ELECTRONICS WORKSHOP II

Designing an Audio Amplifier

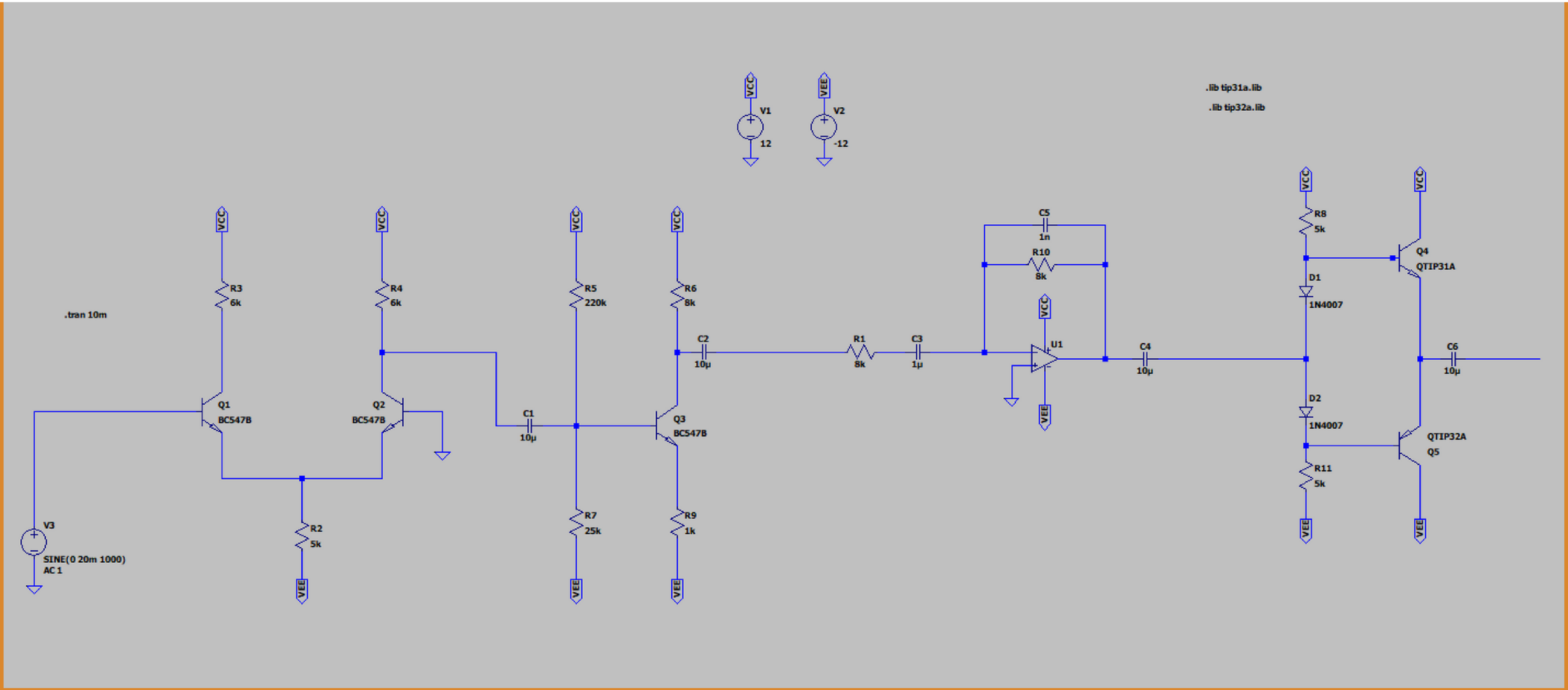
PROJECT OBJECTIVE

To design an Audio Amplifier circuit, having a gain of around 400 first on LTSpice, and then on the breadboard.

THEORY

An audio amplifier is a circuit or device designed to amplify an input audio signal. In other words, it boosts the signal's amplitude without introducing any phase shift. This in reality can be implemented by first passing the input audio signal through an amplifier circuit, then passing it through a bandpass filter so that unwanted frequencies are removed, and then ultimately passing it through a power amplifier so that the output signal is strong enough to the speaker with sufficient force to produce sound. In our simulation, we have assumed a total gain of around 400 (theoretical). Our design includes four stages: differential amplifier stage, CE amplifier stage, bandpass filter and power amplifier stage. The first stages are also often referred to as the Pre-gain and the Gain stages.

