Max(V(out)) measurement as well.

Figure 9. Max(V(out)) from 1st to 6th trace

3.97788	4.41906	4.84520	5.27453	5.64066	6.00193

IV.1.2 AC sweep

We sweep the AC source from a frequency of 1Hz up to 10kHz, while sweeping the „SET" parameter of the potentiometer „POT" between 0 and 1 with a step of 0.2 to see if this change has any effect on the bandwith of the amplifier.

Figure 10. Cutoff_Highpass

16.04409	16.04408	16.04407	16.04406	16.04405	16.04403

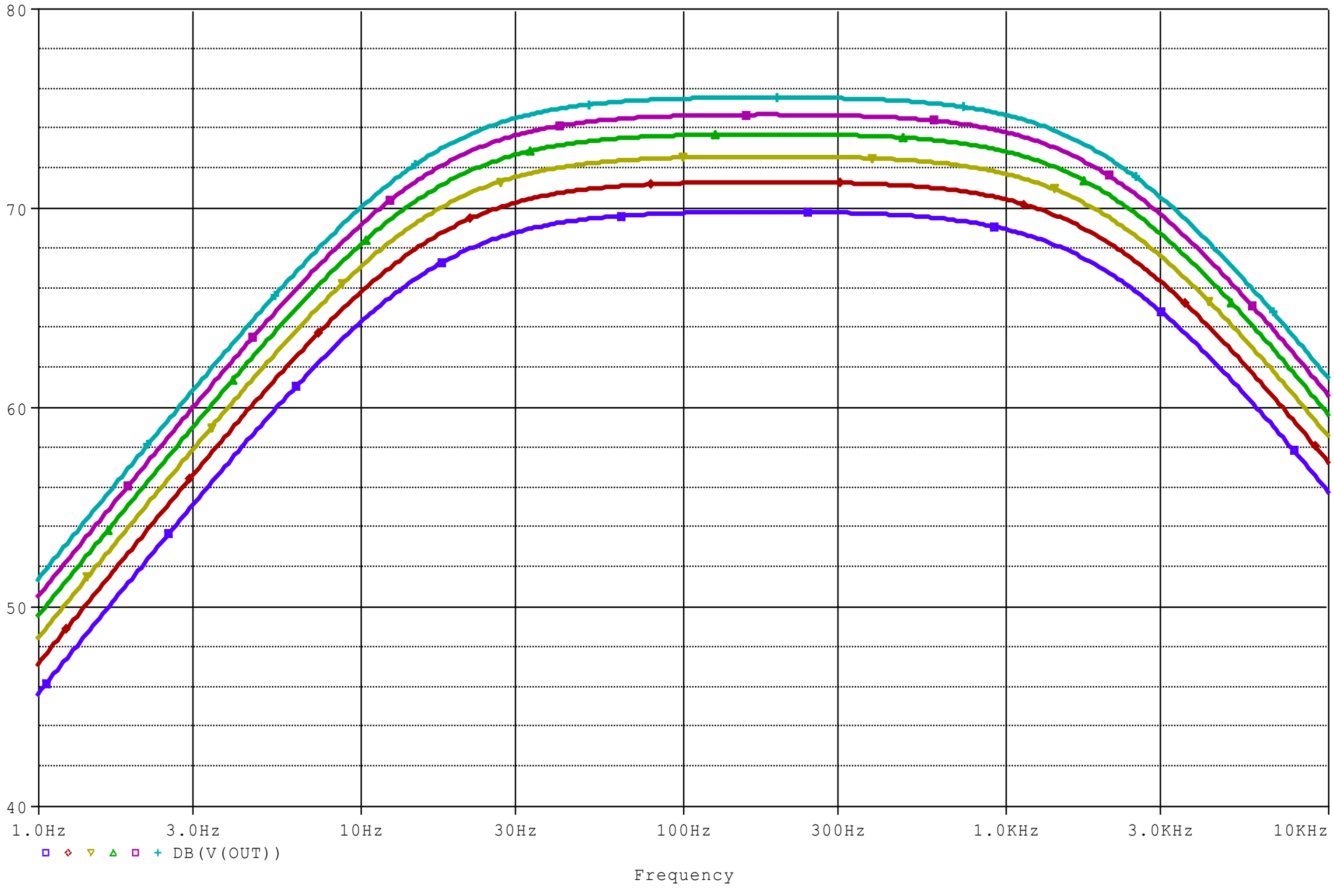
Figure 11. Cutoff_Lowpass

2.06556k	2.06539k	2.06521k	2.06501k	2.06482k	2.06461k

Figure 12. Bandwidth_Bandpass

