Audio Amplifier

EW-2

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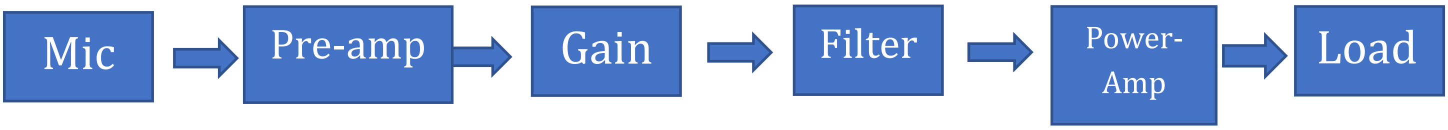
- The goal of audio amplifiers is to reproduce input audio signals at sound-producing output elements, with desired volume and power levels—faithfully, efficiently, and at low distortion.
- Audio frequencies range from about 20 Hz to 20 kHz, So the amplifier must have good frequency response over this range (less when driving a band-limited speaker, such as a *woofer* or a *tweeter*).
- Following are the stages of a general audio Amplifier:

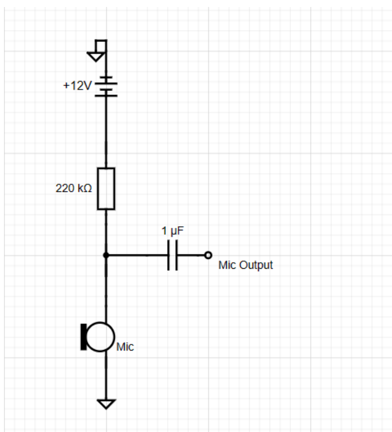


Components Used:

Component Name	Values
1. Resistor	100K, 120, 33k, 8.6k, 1MEG, 330, 4.7K, 75K, 13K, 10K, 120k
2. Capacitor	470u, 1u, 4.7u, 100p, 1n
3. BJT's	BC 547B, BC 557B, Tip 31C, Tip 32 C
4. Opamp	LM 741
5. Mic	
6. Input Source	+-13 V

Mic Stage

- A transducer which converts sound to voltage.
- Microphones produce very small ac signals that have to travel across long wires to the preamplifier; therefore, impedance is vital at this first stage to prevent signal loss



A Simple Mic Circuit

As we can see that this circuit consists of simple components like a resistor and capacitor, here resistor is used to limit current and the capacitor is responsible for amplifier gain which you can connect with this circuit to amplify the signals. This simple condenser mic circuit is to convert the acoustic sound signal into an electric audio signal.

Pre-Amplifier Stage

- **Preamplifier** is a type of electronic amplifier. It doesn't have enough power to feed speakers. Rather a preamplifier amplifies weak signals, for example from a microphone, and removes noise for electronic processing or distribution.

- Preamp boosts a low-level signal, making it line level.

- A typical sensor circuit produces an output voltage between nodes A and B (see Fig. 1), where Vc is called the "common-mode" voltage and Vd the "difference-mode" or "differential" voltage. The common-mode voltage is a result of the biasing arrangement used within the sensor

- We don't require common mode voltage, so we use differential amplifier circuit as pre-amp to amplify differential mode voltage which is the quantity of actual interest.

- The output of differential amplifier is given by:

$$V_{out} = A_d V_{id} + A_C V_{ic}$$

- where Ad is the differential gain, and Ac is the common-mode gain. A good differential amplifier should reject Vic entirely, i.e., it should have Ac = 0. In reality, Ac for a differential amplifier is small but finite, and a figure of merit called the "Common-Mode Rejection Ratio" (CMRR) is used to indicate the effectiveness of the amplifier in rejecting common-mode inputs. The CMRR is defined as