Final Simulation

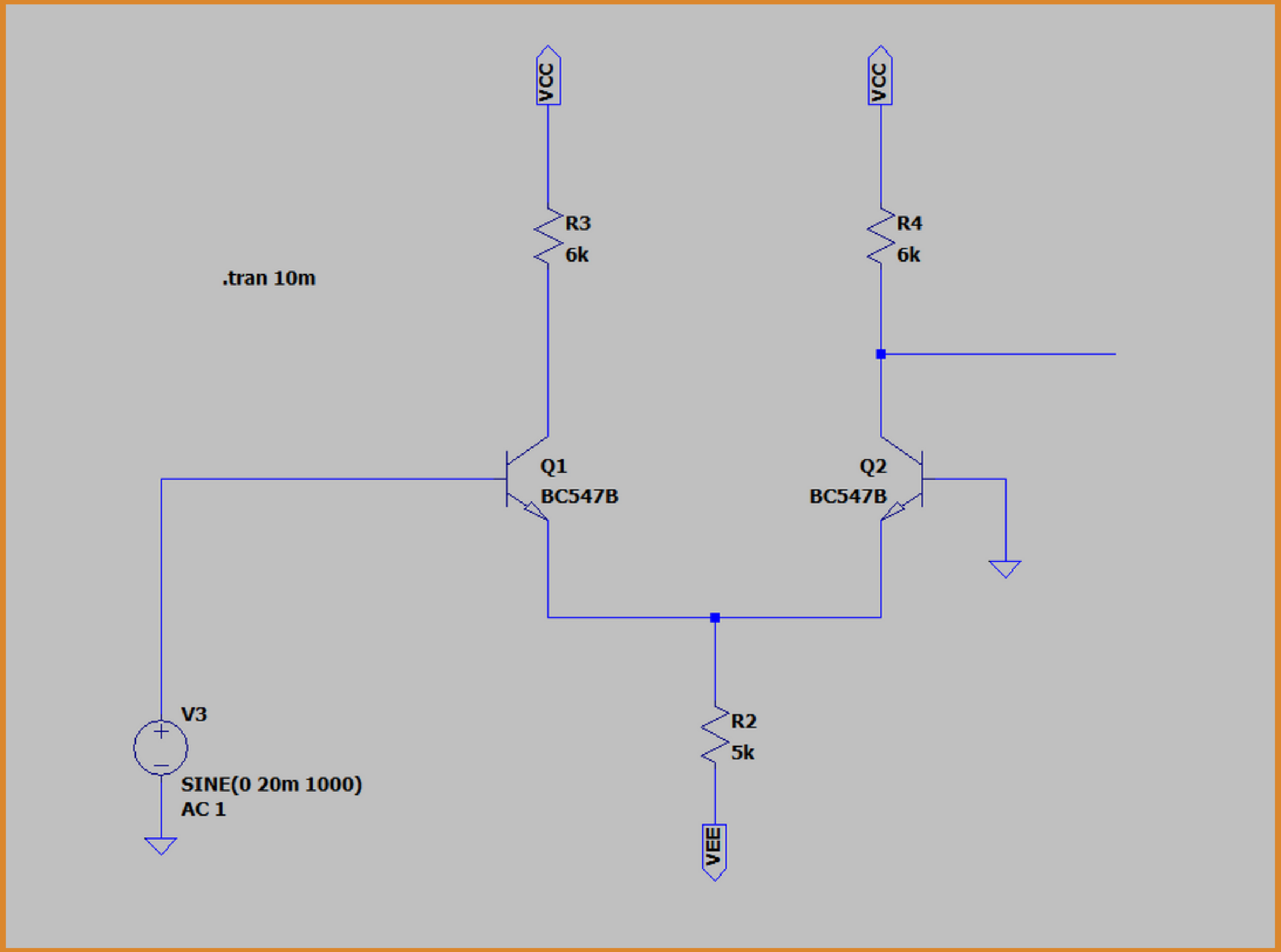


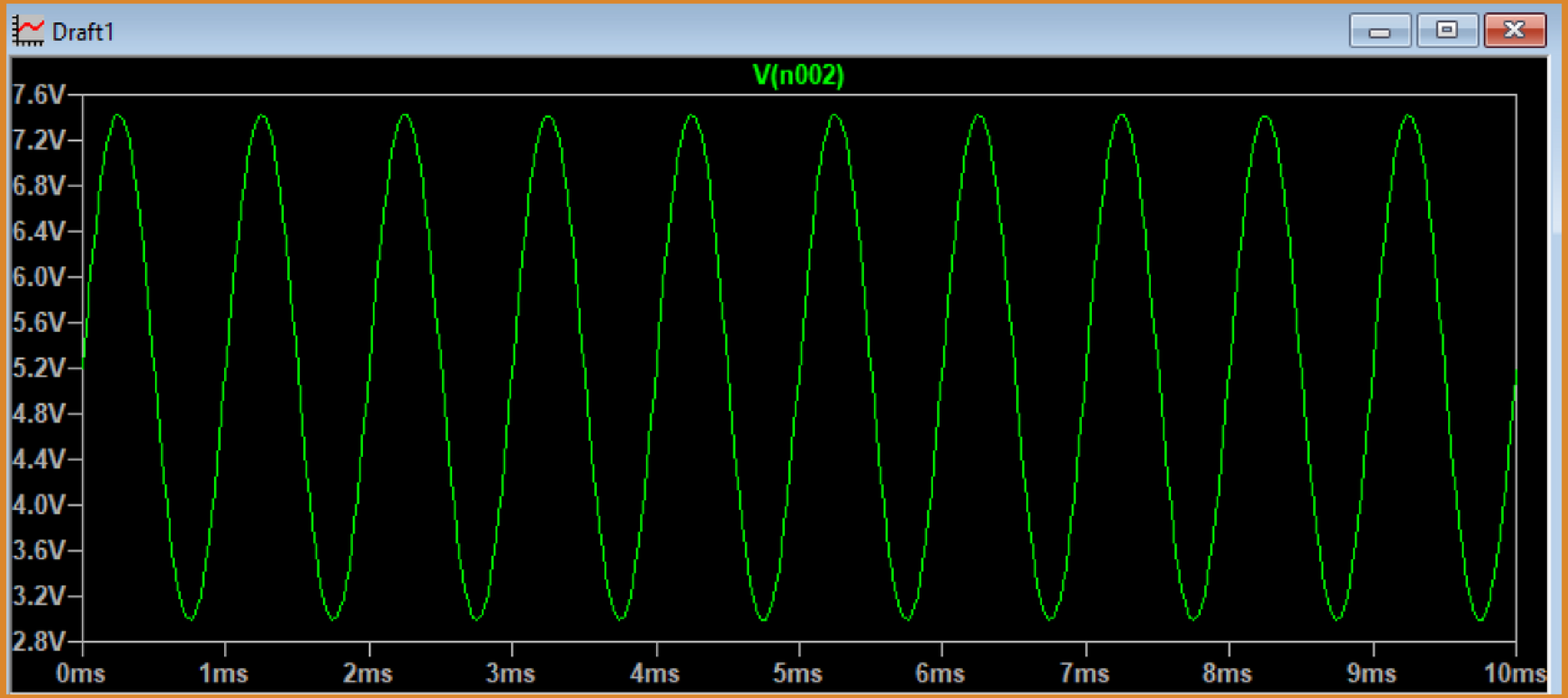
PRE-GAIN STAGE

The first stage, also known as the Pre-Gain stage, consists of the differential amplifier. The importance of this stage is that it amplifies the difference between the two inputs (voltages). Because of this property, it becomes very useful when the input signal that is being transmitted is very susceptible to noise. The difference of the inputs removes the noise, and this then is slightly amplified. This is the stage where the mic, which produces a voltage (input) of 20mV, is connected to circuit for the input.

This stage produces a gain of around 100 and is designed using two npn transistors whose model is BC547B. A resistor of 5k ohms is used in keeping the transistors in the proper biasing region.

LTSpice Simulation of Differential Amplifier

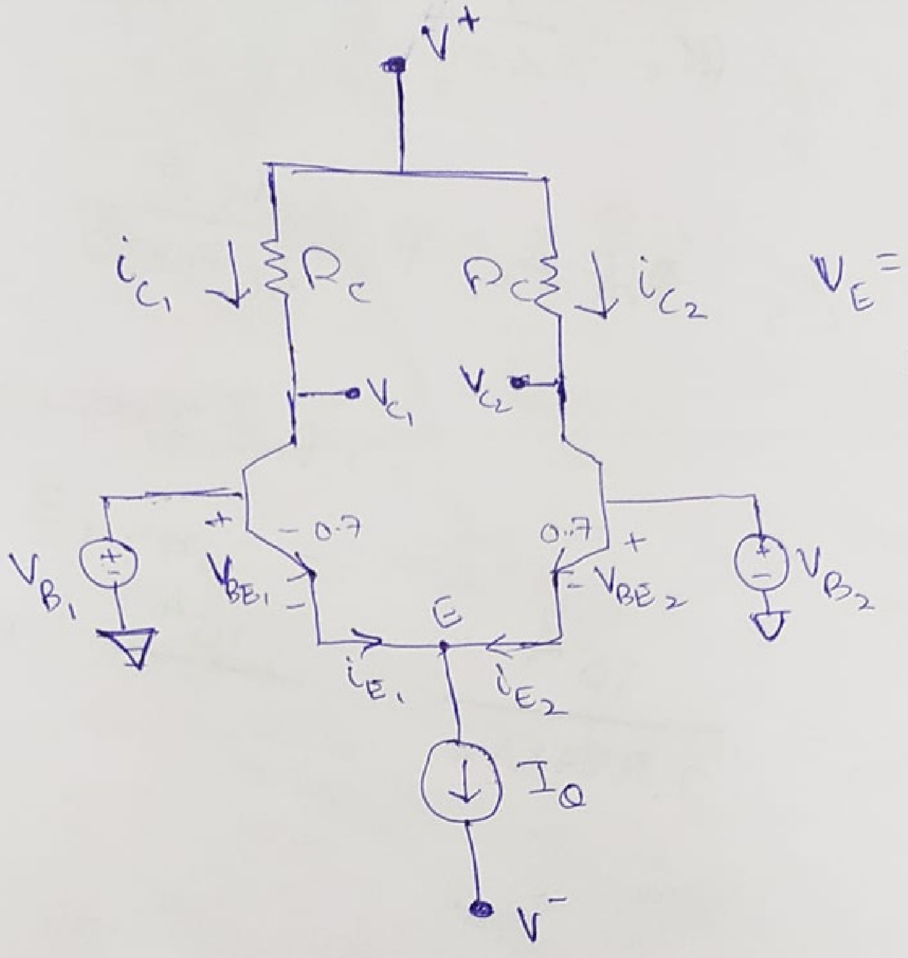




From the simulation it is clear that the pre-gain stage produces a 4.4 pk-pk voltage. This means that the gain is round 200, which is very much near to out theoretical value.

Another reason for using the differential amplifier is that it exhibits greater input and output swing limits, allowing it to handle high input values without causing output clipping. Additionally, differential amplifiers typically have a higher slew rate. Slew rate represents the maximum rate of change of the output voltage with respect to time. It generally is expressed in volts per microsecond (V/μs).