2.04952k	2.04934k	2.04916k	2.04897k	2.04877k	2.04857k

Figure 13. SET sweep in frequency



IV.2 Temperature sweep

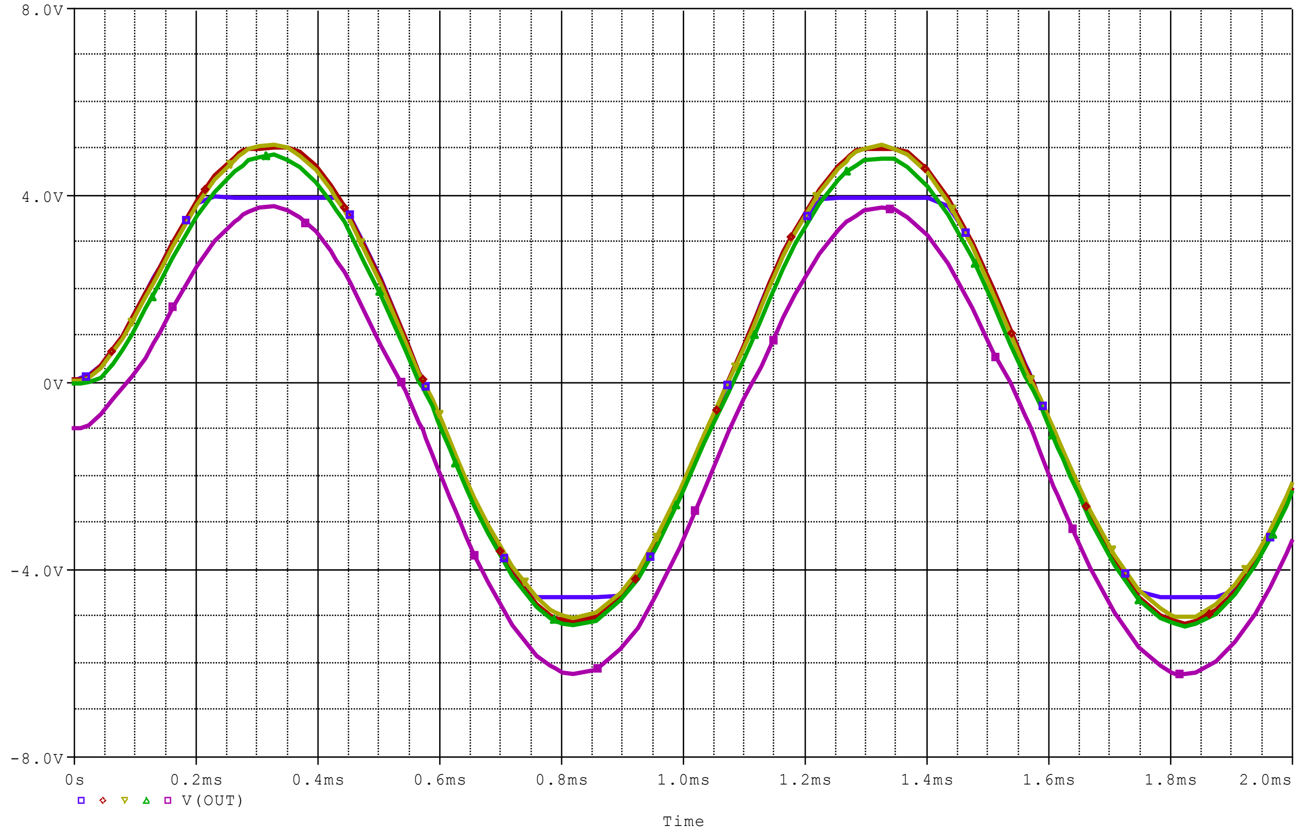
IV.2.1 Time domain

The output of the circuit at room temperature (20°C) is 5.08V. Studying its performance at different temperatures between -150°C and 65°C, it can be seen that the output is maintained within 4.46% of this value. The following temperature sweep was run for [-170 -150 20 65 80] °C. It can be seen that at temperatures as low as -170°C the signal starts getting clipped, while when the temperature gets to 80°C, the output is 26% lower.