$$CMRR = \left|\frac{A_d}{A_c}\right|.$$

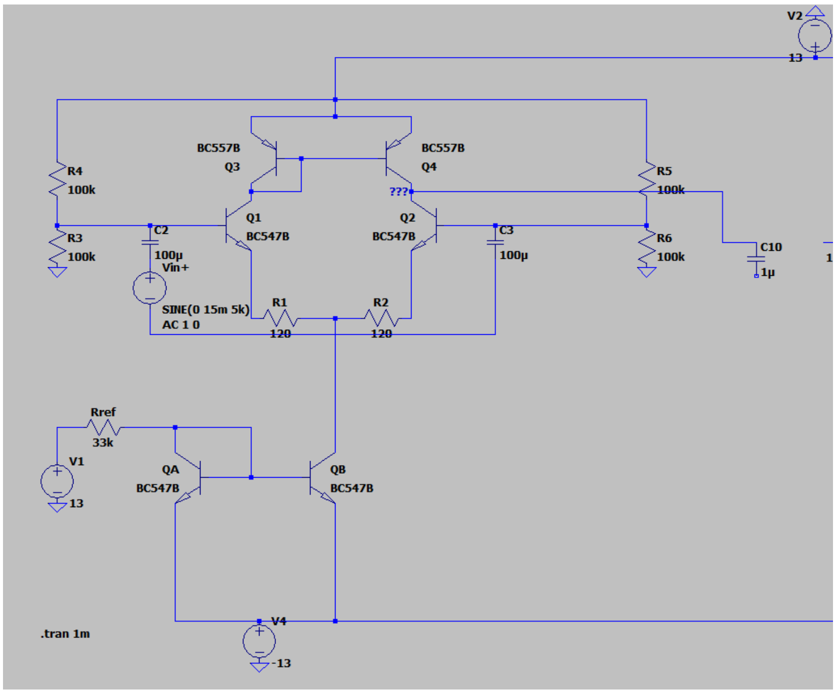
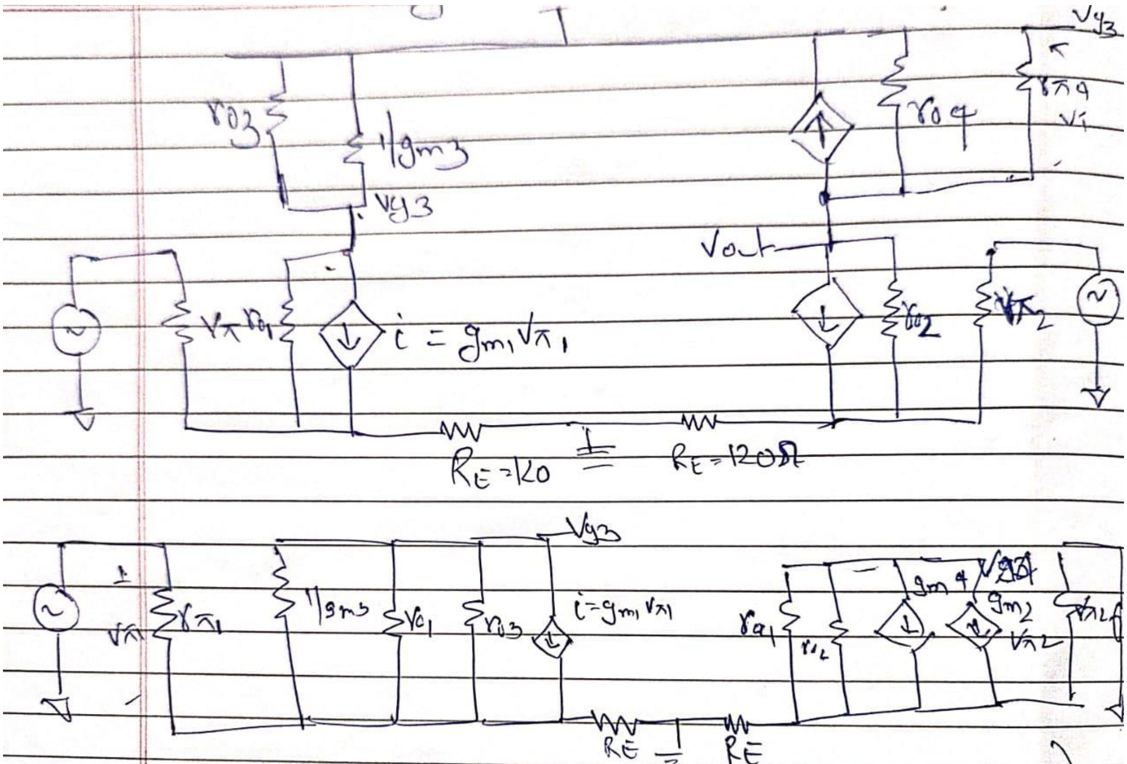


Fig: Pre-Amp Circuit

AC Analysis:

For Small Signal, Point P acts as a virtual ground

So small signal is:



$$V_{out} = (r_{o2} \| r_{o4})(g_{m4} v_{\pi 4} + g_{m2} v_{\pi 2})$$

Since the transistors are matched, we can say

$$V_{out} = (ro_2 \parallel ro_4)(gm_4 v\pi_4 + gm_2 v\pi_2)$$

From Common Emitter- Emitter bias and half circuit we can say:

$$V\pi = \frac{V_{in}}{(1 + gmR_E)}$$

Since all the Transistors are matched and $V_{in} = \frac{V_{id}}{2}$

$$V_{out} = \frac{r_0 gmV_{id}}{4(1 + gmR_E)}$$

, $\beta = 327, r_0 = \frac{Va}{I_C}$, $g_m = \frac{I_C}{V_T} = \frac{393uA}{26mV} = 0.015$

$$\boldsymbol{A_v} = \frac{20.1}{\frac{1}{0.015} + 120} = \boldsymbol{237.31}$$

$$\boldsymbol{R_{out} = r_o = 20\Omega}$$

Ideally, we want common mode gain to be zero but, that is not the case, so we calculate the ration between gain of differential input and differential output to calculate CMRR. The more the CMRR, better is the noise suppression in the differential amplifier.

$$\boldsymbol{A_d = 47.02\ dB}$$
$$\boldsymbol{A_c = -70\ dB},$$

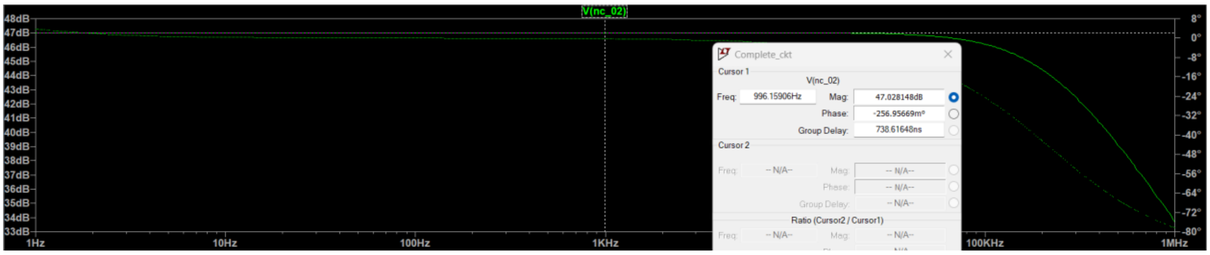
$$\therefore \boldsymbol{CMRR = 117.02}$$

Current Mirror is used to bias the circuit.

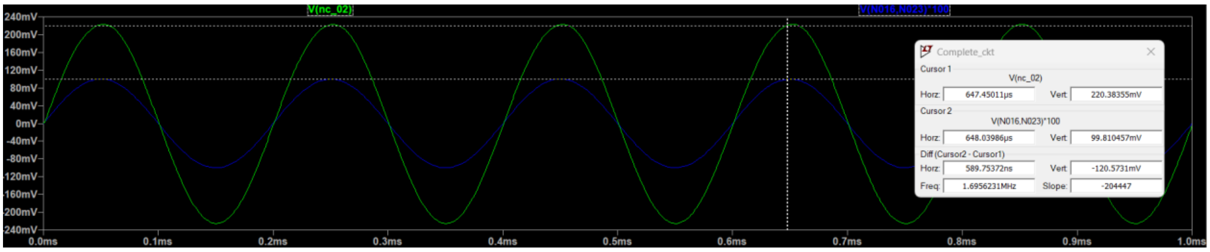
$$I_C = \frac{26}{2 * 33k} = 393uA$$

Current mirror provides the desired bias current and simultaneously achieves a high CMRR.