Stage-1 Calculations



$V_E = V_{B_1} - V_{BE_1}$

$= V_{B_2} - V_{BE_2}$

Since Q_1 & Q_2 are identical; I_Q splits equally.

$\Rightarrow i_{E_1} = i_{E_2} = \frac{I_Q}{2}$

& we know that in CE configuration, we have

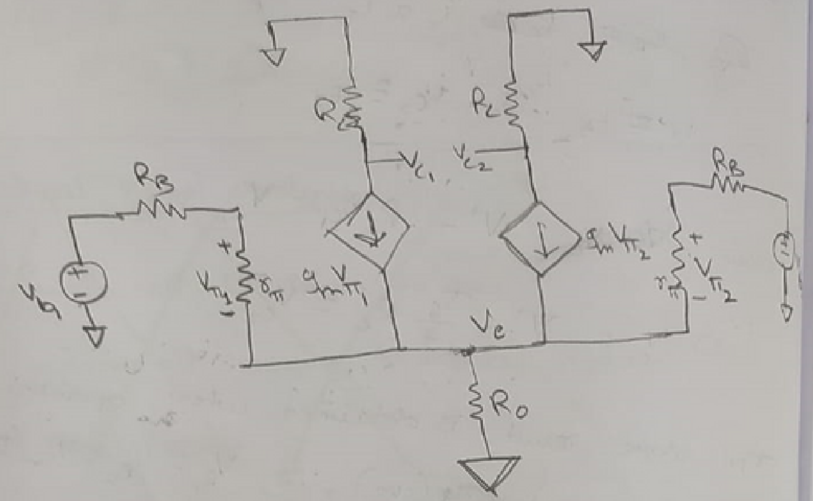
$i_C \approx i_E$

$\Rightarrow i_{C_1} \approx i_{E_1}$ & $i_{C_2} \approx i_{E_2}$

now; $V_{C_1} = V^+ - R_C i_{C_1} = V_{C_2}$

$\Rightarrow V_{C_1} = V^+ - \frac{I_Q}{2} R_C = V_{C_2}$

The above result is obtained when operated in common mode (cm), i.e, $V_{B_1} = V_{B_2} = V_{cm}$ (say)



Since the transistors are biased at the same quiescent current, we have

$r_{\pi_1} = r_{\pi_2} = r_\pi$ & } mention in figure already

$g_{m_1} = g_{m_2} = g_m$

KCL for V_e ; $\frac{V_{\pi_1}}{r_\pi} + g_m V_{\pi_1} + g_m V_{\pi_2} + \frac{V_{\pi_2}}{r_\pi} = \frac{V_e}{R_o}$

we know that $g_m r_\pi = \beta$

$\Rightarrow V_{\pi_1}\left(\frac{1+\beta}{r_\pi}\right) + V_{\pi_2}\left(\frac{1+\beta}{r_\pi}\right) = \frac{V_e}{R_o}$

also; $\frac{V_{\pi_1}}{r_\pi} = \frac{V_{b_1} - V_e}{r_\pi + R_B}$ & $\frac{V_{\pi_2}}{r_\pi} = \frac{V_{b_2} - V_e}{r_\pi + R_B}$

$\Rightarrow (V_{b_1} + V_{b_2} - 2V_e)\left(\frac{1+\beta}{r_\pi + R_B}\right) = \frac{V_e}{R_o}$

$\Rightarrow V_e = \frac{V_{b_1} + V_{b_2}}{2 + \frac{r_\pi + R_B}{(1+\beta)R_o}}$ — (1)

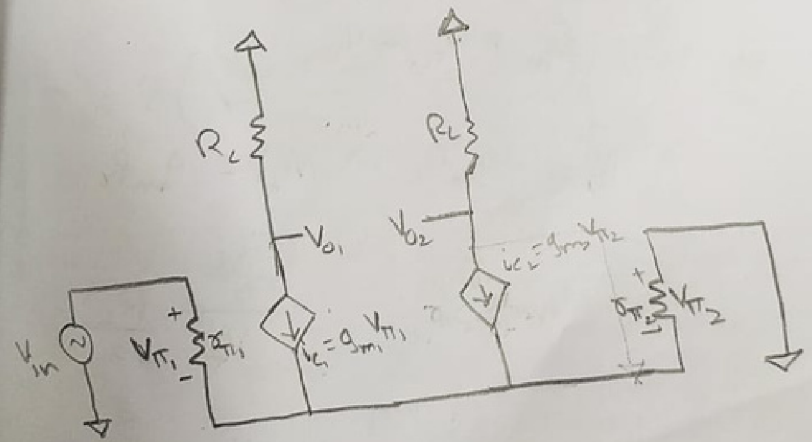
One-sided output at collector of Q_2, we have

$V_o = V_{c_2} = -(g_m V_{\pi_2})R_c = \frac{-\beta R_c (V_{b_2} - V_e)}{r_\pi + R_B}$ — (2)

putting (1) in (2)

$\Rightarrow V_o = \frac{-\beta R_c}{r_\pi + R_B}\left\{\frac{V_{b_2}\left[1 + \frac{r_\pi + R_B}{(1+\beta)R_o}\right] - V_{b_1}}{2 + \frac{r_\pi + R_B}{(1+\beta)R_o}}\right\}$

$= -\beta R_c \, (V_r$



By KVL, $V_{in} - V_{\pi_1} + V_{\pi_2} = 0$

$\Rightarrow \boxed{V_{in} = V_{\pi_1} - V_{\pi_2}}$ — (1)

also; $\boxed{V_{o_1} = -g_m V_{\pi_1} R_c \;\&\; V_{o_2} = -g_{m_2} V_{\pi_2} R_c}$

$\Rightarrow V_{o_1} - V_{o_2} = -g_m R_c (V_{\pi_1} - V_{\pi_2})$ — (2)