Figure 14. Max(V(out)) for [-170 -150 20 65 80] °C

3.97900	5.00758	5.08884	4.85223	3.76654

Figure 15. Temperature sweep [-170 -150 20 65 80] °C



IV.2.2 AC sweep

We repeat the same temperature sweep while running an AC sweep to see how the temperature affects the bandwidth.

Figure 16. Bandwidth_Bandpass [-170 -150 20 65 80] °C

2.04892k	2.04896k	2.04906k	2.04908k	2.04909k

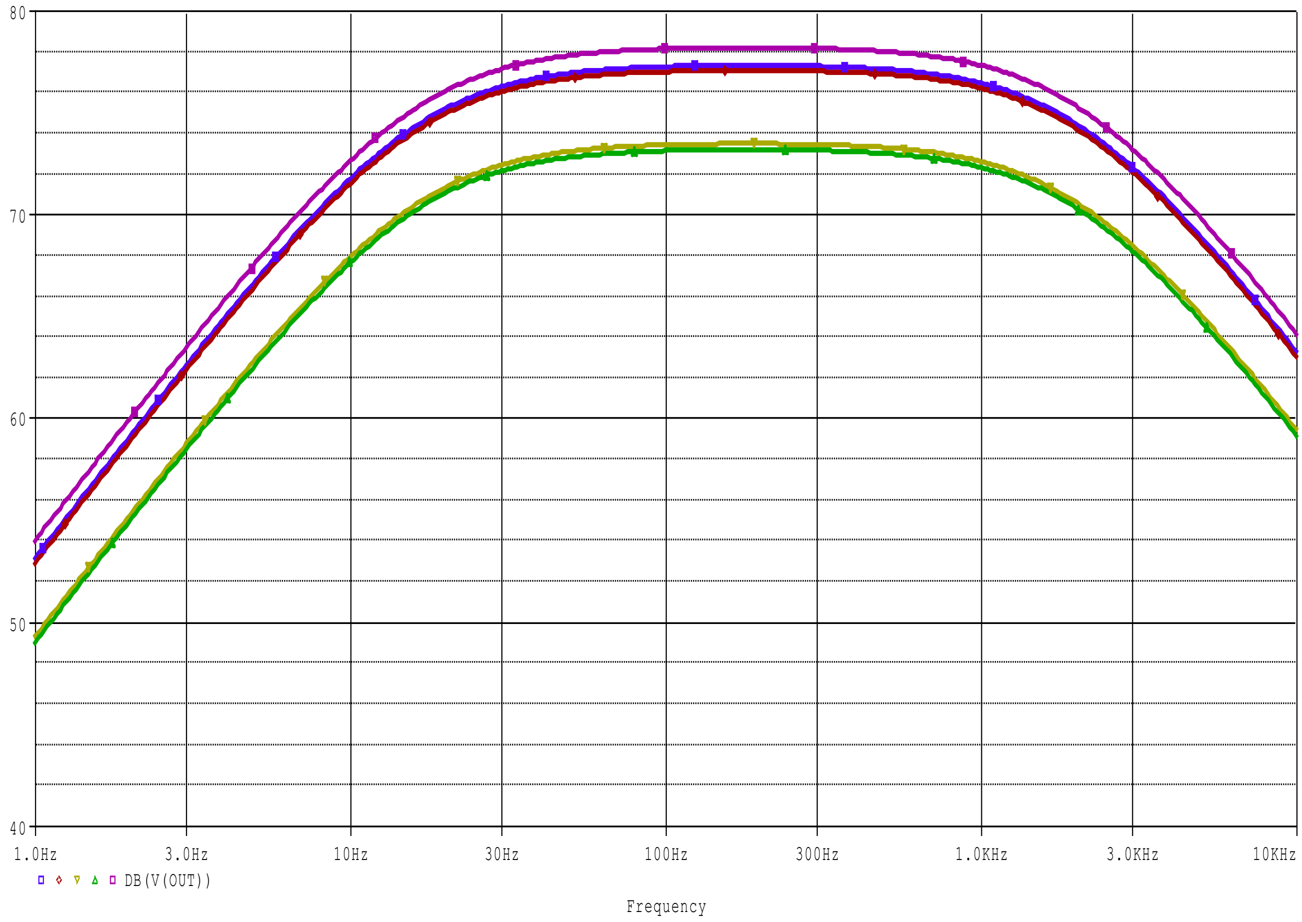
Figure 17. Cutoff_Highpass [-170 -150 20 65 80] °C

