Four-stage AM Radio Receiver Design

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***Abstract*—A simple AM receiver is designed using four stages: a band pass filter, an envelope detector, a low pass filter, and a gain stage. The design is simulated using LTSpice. The receiver was able to recover message signals with mean THD = 7.249%, and was able to amplify 1kHz message signals with mean gain = 3.2903 V/V. Overall, the design was able to meet the desired requirements with distortion grade within the acceptable range and with the minimum gain greater than 3V/V.**

I. Introduction

Communication is - like "lugaw" - essential in people's daily life. This can be easily done by having a transmitter and a receiver on the source and the destination, respectively, of the message. However, most of our messages are at low frequencies which requires us to build long antennas to make communication possible. Hence, modulation techniques are developed to address this cost problem. A common modulation technique is AM modulation.

In an AM communication system, a high frequency carrier is modulated by the transmitter into the original message. The output signal of a transmitter then takes the form of

$$A(1 + \mu m(t))c(t) \tag{1}$$

where A the gain, μ the modulation index, $m(t)$ the message signal, and $c(t)$ the carrier signal. The output signal is then sent into the channel which introduces noise to the message. The signal is then received by a receiver. The original message is recovered by rectifying the signal, detecting the envelope, and filtering high frequency carriers.

In this paper, we design an AM radio receiver that demodulates signal at carrier frequencies of 550kHz, 600kHz, and 650kHz which carry messages ranging from 1kHz to 8kHz.

II. AM Receiver Design

The AM receiver composes of four stages: the bandpass filter (BPF), the envelope detector, the low pass filter (LPF), and the gain stage. In this section, we discuss the design of each stage and how they can meet the desired specifications.

A. Bandpass filter design

In BPF design, the filter is a parallel LC circuit series with a 50Ω resistor which is modelled as the radio antenna. A variable capacitor is used to act as a dial for switching received frequencies. Mathematically, this capacitor $C_{var}$is modelled as a linear equation given by

$$C_{var} = kC_{max} \tag{2}$$

where k is some value between 0 to 1.

Note that we have to detect carrier frequencies 550kHz, 600kHz, and 650kHz. Hence, we initially set the passband of the BPF to be at least 500kHz with maximum bandwidth of 30kHz to avoid overlapping frequencies. Our equations for the bandwidth and resonant frequency of the BPF are the following:

$$BW = \frac{1}{2\pi k R_s C_{max}} \tag{3}$$

$$f_0 = \frac{1}{2\pi\sqrt{kLC_{max}}} \tag{4}$$

Notice that at maximum k ($k = 1$), the bandwidth and resonant frequency are at minimum. We observe a trend where detecting higher frequencies increases the bandwidth of the BPF response, which may cause overlaps. At $k = 1$, we set $f_0 = 500kHz$. From Eq. 4, we compute $LC_{max} \approx 1.0132 \times 10^{-13}$. This can be approximated using standard values of $L = 0.51H$ and $C_{max} = 0.20\mu F$.

Computing for k for each carrier frequencies, the values are 0.8209, 0.6898, 0.5878 for 550kHz, 600kHz, 650kHz, respectively. From Eq. 3, the bandwidths are 19.387kHz, 23.072kHz and 27.077kHz, respectively.

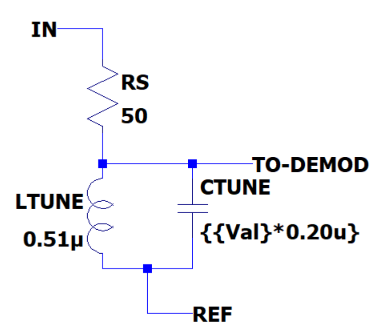

Fig. 1. Bandpass Filter Schematic

B. Envelope detector design

The envelope detector is a parallel RC series to a 1N4148 diode. Since the RC acts as filter, we need message frequencies below 8kHz to pass through and carrier frequencies above 550kHz to be filtered out. The cut-off frequency is given by:

$$f_{co} = \frac{1}{2\pi RC} \tag{5}$$

We set the cut-off frequency at 40kHz. This gives $RC = 3.979 \times 10^{-6}$. In the design, we used $R = 1k\Omega$ and $C = 3.9nF$.