(1)&(2) $\Rightarrow V_{od} = -g_m R_c V_{in}$

$\Rightarrow \boxed{\frac{V_{od}}{V_{in}} = -g_m R_c}$

$\Rightarrow \boxed{A_d = -g_m R_c}$ $\boxed{r_\pi = \frac{\beta}{g_m}}$

we have $V_{in} = V_{\pi_1} - V_{\pi_2}$

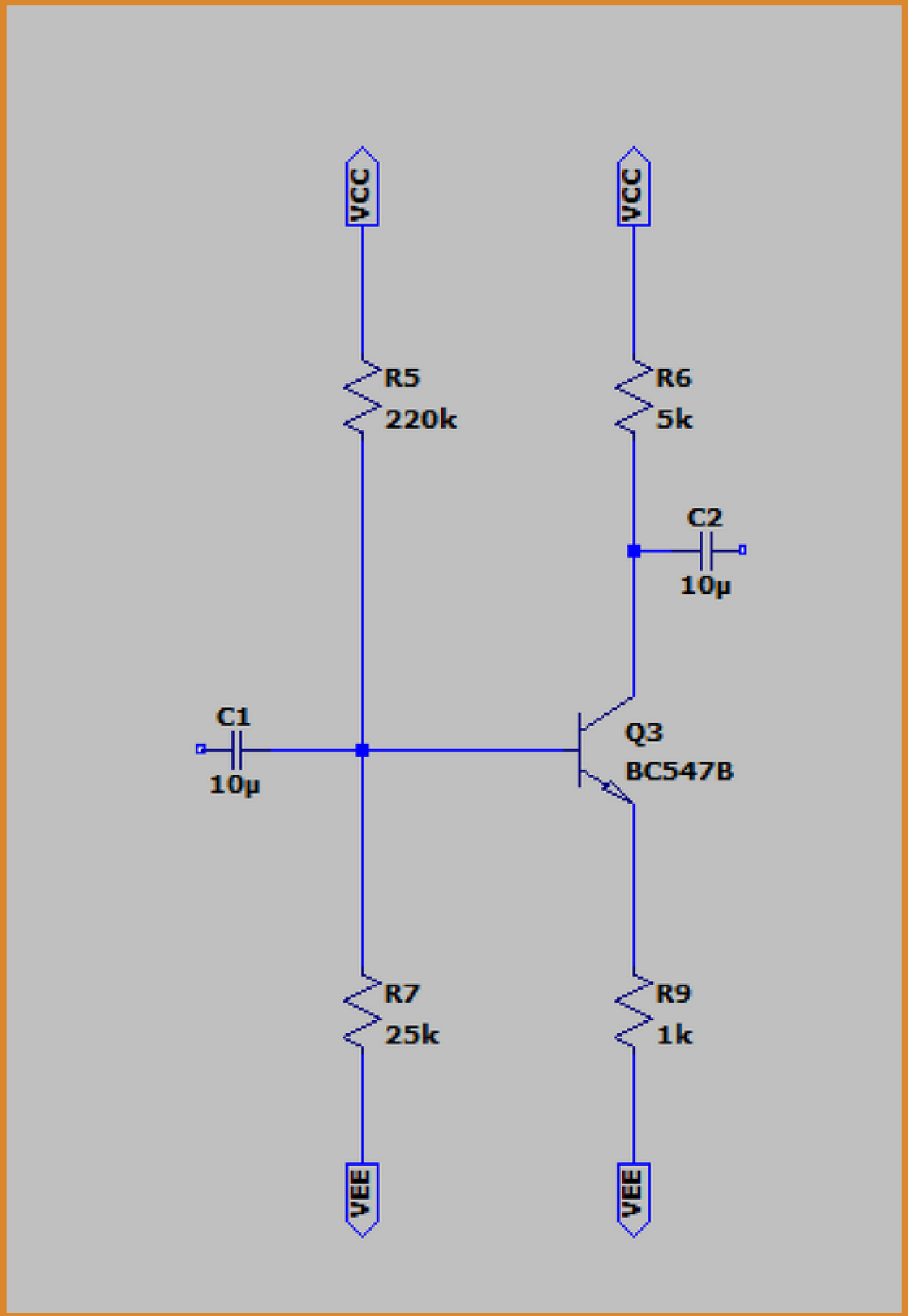
$\therefore A_d = -g_m R_c \Rightarrow |A_d| = g_m R_c$

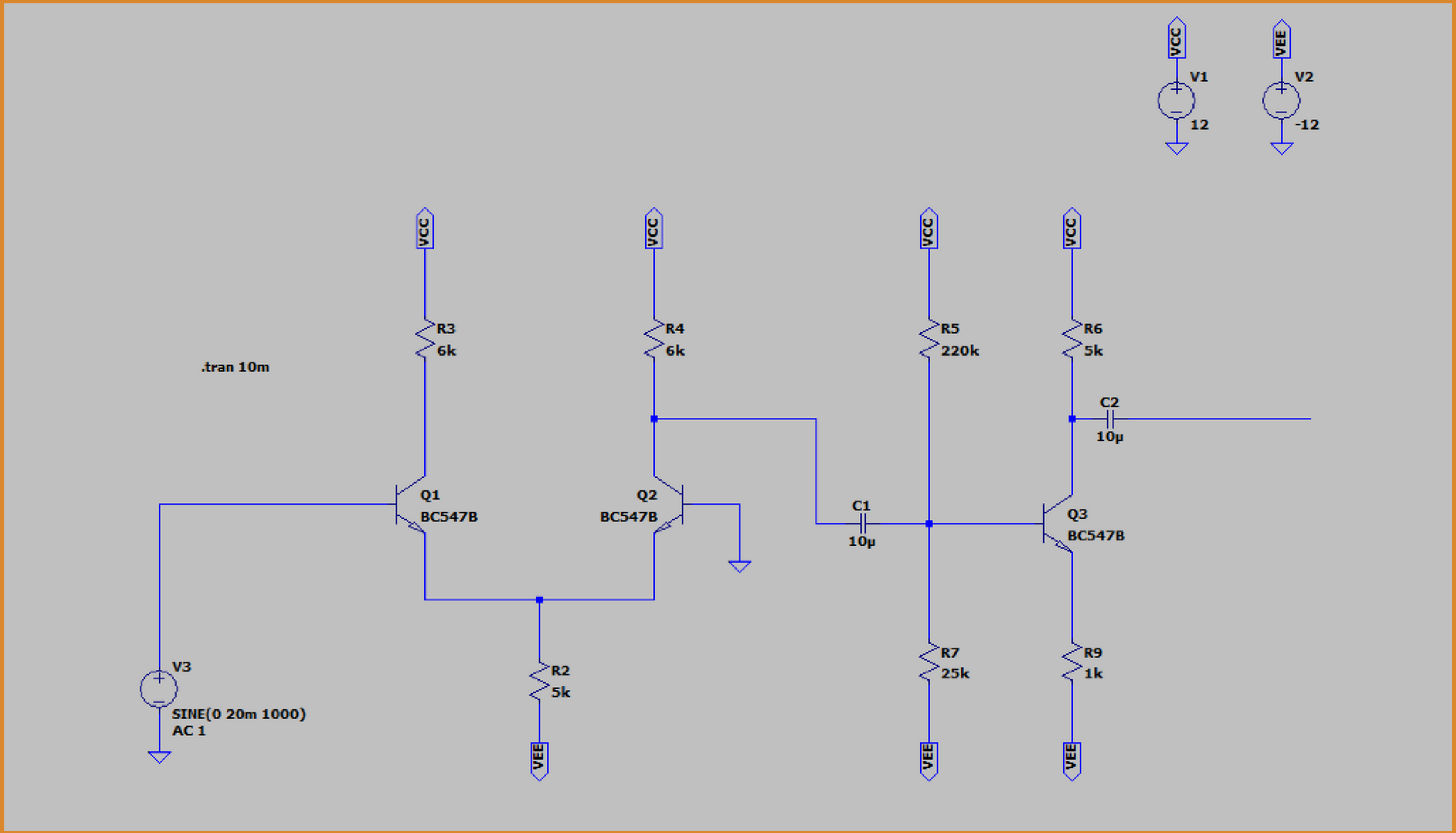
now, $g_m = \frac{I_{od}}{V_{in}} = \frac{\frac{I_{EE}}{2}}{V_T} \cdot \frac{R_c}{2}$