Simulation:



- The gain in simulation is **47dB,** which is close to **223**



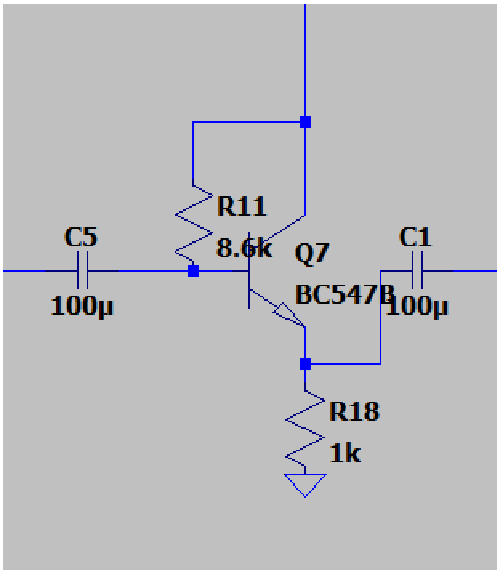
Gain when rest of the circuit is attached: *39.1*

Summary:

Gain	**231**
R_{out}	$\mathbf{20.1\Omega}$

Buffer Stage

The gain obtained in the differential amplifier stage is affected by the stages ahead, because of the changes in current drawn and reactance of further stages. To make the differential amplifier stage independent of the other stages, we can use a buffer stage, also called a **Source Follower.** The gain of a source follower is ideally equal to 1, and has a high input resistance, and a low output impedance (like a voltage source).



DC Analysis:

$$V_{CC} = 13V$$

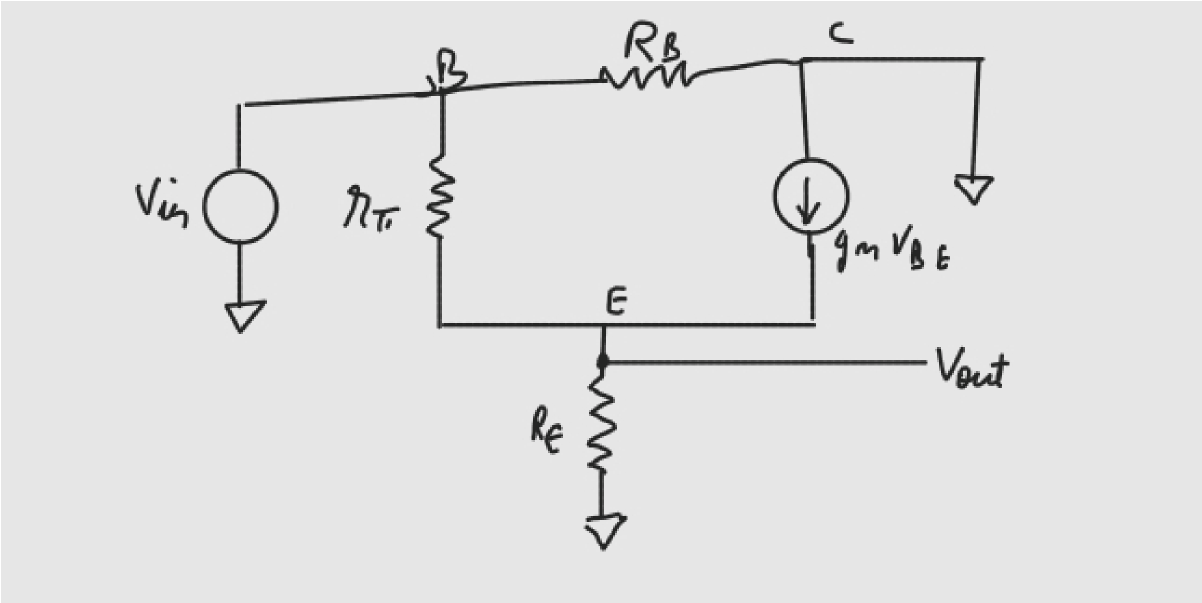
$$V_{BE} = V_{CC} - I_C * R_E$$

Assuming $I_B \to 0, V_B \approx V_{CC}$ and in forward bias of base and emitter, $V_{BE} \approx 0.7V$

$$I_C = \frac{V_{CC} - V_{BE}}{R_E} = \frac{12.3}{1000} = 12.3mA$$

AC Analysis:

The circuit above is the source follower circuit used. Small signal model of the source follower is (Ignoring) the early effect:



Gain

Therefore, gain can be derived using KCL at E:

$$\frac{\{V_{BE}\}}{\{r_\pi\}} + g_m * V_{BE} = \frac{V_{out}}{R_E}$$

$$V_{BE}\left(\frac{1}{r_\pi} + g_m\right) = \frac{V_{out}}{R_E}$$

$$V_{BE} = V_{out} - V_{in} \; and \; g_m * r_\pi = \beta$$

$$A_v = \frac{R_E(1+\beta)}{r_\pi + R_E(1+\beta)}$$

$$A_v = \frac{R_E}{\frac{r_\pi}{1+\beta} + R_E} \approx \frac{R_E}{\frac{r_\pi}{\beta} + R_E}$$

Here, $\beta = 327, r_\pi = \frac{\beta}{g_m}, g_m = \frac{I_C}{V_T} = \frac{12.3mA}{26mV} = 0.473$

$$\therefore r_\pi = \frac{327}{0.473} \approx 691\Omega$$

$$A_v = \frac{1000}{\frac{691}{327} + 1000} = 0.998$$

$$\boldsymbol{A_v = 0.998}$$

Input Impedance:

Input impedance can here be similarly calculated, to get: $R_{in} = \left(r_\pi + R_E(1+\beta)\right)||R_C$

Where, $r_\pi = 691\Omega, R_E = 1k\Omega, \beta = 327, g_m = 0.473$

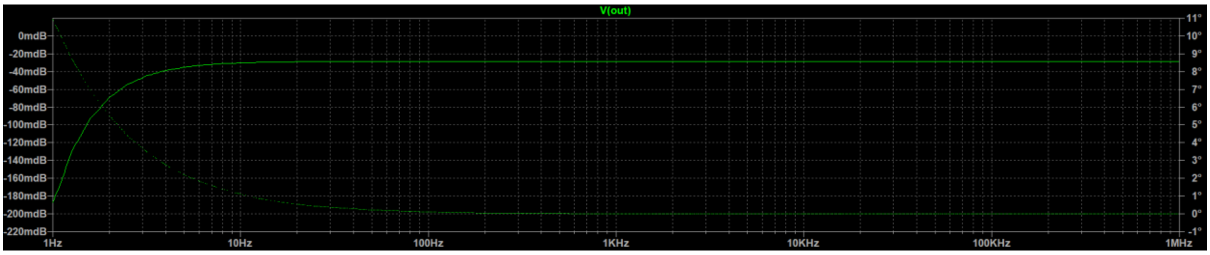
$$\boldsymbol{R_{in} = 8380.7\ \Omega}$$

Output Impedance:

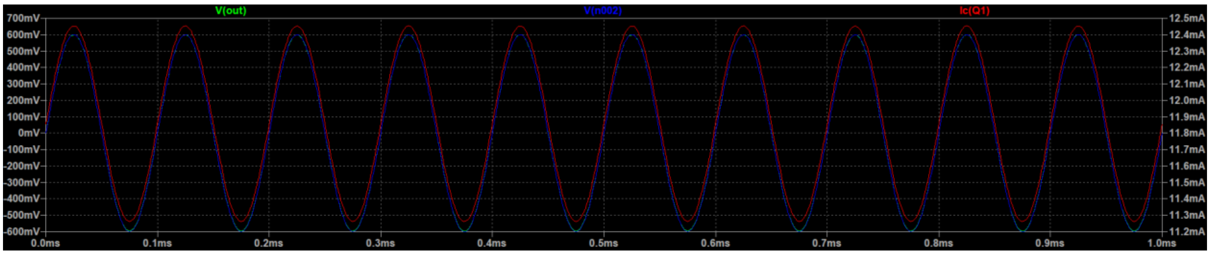
Output impedance is calculated using: $R_{out} = \frac{1}{g_m}||R_E$

$$\boldsymbol{R_{out} = 2.11\ \Omega}$$

Simulation:



- The gain in simulation is **-20mdB,** which is close to 1



- The output and input coincide, and the current is centred around **12mA**

Summary

Gain	**0.998**
$\boldsymbol{R_{in}}$	$\boldsymbol{8.3k\Omega}$
$\boldsymbol{R_{out}}$	$\boldsymbol{2.11\Omega}$

∴We see that the input impedance is high and the output impedance is small and gain is 1, so the previous stage sees this as a voltmeter, and the next stage sees this as a voltage source, and the gain of either side is unaffected.

Gain Stage

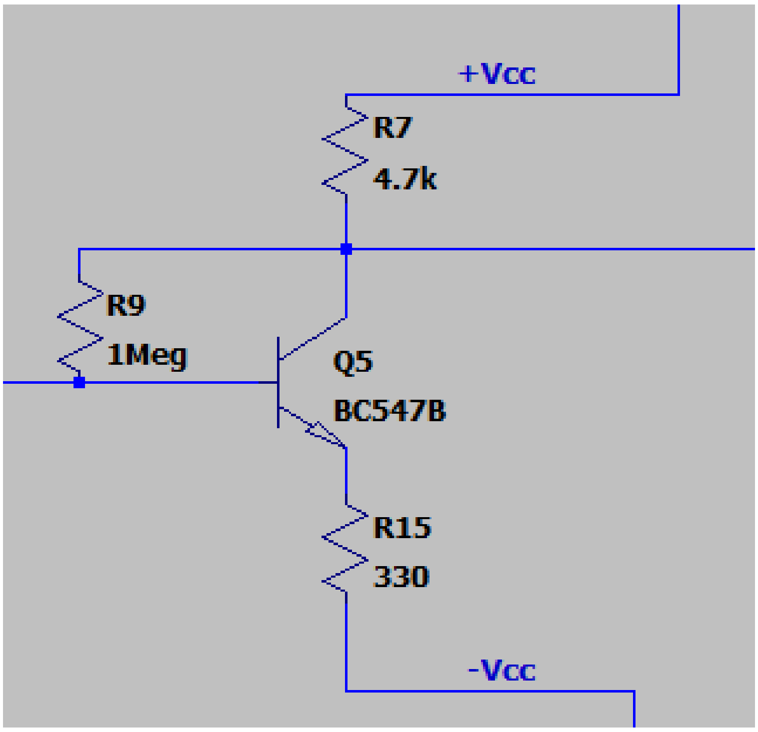
Gain stage here is used to increase the total gain obtained to around 500. For this, we use a **CE Amplifier** setup, with **emitter degeneration and self-biasing**. The CE amplifier is simple amplifier circuit that gives voltage gain, with little to no current gain. The input is provided at the Base, and the output is taken from the Collector.

The resistor at the emitter is improves the linearity of the circuit. It also **increases the input impedance**, which is desirable, as explained in the buffer stage.