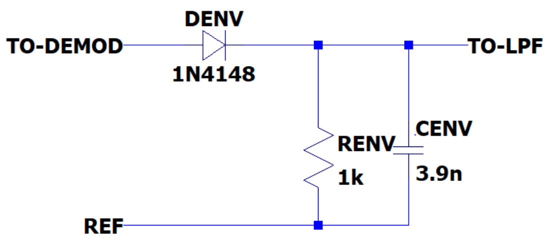

Fig. 2. Envelope detector schematic

C. Low pass filter design

For the LPF stage, an active filter is used due to the following reasons:

1) Using an active filter saves us from the problem of loading effects due to succeeding stages.
2) An active filter can add gain to its output, which reduces the number of stages in the gain stage.

In the design, we initially used a second-order butterworth filter [1].

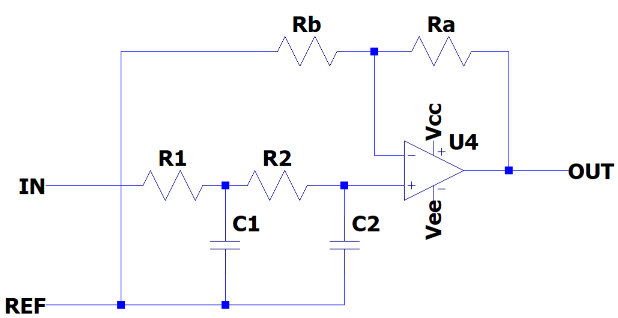

Fig. 3. Second-order butterworth filter

Setting $R_1 = R_2$ and $C_1 = C_2$ to simplify analysis, we get the transfer function of the LPF

$$G(s) = \frac{\frac{A}{(RC)^2}}{s^2 + s\frac{3-A}{RC} + \frac{1}{(RC)^2}} \tag{6}$$

where $A = 1 + \frac{R_A}{R_B}$ is the passband gain of the LPF.

This gives us the cutoff frequency of the LPF, as well as the damping factor ζ.

$$f_0 = \frac{1}{2\pi RC} \tag{7}$$

$$\zeta = \frac{3-A}{2} \tag{8}$$

We set the cut-off frequency at 55kHz since this is one decade away from the smallest carrier frequency and this satisfies the inequality $max(f_m) \leq f_{co} \leq min(f_c)$. Thus, the RC values for the second order LPF is 2.8937×10^{-6}. We used $R = 1k\Omega$ and $C = 3.0nF$.

The LPF was implemented and simulated in LTSpice using an LF353 operational amplifier. The order of the LPF is incremented by cascading the same circuit until the half-power frequency f_{-3db} is between 8kHz and 15kHz. Hence, we used a sixth order butterworth filter. Note that while increasing the order may further smoothen the input signal, the sixth order filter is the most cost-optimized that fits the requirements.

The same cut-off frequencies are used on the three stages of LPF. This is because we want to increase the steepness of frequency response. Using different (but relatively near) cut-off frequencies results to a frequency response which is rounded at the corner frequency. This requires us the add more stages to reach desired half power frequency which is not cost-effective.

Moreover, for each filter, the gain must not exceed three to avoid the LPF response to be undamped. In the design, we used a $2.5 \times 2 \times 2$ gain for the cascaded butterworths which gives us a total of 10. Therefore, for an input signal of at least 100mV, the gain stage will now only require a gain of at least 3.

The final filter design is shown below.

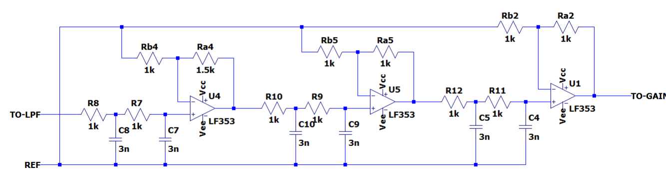

Fig. 4. Low pass filter design

D. Gain stage design

The gain stage is an AC-coupled two-stage CE-CC amplifier. The common-emitter (CE) topology is used to introduce gain while the common-collector (CC) amplifier is used to control the output load seen by the former. In the design process, we first design the CC amplifier, then design the CE amplifier based on the input resistance of the CC amplifier. In both stages, 2N3904 is used which is an NPN transistor with forward beta of 300 according to the SPICE model from the LTSpice simulator.