CE AMPLIFIER

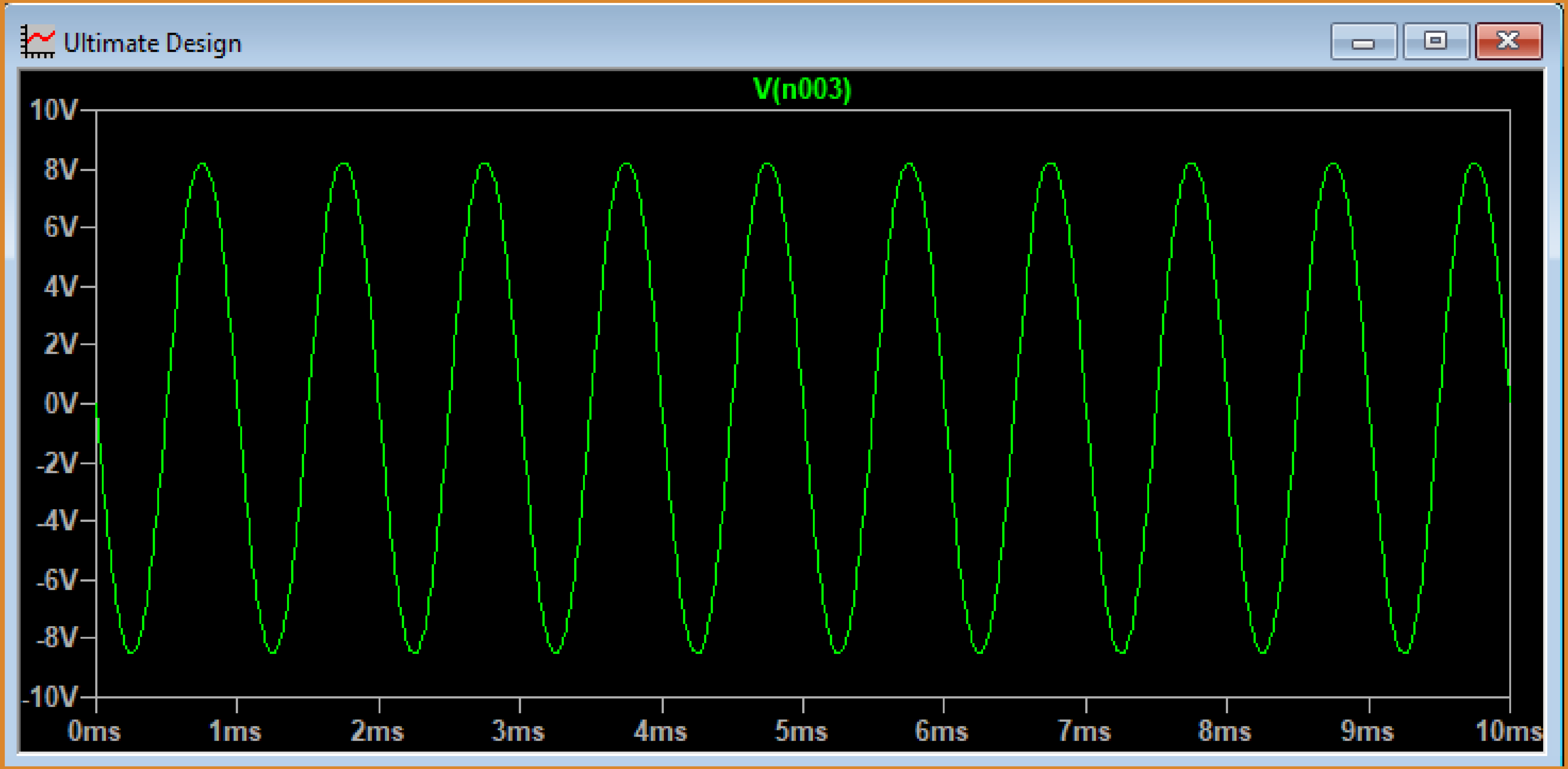
This is also known as the Gain stage, and the main amplification takes place here. Since from the first stage we have got a gain of 100 and out net gain is around 400, the objective of this stage is to provide us a further gain of 4. In order to achieve this, we use a CE amplifier circuit. The circuit has been implemented as follows (also includes the first stage). The working very much similar to that of a general CE amplifier.

CE amplifier individually and along with differential amplifier





The waveform for the simulation has been obtained as shown below. Clearly, the output generated is having a gain of around 4 (considering only CE amplifier stage) as the output of the pre-gain stage is around 2.2V, while that of this is around 8V



Stage-2 Calculations

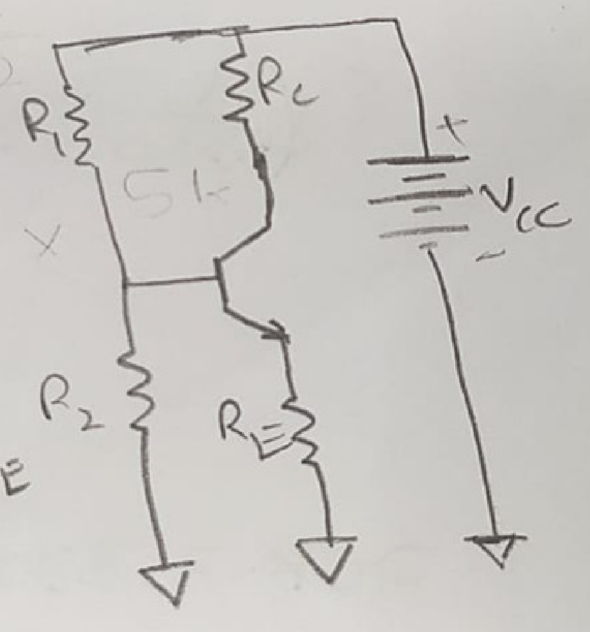
CE amplifier

$I_E = 5mA$; $\beta = 330$; $V_{BE} = 0.7V$

$$R_B = \beta\left(\frac{V_{BB} - V_{BE}}{I_E} - R_E\right)$$

$$A_V = \frac{R_C}{R_E} (= 8) \Rightarrow R_C = 8R_E$$

$$R_B = \left(\frac{1}{R_1} + \frac{1}{R_2}\right)^{-1}$$



$R_1 = 220k\Omega$. $R_2 = 22k\Omega$

now, $V_{BB} = \frac{V_{cc} R_2}{R_1 + R_2} = \frac{V_{cc} \times 22}{220 + 22}$

$= 12 \times 0.0909 \approx 1.09$

we know that

$$I_E = \frac{V_{BB} - V_{BE}}{\frac{R_B}{\beta} + r_{EE} + R_E}$$

$r_{EE} = 26mV / I_E = \frac{26mV}{5mA} = 5.2$

now, $R_B = \beta \left[\frac{V_{BB} - V_{BE}}{I_E} - r_{EE} + R_E \right]$

$\& \left(\frac{1}{220} + \frac{1}{22} \right)^{-1} = \left(\frac{1 + 10}{220k} \right)^{-1} = \frac{220k}{11}$

$= 20k$

$\therefore 20k = 330 \left[\frac{1.09 - 0.7}{5m} - 5.2 + R_E \right]$

$60.60 = 218.18 - 5.2 + R_E$

$\Rightarrow R_E = 218.18 - 5.2 - 60.6$

$\Rightarrow R_E = 152.38$

$\therefore R_C = 8 R_E = 1219$

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we know that gain $|A_d| = g_m R_C$

$\& \; g_m = \frac{I_{out}}{V_{in}} \Rightarrow \frac{(I_{EE}/2)}{V_T} \cdot \frac{R_C}{2}$

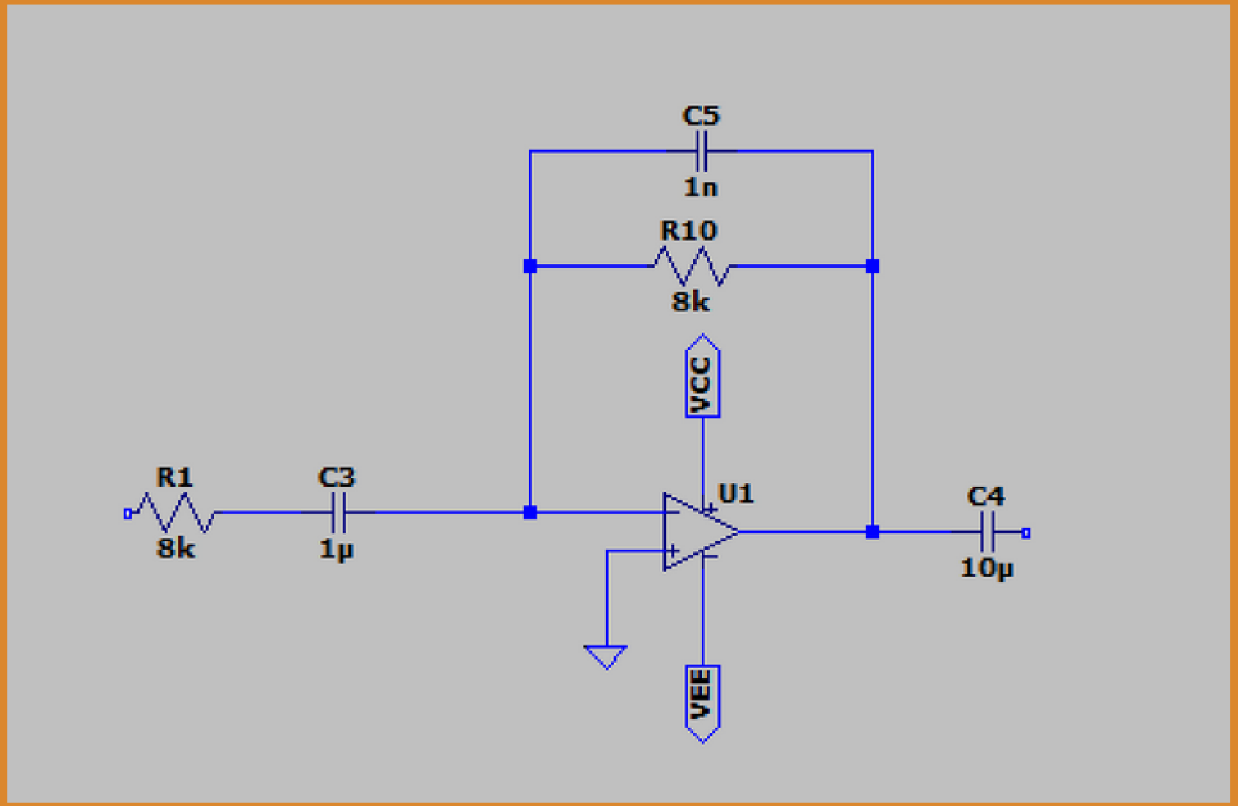
$\Rightarrow 50 \approx \frac{1mA}{26mV} \times \frac{R}{2}$