Self-Biasing:-

We use self-biasing to bias the CE amplifier, which provides a feed back loop, to maintain the BJT in forward active region. When V_{out} increases, V_{BE} increases as V_B increases, because $V_B \approx V_C \because I_B \approx 0$, so $I_C\ increases$, which reduces $V_{out} = V_{cc} - I_C R_C$, making a **negative feed back loop.**

Circuit Diagram



DC Analysis:

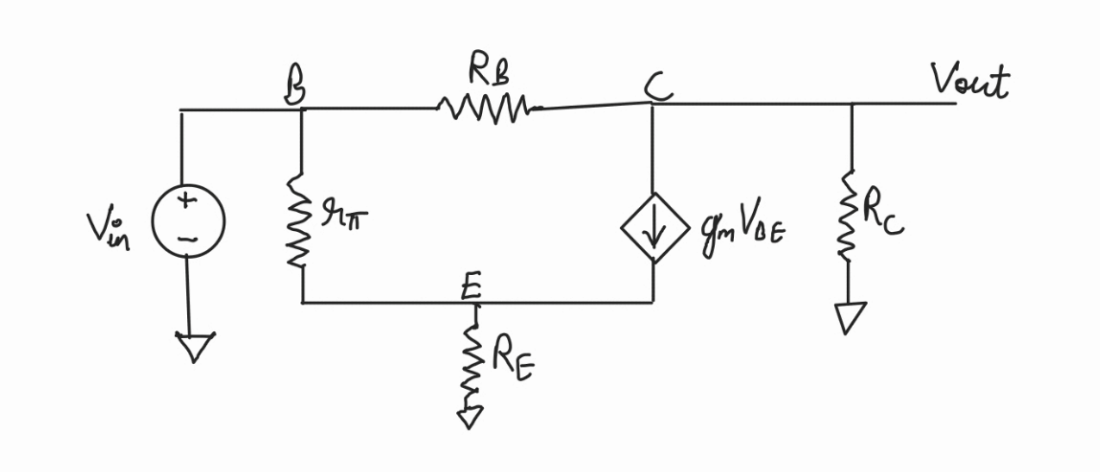
$$V_{BE} = V_B - I_C R_E + V_{cc}$$
$$V_B \approx V_C = V_{cc} - I_C R_C$$

$V_{BE} \approx 0.7V$ in forward active region

$$0.7 = 2 * V_{cc} - I_C(R_E + R_C)$$
$$I_C = \frac{25.03}{12330} = 2.051mA$$

AC Analysis:

Small signal model:



Gain:

KCL at C:

$$\frac{V_{out}}{R_C} + g_m V_{BE} + \frac{V_{out} - V_{in}}{R_B} = 0$$

$$R_B = 1e6 \Rightarrow \frac{V_{out} - V_{in}}{R_B} \approx 0$$

$$V_E = I * R_E$$

$$V_E = \left(g_m V_{BE} + \frac{V_{BE}}{r_\pi}\right) * R_E$$

$$V_{BE} = V_{in} - V_E$$

$$V_{BE} = \frac{V_{in}}{1 + \left(g_m + \frac{1}{r_\pi}\right) . R_E}$$

$$\Rightarrow \frac{V_{out}}{V_{in}} = A_v = -\frac{g_m R_C}{1 + \left(g_m + \frac{1}{r_\pi}\right) . R_E}$$

$$g_m \gg \frac{1}{r_\pi}$$

$$A_v = -\frac{R_c}{\frac{1}{g_m} + R_E}$$

$$A_v = -\frac{4700}{330 + 2.12} \approx 14.1$$

NOTE: After adding the filter, there is a drop in the gain of the circuit, because of the reactance of the filter stage.

Input Impedance:

Input impedance for Common Emitter with emitter degeneration comes to be:

$$R_{in} = r_\pi + (1 + \beta) * R_E$$

Here, $\beta = 327, R_E = 330\Omega, r_\pi = 691\Omega$

$$R_{in} = 691 + (328) * 330$$
$$R_{in} = 108931\Omega = 108.9k\Omega$$

$$\boldsymbol{R_{in} = 108.9k\Omega}$$

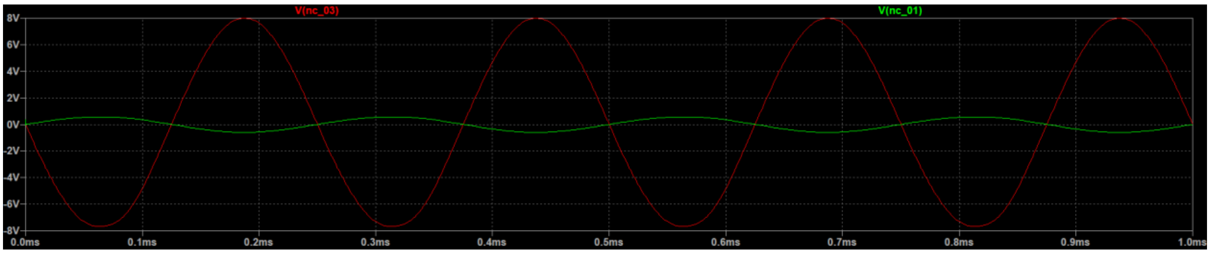
Output Impedance

If Early effect is neglected, the emitter resistance does not affect the output resistance, and is equal to:

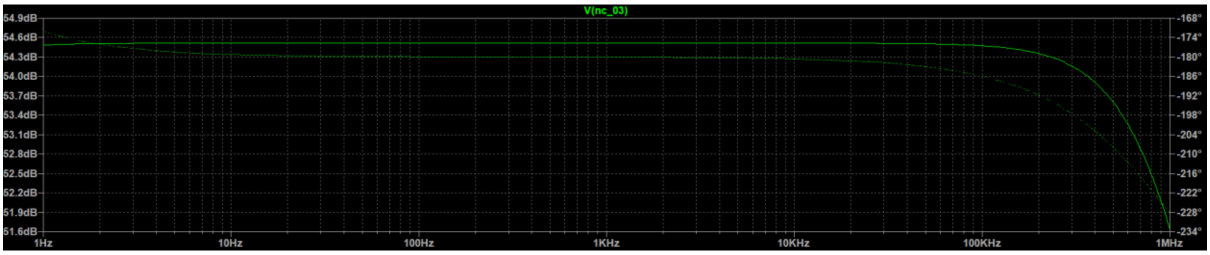
$$R_{out} = R_C$$
$$\boldsymbol{R_{out} = 4.7k\Omega}$$

Simulation:

Transient:



AC analysis:



We observe that the gain is **54.5 dB,** of the circuit, up to the gain stage, which is about **530** gain value.