The CC amplifier is fixed bias. The DC operating point of the NPN is set such that $V_{CE,Q} = 4.5V$ and $I_{C,Q} = 30mA$. To achieve this, we set the emitter resistance $R_{E,cc}$ to 150Ω and the base resistance $R_{B,cc}$ to be $38k\Omega$. The input resistance $R_i$of this buffer is given by

$$R_i = R_{B,cc}||[(\frac{\beta}{g_{m,cc}}) + (\beta + 1)(R_{E,cc}||R_L)] \tag{9}$$

where $g_{m,cc} = \frac{I_{c,cc}}{V_T}$ the transconductance of the transistor with V_T the thermal voltage, and R_L the transistor load. With the above quantities, the input resistance is approximately $20.410k\Omega$.

Meanwhile, we used a voltage divider bias with emitter degeneration for the CE amplifier. The use of emitter resistor is to limit the gain since we only need at least a 3V/V gain. For this topology, the gain A_v is given by

$$A_v = \frac{g_{m,ce}(R_c||R_L)}{1 + g_{m,ce}R_E} \tag{10}$$

Using $g_{m,ce} = \frac{I_{c,ce}}{V_T}$ and assuming large β, the collector current is given by

$$I_{C,ce} = \frac{A_v(1 + \frac{V_{E,ce}}{V_T})(\frac{V_T}{R_L})}{1 - A_v(1 + \frac{V_E}{V_T})(\frac{V_T}{V_{CC} - V_{C,ce}})} \tag{11}$$

Setting $A_v = 3.5$, $V_E = \frac{1}{10}V_{CC}$ and $V_C = 5.4V$, and using the input resistance of the CC amplifier as the load, we calculate the DC operating point to be $I_{C,ce} \approx 1.5924mA$. This is achieved using a network of resistors. Figure 5 shows the CE-CC amplifier design for the gain stage.

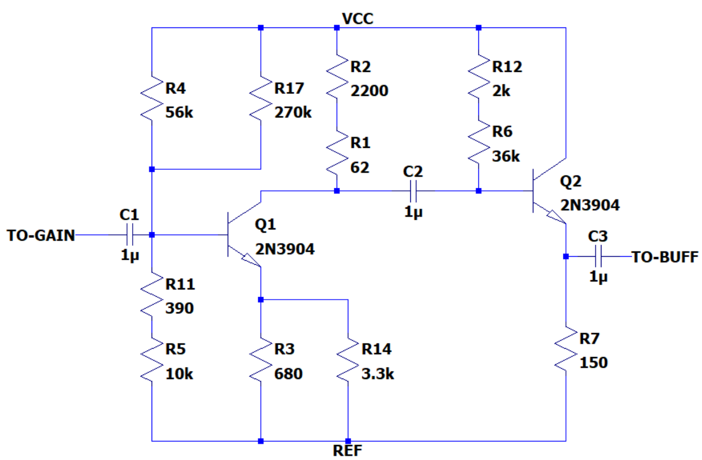

Fig. 5. Gain stage design

To reiterate, the two stages are sufficient enough to provide the gain since most of the gain has been introduced by the active LPF. Only the NPN-type of transistor is used because 2N3904 has higher β than that from the PNP 2N3906, which makes the approximation $I_C \approx I_E$ more acceptable. Moreover, in the simulation, there is minimal difference on the transient response with using a PNP-CE amplifier on that with using an NPN-CE amplifier.

III. Results

The design in Section II is simulated in LTSpice. In this section, we discuss the transient responses and some behavior of the blocks used for the AM receiver.

Before proceeding, we first define the test cases used in the simulations. Note that in all test cases, the waveforms are at unity gain.

1) All messages sent at 1 kHz.
2) All messages sent at 8 kHz.
3) Messages at 8kHz, 5kHz, and 2 kHz for 550kHz, 600kHz, and 650kHz carriers.

In the simulation, an additional stage (the buffer stage) is introduced to model the output load of the AM radio receiver.

A. Band Pass Filter Responses

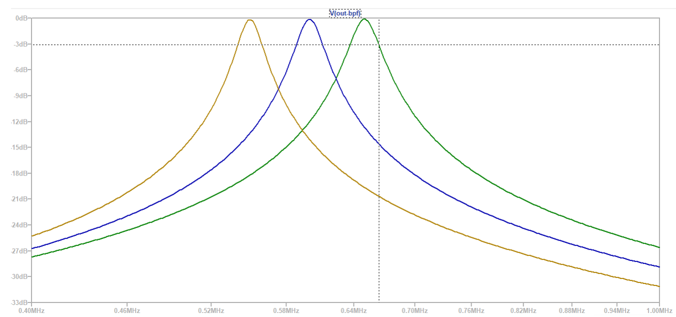

Fig. 6. AC response of the Band Pass Filter with the variable capacitance set at 550kHz (brown), 600 kHz (blue), 650kHz (green)

Figure 6 shows the AC response of the BPF at the selected carrier frequencies. At 550kHz, the gain of the received signal is 0.984V/V with bandwidth 19.886kHz. At 600kHz, the gain is 0.987V/V with bandwidth 23.624kHz. At 650kHz, the gain is 0.989V/V with bandwidth 27.691kHz. These show the simulated bandwidths are almost equal to the computed values from the design part. Hence, we have successfully addressed the tradeoff between detection frequencies and overlaps.