16.04406	16.04406	16.04406	16.04406	16.04407

Figure 18. Cutoff_Lowpass [-170 -150 20 65 80] °C

2.06496k	2.06501k	2.06511k	2.06512k	2.06513k

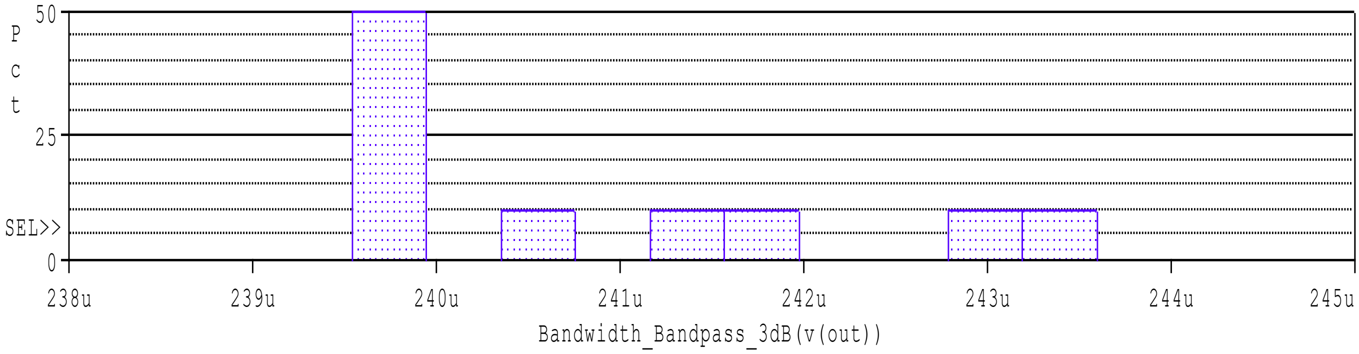
Figure 19. AC sweep [-170 -150 20 65 80] °C



IV.3 Monte Carlo

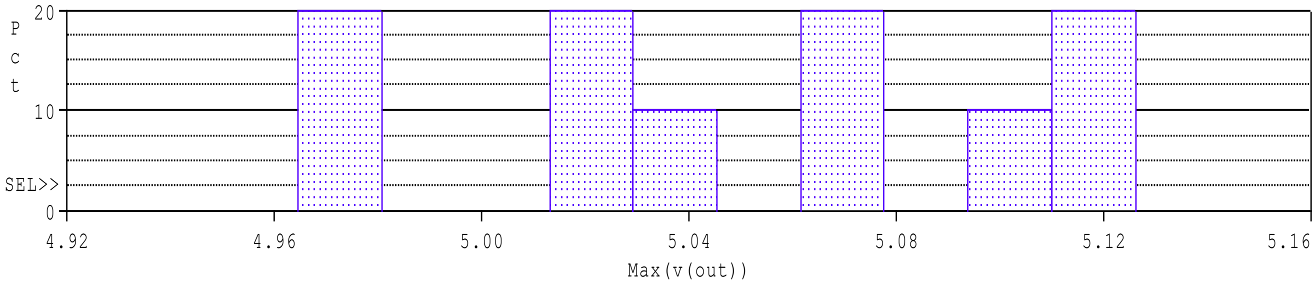
We run a Monte Carlo simulation to see how the circuit behaves when the component values vary. Monte Carlo determines, statistically, the circuit’s behavior when the components values are changed within their tolerance domain. This analysis also calculates the productivity that can be used for statistical analyses of the production.