Summary

Gain	**14.1**
$\boldsymbol{R_{in}}$	$\boldsymbol{108.9k\Omega}$
$\boldsymbol{R_{out}}$	$\boldsymbol{4.7k\Omega}$

∴We see that the input impedance is high and the output impedance is small and gain is high.

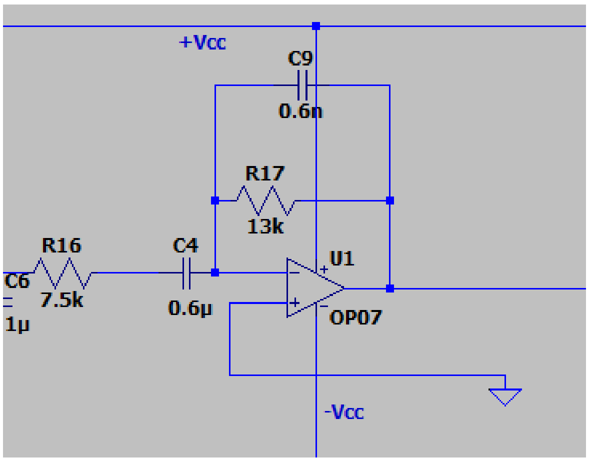
After this stage, we reach the required gain of more than 500, while also not cutting off the frequencies in the range of 20-20kHz.

Filter Stage:

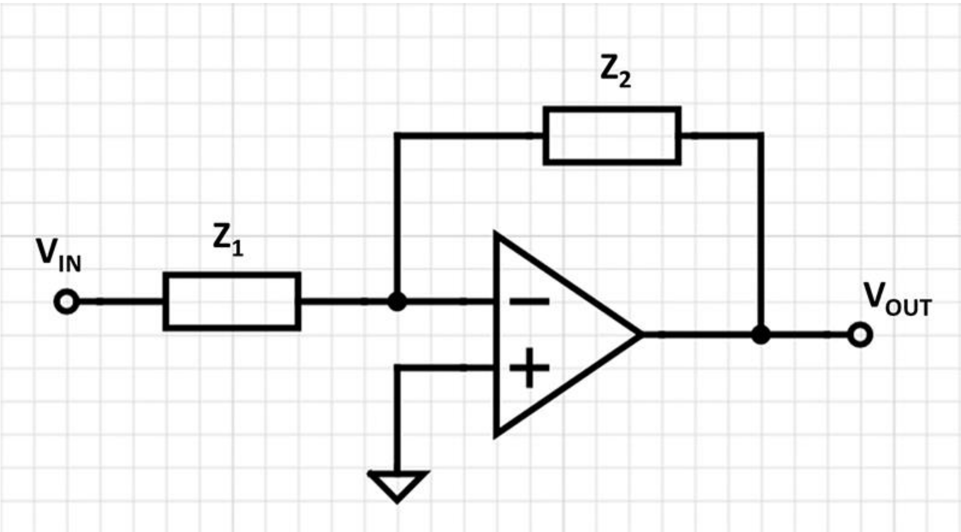
The filter stage is used to filter out the frequencies that are not audible to human ears, i.e. frequencies below **20Hz** and above **20kHz.** To this effect, we use an **Inverting Band Pass Active Filter**, which uses an Op-Amp with a low pass and high pass filters, to make a band pass filters, with lower 3dB cut off at 20Hz and the higher 3 dB cut off at 20kHz. This helps to reduce the wastage of power, which would have been otherwise used to amplify noise in these inaudible frequency ranges.

The reason for using and active filter, is that if we used a passive filter, the band pass frequency would be affected by the resistance of the load, which would start acting like a high pass filter, shifting the cut off region. Using the Op Amp, we make the filter active, whose pass band width is independent of load.

Circuit:



Transfer Function:



$$A_v = -\frac{Z_2}{Z_1}$$

$$Z_2 = \frac{R_2}{j\omega C_2\left(R_2 + \frac{1}{j\omega C_2}\right)} = \frac{R_2}{j\omega R_2 C_2 + 1}$$

$$Z_1 = R_1 + \frac{1}{j\omega C_1} = \frac{j\omega R_1 C_1 + 1}{j\omega C_1}$$

$$A_v = -\frac{R_2 * j\omega C_1}{(j\omega R_2 C_2 + 1) * (j\omega R_1 C_1 + 1)}$$

$$R_2 C_2 = \frac{1}{\omega_H}; R_1 C_1 = \frac{1}{\omega_L}$$

$$A_v = -\frac{R_2 * j\omega C_1}{\left(\frac{j\omega}{\omega_H} + 1\right) * \left(\frac{j\omega}{\omega_L} + 1\right)}$$

$$A_v = -\frac{j\omega}{\omega_L}\left(\frac{R_2}{R_1}\right) \cdot \frac{1}{\left(\frac{j\omega}{\omega_H} + 1\right) * \left(\frac{j\omega}{\omega_L} + 1\right)}$$

$$|A_v| = \frac{\omega R_2}{\omega_L R_1} \cdot \frac{1}{\sqrt{\left(\frac{\omega^2}{\omega_H^2} + 1\right) * \left(\frac{\omega^2}{\omega_L^2} + 1\right)}}$$

Poles:

$$\boldsymbol{P_1 = j\omega_L}$$
$$\boldsymbol{P_2 = j\omega_H}$$

Zeros:

$$\boldsymbol{Z_1 = 0}$$

Max Gain:

$$A_v Max = -\frac{R_2}{R_1} = 1.6$$

- This gain is used to compensate for the loss in gain caused due to attaching the filter.