Moreover, the plot shows that the gain for all carrier frequencies are very close to unity (0 dB). Figure 7 shows the transient response of the bandpass filter given the message signal follows test case 3.

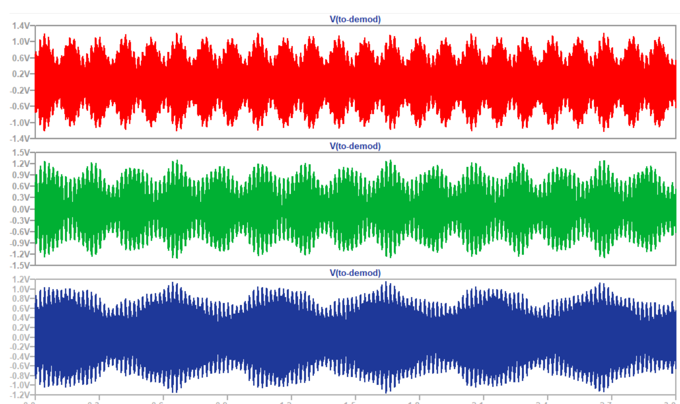

Fig. 7. Transient response of the band pass filter with the variable capacitance set at 550kHz (red), 600 kHz (green), 650kHz (blue)

B. Envelope detector responses

As shown in Figure 8, the envelope detector is able to trace the envelope of the waveform containing the messages. Using the testbench for Milestone 1, the block was also able

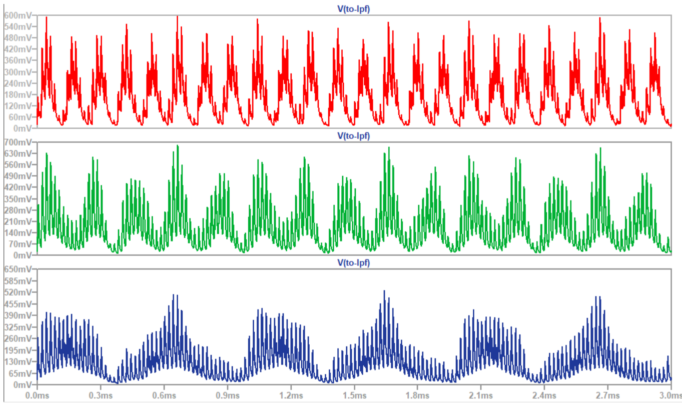

Fig. 8. Transient response of the envelope detector with $F_c = 550kHz$ (red), $F_c = 600kHz$ (green), and $F_c = 650kHz$ (blue).

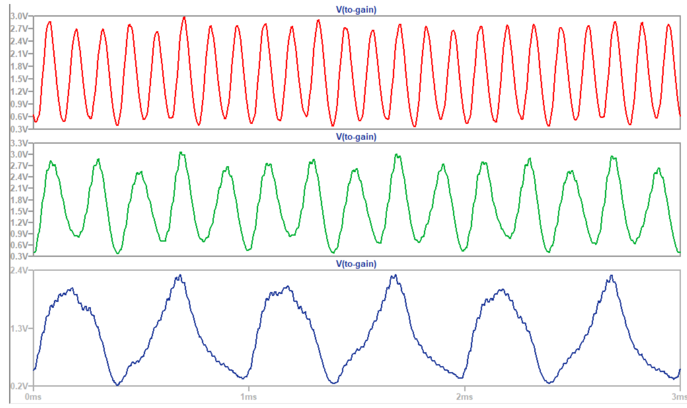

Fig. 10. Transient response of the LPF with $F_c = 550kHz$ (red), $F_c = 600kHz$ (green), and $F_c = 650kHz$ (blue).

to achieve the minimum amplitude threshold required for receiving 2kHz, 5kHz and 8kHz signals.

C. Low pass filter response

In Figure 9 the cut-off frequency is at 10.199kHz, the DC gain at 9.999V/V and the gain at 8kHz at 8.008V/V.