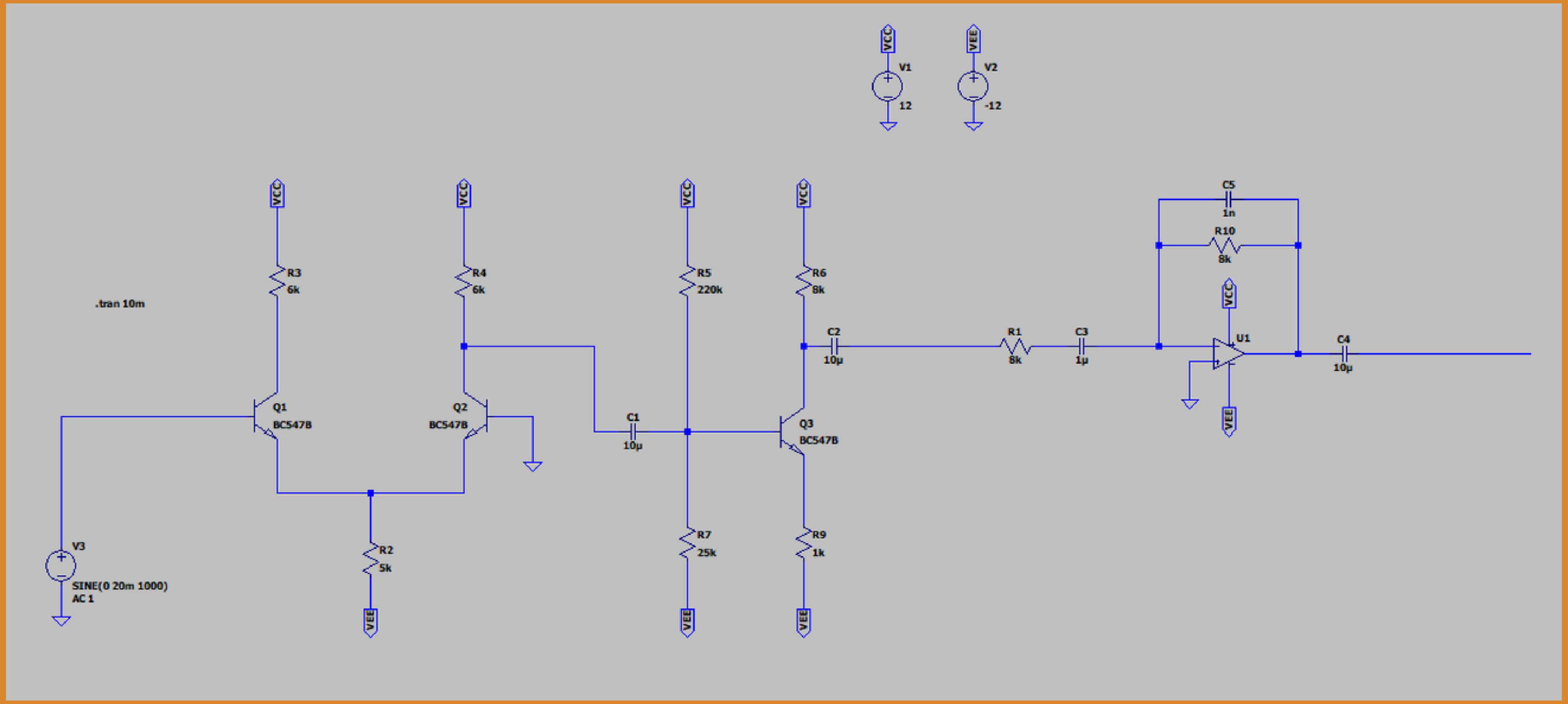
$\Rightarrow R = 2.6k\Omega$

BANDPASS FILTER

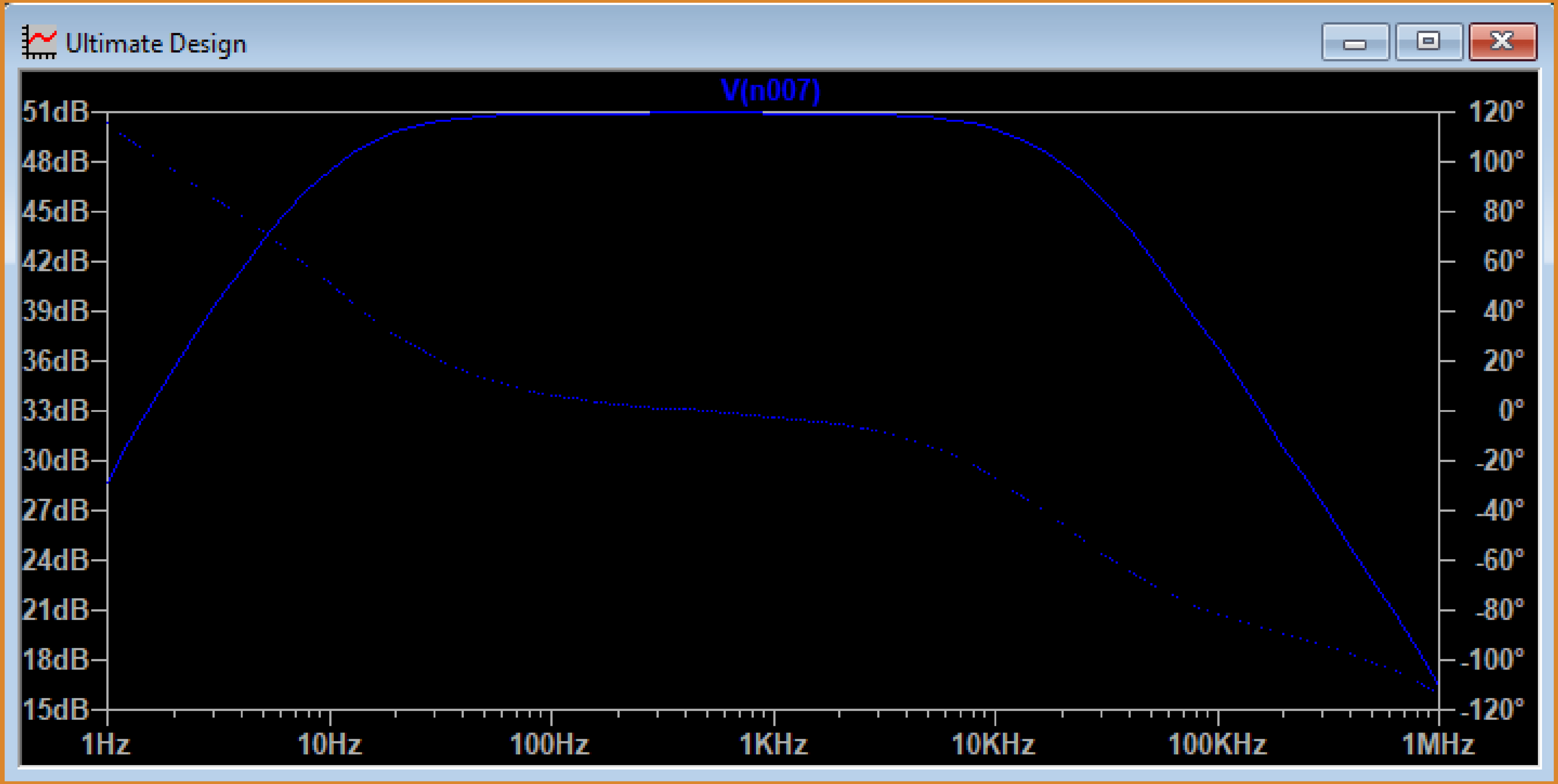
In our project, the signal requirements dictate that we restrict it to the 20 Hz to 20 kHz range. To achieve this, we opted for an active bandpass filter. Unlike passive filters, which can introduce attenuation, the active filter maintains a unity gain. Additionally, the active filter allows us to precisely control the cutoff frequencies, ensuring optimal performance. In order to have unity gain the ratio of the resistors used should be equal to one, i.e., they should have the same values.