Cut-Off Frequency:

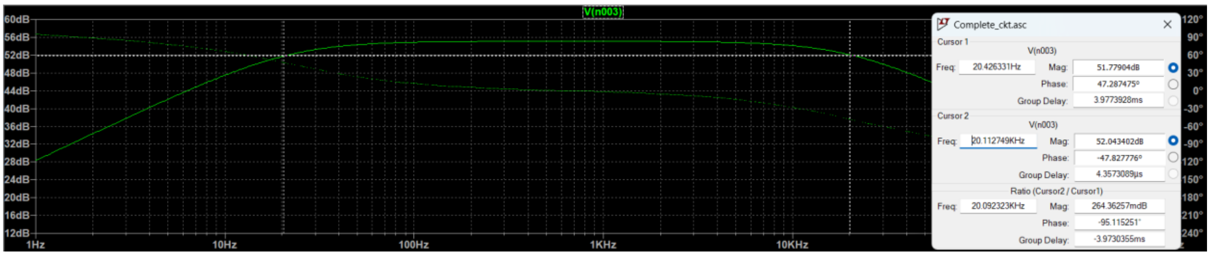
$$\omega_L = \frac{1}{R_1 C_1} \Rightarrow f_L = \frac{1}{2\pi R_1 C_1} = \frac{1}{2\pi * 7500 * 0.6e - 6}$$

$$f_L \approx 20Hz$$

$$\omega_H = \frac{1}{R_2 C_2} \Rightarrow f_H = \frac{1}{2\pi R_2 C_2} = \frac{1}{2\pi * 13000 * 0.6e - 9}$$

$$f_H \approx 20kHz$$

Simulation:



Power Stage:

- The power amplifier amplifies the Power of the signal to drive loads of output devices like speakers and headphones.

- Class B amplifier is a type of power amplifier where the active device (transistor) conducts only for one half cycle of the input signal. That means the conduction angle is 180° for a Class B amplifier. Since the active device is switched off for half the input cycle, the active device dissipates less power and hence the efficiency is improved. Theoretical maximum efficiency of Class B power amplifier is 78.5%.

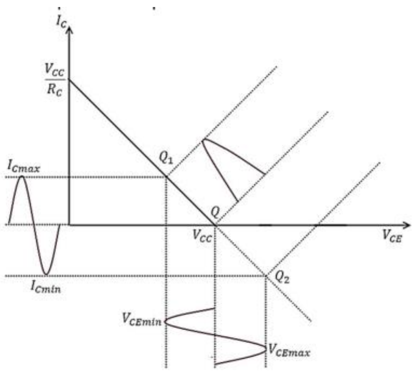
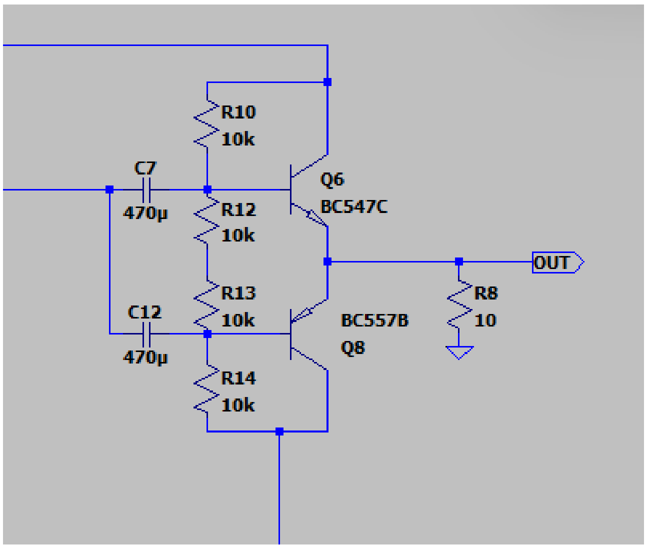


Fig.- Output characteristics Curve



- To realize a practical Class B amplifier is to use a pair of active devices (transistors) arranged in push-pull mode where one transistor conducts one half cycle, and the other transistor conducts the other half cycle

- The output from both transistors are then combined to get power amplified replica of the input.

$$Current\ Gain = \frac{I_c}{I_b} = \beta_{ac}\ ;\ \ C.G_{max} = 650$$

$$I_b = \frac{V_{bb} - V_{be}}{R_B}$$

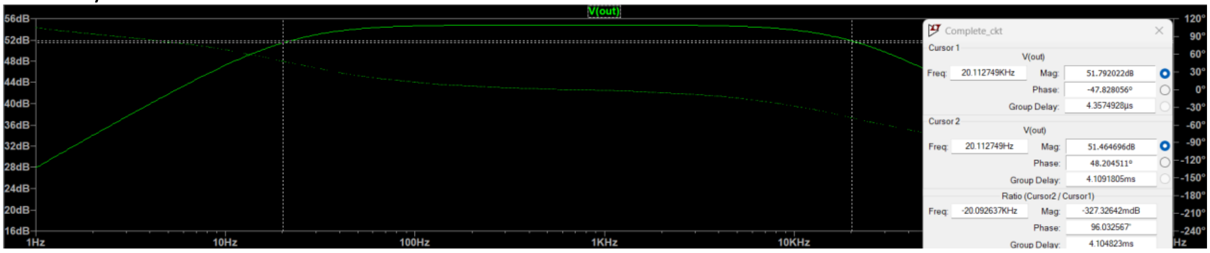
Final output:

- V_{in} = sine wave of 15mV @ 5kHz
  Load = 10 ohms

$$P_{avg} = \frac{6.3}{2} = 3.15\,W$$

$$A_v = \frac{V_{out_{max}}}{V_{in_{max}}} = \frac{7.7}{0.015} = 513$$

AC Analysis: -3db cut-off at: 20.1KHz and 20.1Hz

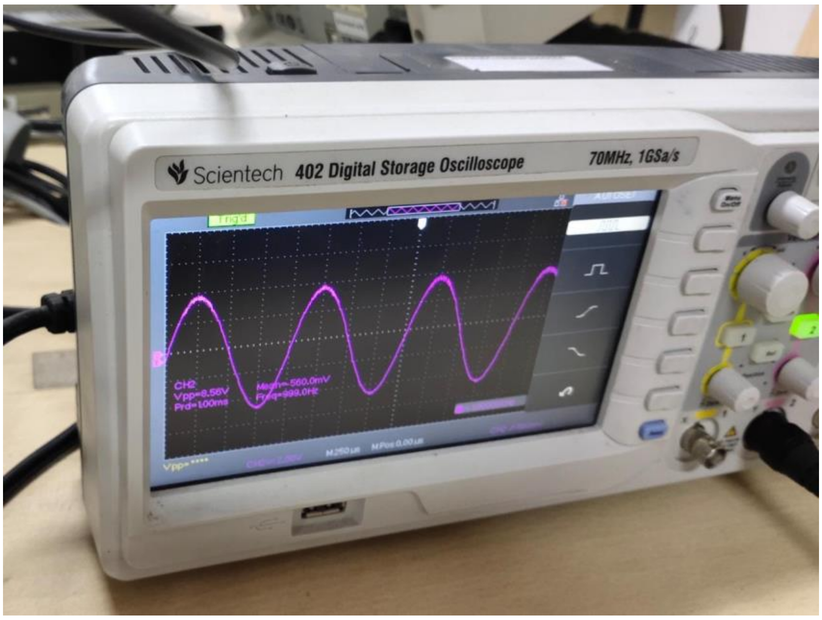


Hardware output:

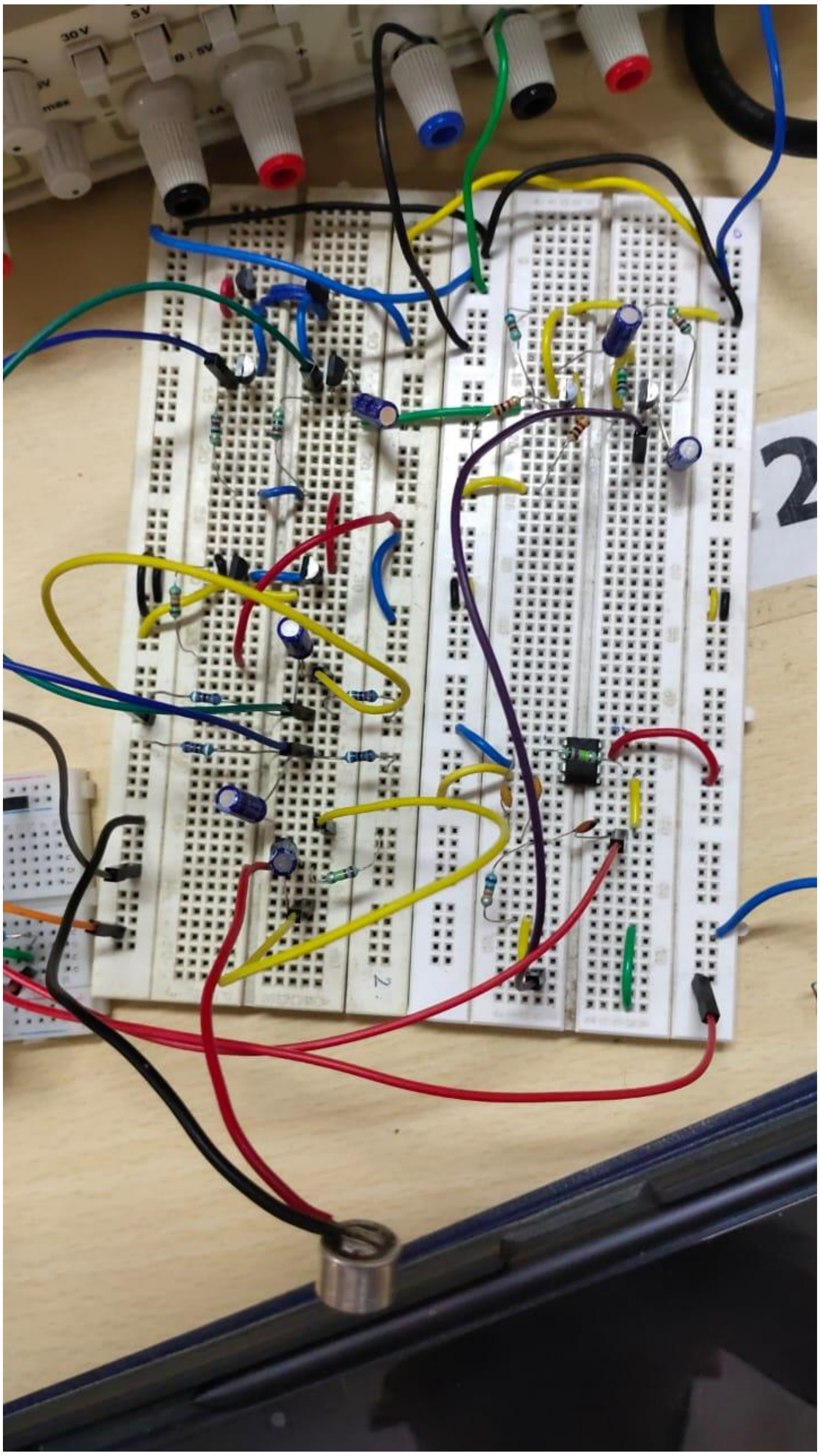
- V_{in} = sine wave of 10mVpp @ 1kHz
  Load = 10 ohms

$$P_{avg} = \frac{8.6 * 0.5}{2} = 2.15\,W$$

$$A_v = \frac{V_{out_{max}}}{V_{in_{max}}} = \frac{8.6}{0.01} = 860$$



Final Output on hardware



Final Hardware

Conclusion

We have an Audio Amplifier, which can take input from a microphone, and drive a speaker to amplify the audio given in to the microphone. The circuit rejects noise and inaudible frequencies, to provide a high efficiency amplifier circuit.