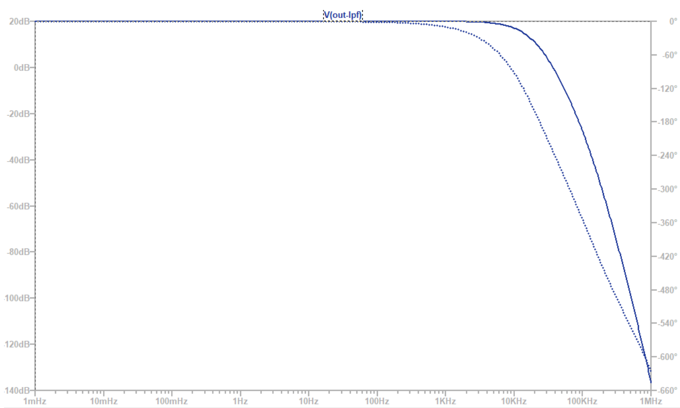

Fig. 9. AC response of the low pass filter

While the DC gain meets the computed value, the gain at 8kHz is off by 2V/V. This is a trade-off in the design of the LPF in which trying to get the cut-off frequency close to the message signal frequency reduces the gain at higher frequencies due to the non-idealities of the LPF. To address this, we added a margin of 0.5V/V for the target gain in the gain stage.

Meanwhile, Figure 10 shows the transient response of the LPF using test case 3. We can see another tradeoff where at lower message frequencies, distortion is more noticeable.

D. Gain stage response

We first evaluate the gain stage using test signals at different frequencies. At 1kHz, the gain is 3.445 V/V while at 8kHz, the gain is 3.447 V/V. These are relatively close to the target gain of 3.5V.

Cascading the gain stage into the LPF of the AM receiver, the gain stage has the following transient response. All test cases were used for the message signal. Distortion grades (THD) are calculated through the checker. This is given by

$$THD = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + V_5^2 + V_6^2}}{V_1} \tag{12}$$

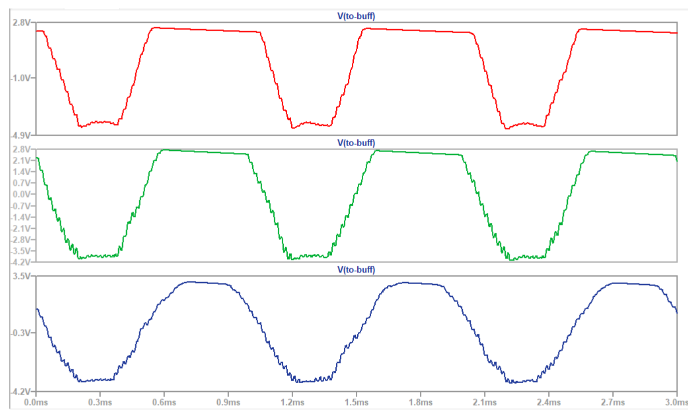

Fig. 11. Transient response of the gain stage with $F_c = 550kHz$ (red), $F_c = 600kHz$ (green), and $F_c = 650kHz$ (blue) with all carriers carrying 1kHz message.

For test case 1, the gain is also calculated. From the simulation, the THD of 550kHz is 16.807% with gain of 3.434, the THD of 600kHz is 13.899% with gain of 3.394, the THD of 650kHz is 5.035% with gain of 3.043%.

We observe a trend where at higher carrier frequencies, less gain can be introduced but the output signal becomes less distorted. Figure 11 shows the distortion is caused by the clipping (the peaks are pushed into saturation/cut-off region due to high gain) on the CE amplifier. At higher carrier frequencies such as the signal at 650kHz, there is less distortion at the cost of marginal gain. This is a tradeoff that we observed in the gain stage. Nonetheless, the THD of the output signals remain at the acceptable range ($THD < 0.46$).