Figure 20. Bandwidth_Bandpass of Monte Carlo

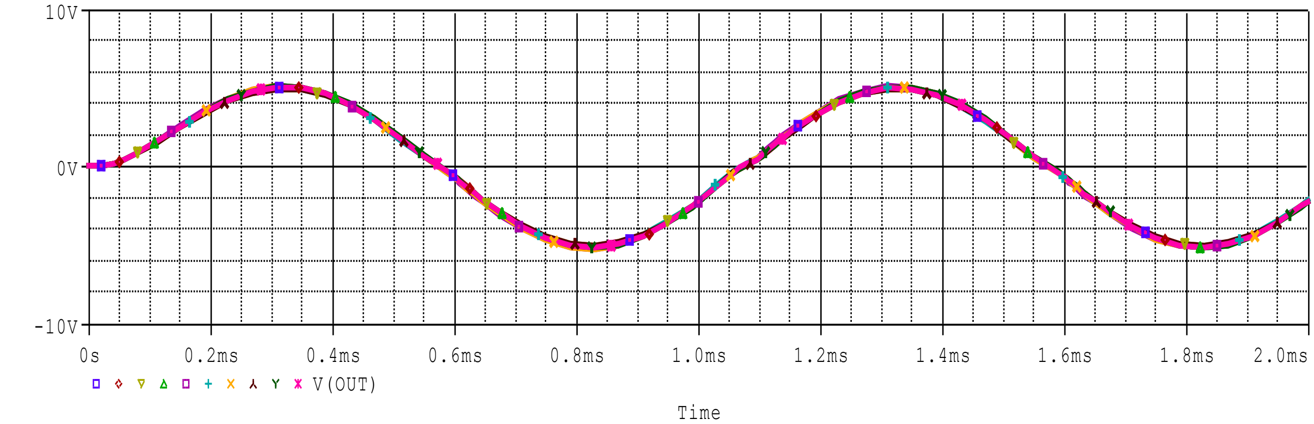


n samples	= 10	sigma	= 1.50074e-06	median	= 0.000240229	3*sigma	= 4.50221e-06
n divisions	= 10	minimum	= 0.000239542	90th %ile	= 0.000243303		
mean	= 0.000240913	10th %ile	= 0.000239587	maximum	= 0.000243598		

Figure 21. Max(V(out)) of Monte Carlo



n samples	= 10	sigma	= 0.058857	median	= 5.05665	3*sigma	= 0.176571
n divisions	= 10	minimum	= 4.9647	90th %ile	= 5.12486		
mean	= 5.05282	10th %ile	= 4.96607	maximum	= 5.12612		



IV.4 Worst-Case

The worst-case simulation calculates the performance of the circuit under worst-case conditions. The goal of this analysis is to determine the maximum or minimum values of circuit parameters such as voltage, current, power, and temperature that could occur during operation, due to variations in component tolerances or other factors that may affect circuit performance.