Bandpass filter individually and along with the circuit.

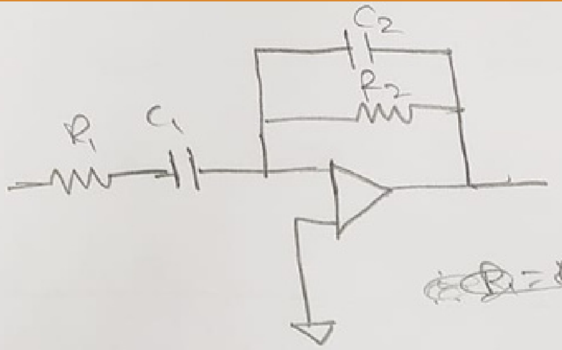




As we can see from the frequecy analysis, after the implementation of the bandpass filter, only the frequencies in the range 20Hz to 20kHz are being allowed and the rest of the frequencies are getting attenuated.



Stage-3 Calculations



$R_1 = R_2 = R$

$$f_{c_1} = \frac{1}{2\pi R C_1} \; ; \; f_{c_2} = \frac{1}{2\pi R_2 C_2}$$

$$\Rightarrow 20 = \frac{1}{2\pi R_1 C_1} \; ; \; 20k = \frac{1}{2\pi R_2 C_2}$$

$$\Rightarrow 20 = \frac{1}{2\pi R C_1} \; ; \; 20k = \frac{1}{2\pi R C_2}$$

$$\Rightarrow R C_1 = \frac{1}{40\pi} \; ; \; R C_2 = \frac{10^{-3}}{40\pi}$$

$$C_2 = 1nF \Rightarrow R = \frac{10^{-3}}{40\pi \times 10^{-9}} = \frac{10^5}{4\pi}$$

$$\Rightarrow R = 7{,}957.74\,\Omega$$

$$\Rightarrow 7.9 \times 10^3$$

$$\Rightarrow C_1 = \frac{10^{-4}}{7.957 \times 4\pi} = \frac{10^{-4}}{\cancel{\quad}} = 1\mu F$$

POWER AMPLIFIER

After achieving voltage amplification and filtering, the next critical step is driving the speaker. However, directly connecting the speaker to the filter output would result in attenuation of the gain, rendering it insufficient to drive the speaker effectively. To address this, we introduce a power amplifier.

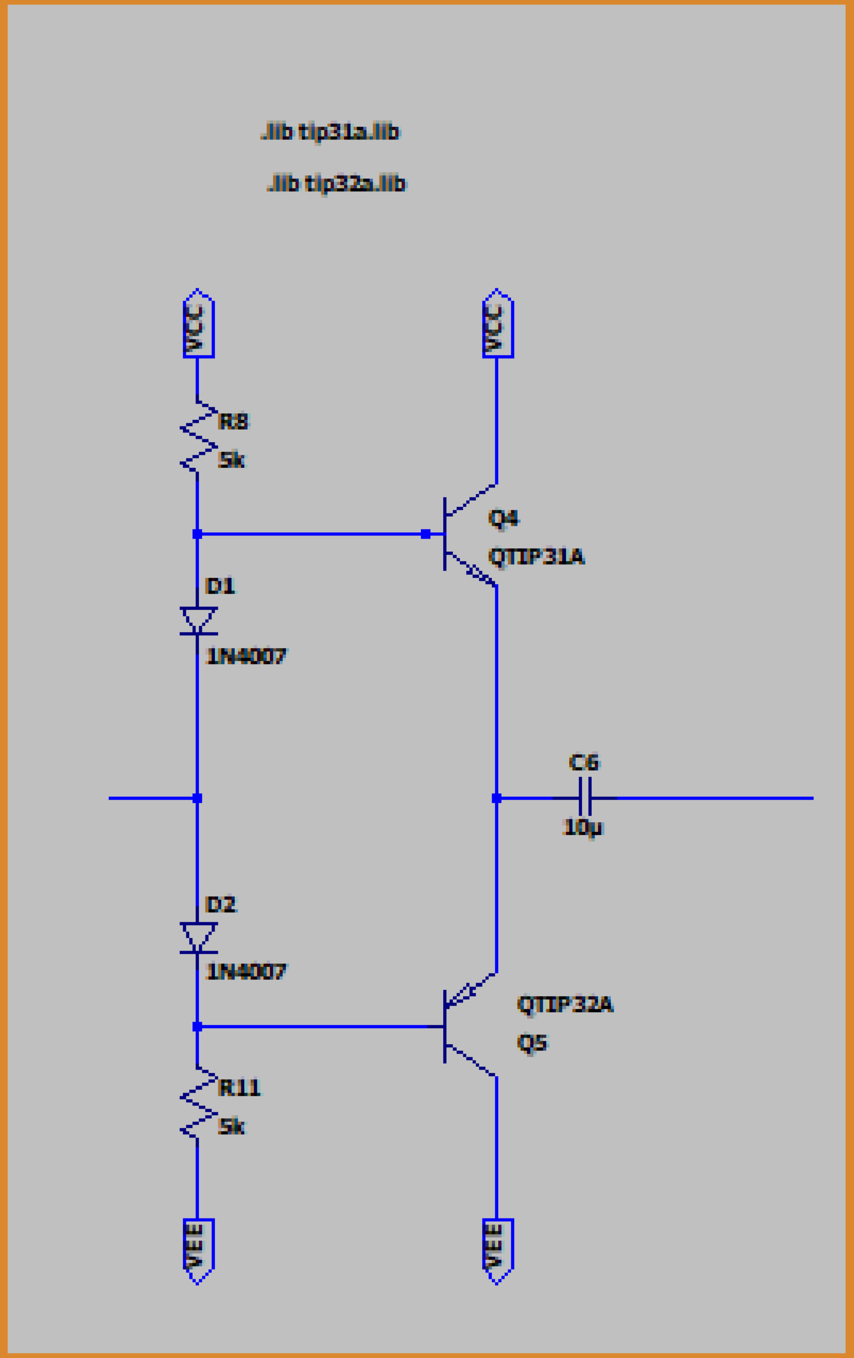
Here's why we choose a class AB power amplifier:

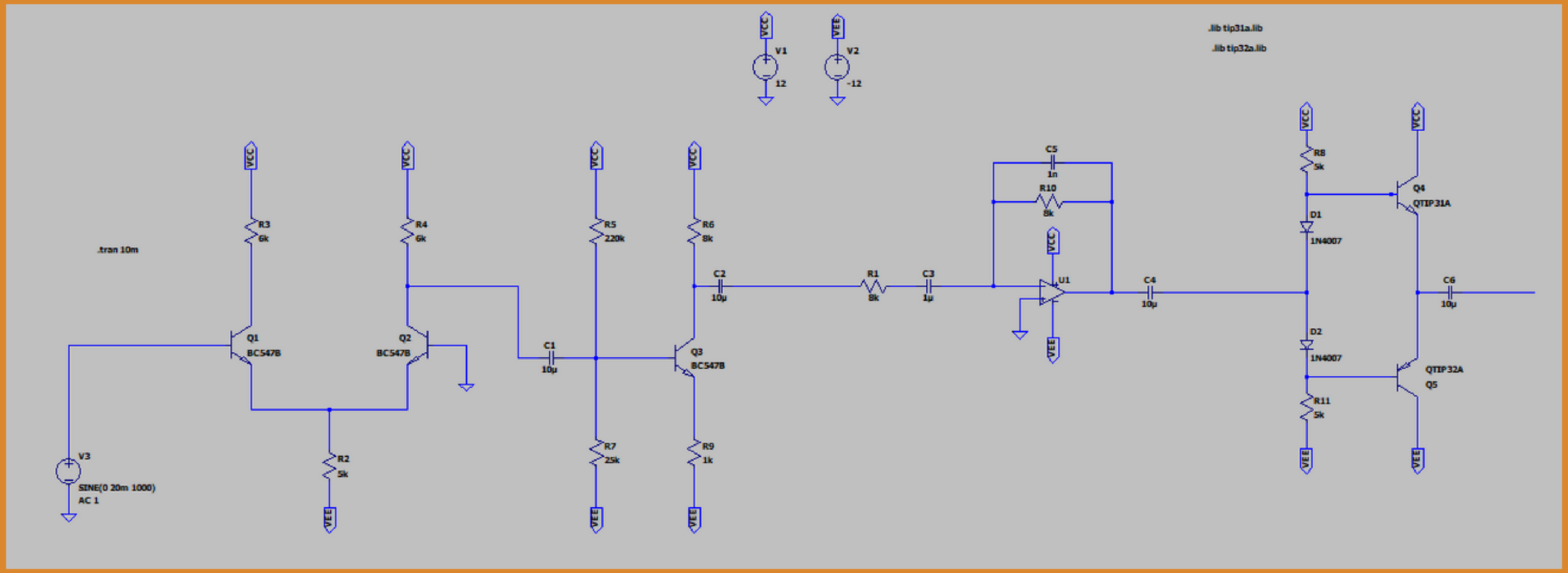
- Class-A Limitations: Class-A power amplifiers, while providing excellent linearity, struggle with handling large inputs due to their continuous operation and high-power dissipation.
- Class-B Distortion: Class-B power amplifiers operate in a push-pull configuration, but they suffer from distortion at low signal levels due to the crossover region where both transistors are partially conducting.

- Class-C Oscillations: Class-C amplifiers are efficient but prone to LC oscillations, leading to distortion and poor audio quality.
- Class AB Advantages:

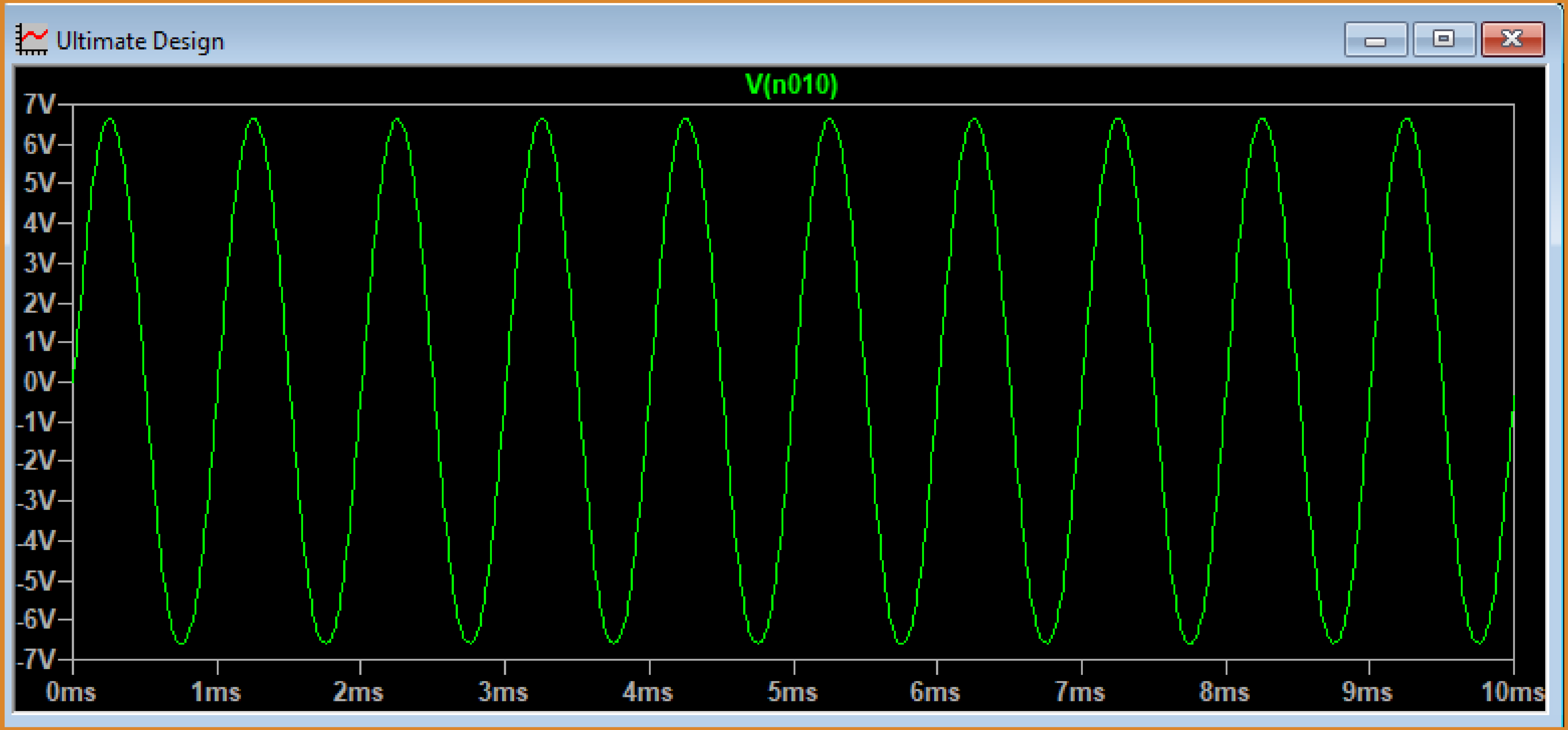
1. Low Distortion: Class AB strikes a balance by combining elements of both Class A and Class B. Its distortion remains below 0.1%.
2. High Sound Quality: The resulting sound quality is excellent, making it suitable for audio applications.
3. Linear Behavior: Class AB amplifiers exhibit linear behavior, crucial for faithful audio reproduction.
4. Crossover Elimination: Most importantly, they effectively eliminate crossover distortion, ensuring smooth transitions between the two halves of the push-pull output stage.
5. In summary, the class AB power amplifier provides the necessary power, minimal distortion, and superior sound quality, making it an ideal choice for driving speakers in our audio system.

Powe amplifier individually and with the rest of the circuit.





The simulation will show the similar result for the voltage, but actually what is happening is that the power of the signal is getting increased with the voltage remaining constant (meaning there is an increase in the current).



THANK YOU!

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