Meanwhile, for test case 2, the THD of 550kHz is 0.349%, the THD of 600kHz is 3.089%, and the THD of 650kHz is

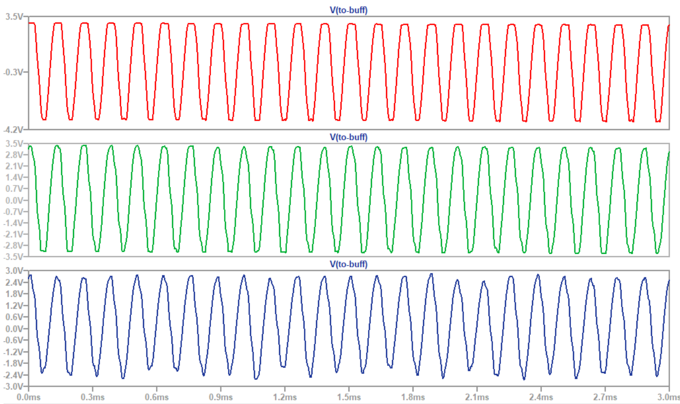

Fig. 12. Transient response of the gain stage with $F_c = 550kHz$ (red), $F_c = 600kHz$ (green), and $F_c = 650kHz$ (blue) with all carriers carrying 8kHz message.

7.784%. In these cases, the effect of distortion due to clipping is reduced.

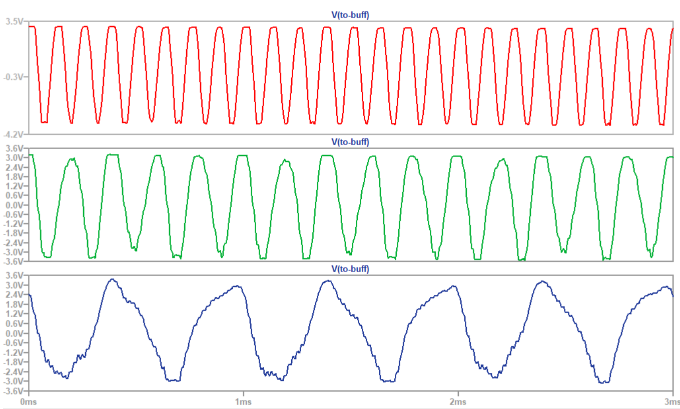

Fig. 13. Transient response of the gain stage with $F_c = 550kHz$ (red) carrying 8kHz message, $F_c = 600kHz$ (green) carrying 5kHz message, and $F_c = 650kHz$ (blue) carrying 2kHz message.

For test case 3, the THD of 550kHz carrying 8kHz message is 6.953%, the THD of 600kHz carrying 5kHz message is 5.034%, and the THD of 650kHz carrying 2kHz message is 6.287%. We see here that the distortion introduced was mostly due to the tradeoff on the LPF stage.

IV. Conclusion

In this section, we give an overview of the final design, the tradeoffs for each block, and how are these addressed. The AM receiver consists of four major stages: the BPF, envelope detector, the LPF, and the gain stage.

The BPF is used to select the carrier frequecy to be demodulated. This is an LC circuit in parallel with a 50Ω antenna. The LC value is selected such that the maximum bandwidth is approximately 30kHz to avoid overlaps between frequencies. In the simulation, we were able to control the bandwidth of the 550kHz carrier, the 600kHz carrier and the 650kHz carrier at 19.886kHz, 23.624kHz and 27.691kHz, respectively.

The envelope detector is an RC circuit in series to a rectifier diode. The RC value is selected to have a cut-off frequency of 40kHz to allow message signals of frequencies less than 8kHz to pass through. The envelope of the message signals from all three carrier frequencies were recovered in the simulation with minimum amplitude threshold met.

The LPF used is a sixth-order butterworth filter with cut-off frequency set at 55kHz and the overall gain set at 10 V/V. In the simulation, the active filter was able to filter out the carrier frequencies with $f_{-3dB} \approx 10.2kHz$. Moreover,we observe a trend due to the non-idealities of the butterworth filter in which the gain is reduced at higher frequencies. To address this, we increase the target gain in the next stage.

In the gain stage, we used a two-stage CE-CC amplifier to introduce a target gain of 3.5 V/V. The CC amplifier is designed to load the CE amplifier with $20.41k\Omega$, while the CE amplifier is a voltage divider biased amplifier with emitter degeneration that introduces the 3.5 V/V gain. A tradeoff that is prominent in the gain stage is the distortion vs. gain tradeoff. In order to achieve a gain of at least 3V, we risk putting the peak of the output signal outside of the forward active region of the CE amplifier - increasing distortion.

Overall, the design was able to make the distortion grade of the output signal acceptable for all test cases. For 1kHz message signals, the design was also able to exceed the minimum output amplitude of 3V. Hence, the design meets the desired requirements for the project.

References

[1] Electrical4U, “Butterworth filter: What is it?” 2016. [Online]. Available: https://www.electrical4u.com/butterworth-filter/