Figure 22. Worst Case

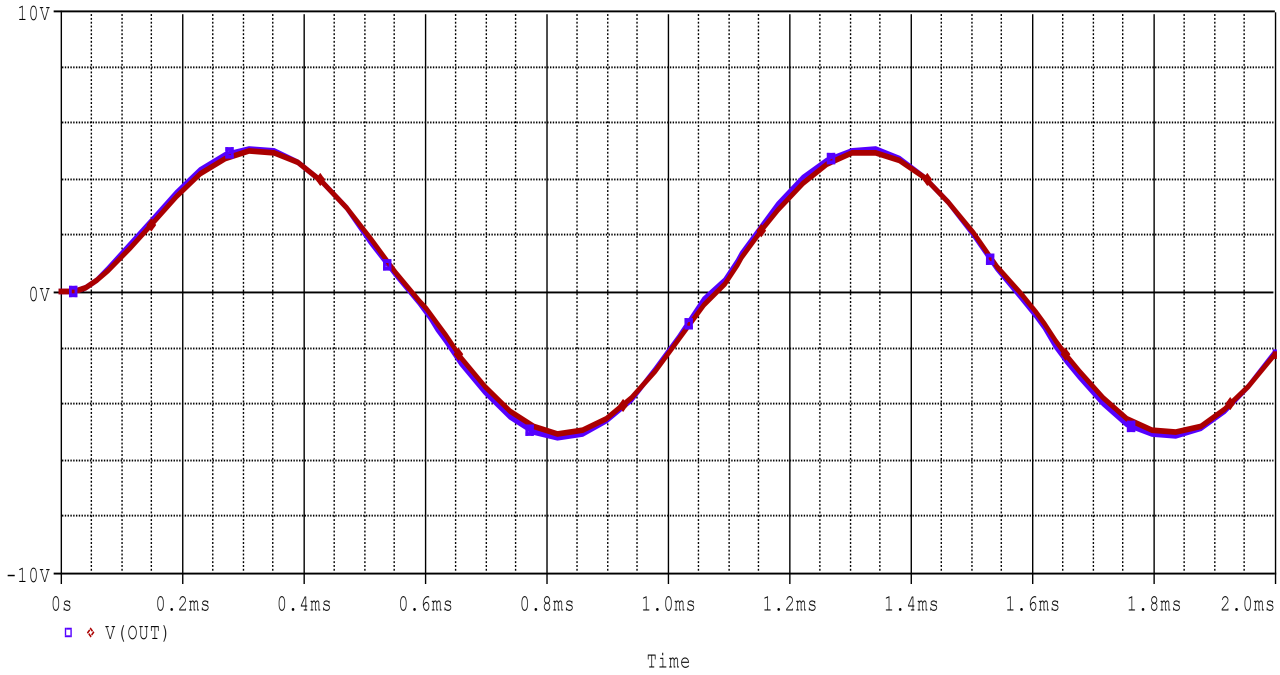
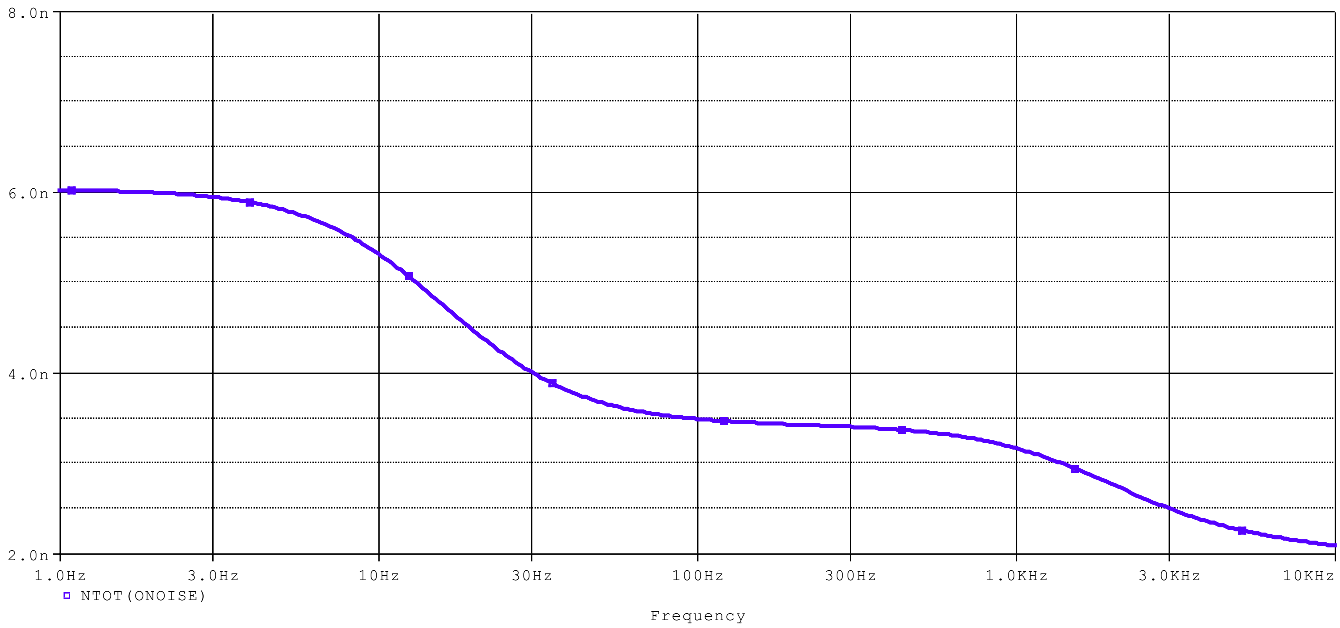


Figure 23. Max(V(out))

max(v(out))	5.07246	4.97191

IV.5 Noise

The maximum noise in the circuit happens at lower frequency. The maximum value of the NTOT(ONOISE) trace is only 6.02n.



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