

WASHINGTON STATE UNIVERSITY
SCHOOL OF ELECTRICAL ENGINEERING AND COMPUTER SCIENCE

EE 352, ELECTRICAL ENGINEERING LABORATORY

LAB PROJECT

AM Transmitter/Receiver

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Abstract

In this project, an AM transmitter and receiver was designed and simulated using LTspice. The AM transmitter uses an input message signal between 400 Hz and 8 kHz and mixes the signal with a carrier frequency of 72 kHz, generated by a Wien oscillator. The transmitter amplifies the signal to be carried across a $50\ \Omega$ BNC cable to the receiver with $50\ \Omega$ impedance. The receiver uses a peak detector with a Butterworth bandpass filter to detect and restore the envelope message signal. This signal is passed to a Schmitt trigger comparator and a buffer amplifier, which drives an $8\ \Omega$ speaker. The project was simulated using LTspice. The simulations show that the transmitter-receiver design met the required specifications.

1 Introduction

In this project, a transmitter was designed to transmit an amplitude modulated (AM) signal across a BNC cable and a receiver will restore the original message signal and output the signal through a speaker. In amplitude modulation, a carrier signal is used to transmit a message signal. This is done by modulating the carrier amplitude proportionally to the message signal, as depicted in Figure 1. This idea is particularly useful when transmitting over-the-air, as the receiver must only know the transmission frequency and a bandwidth to receive a message signal.

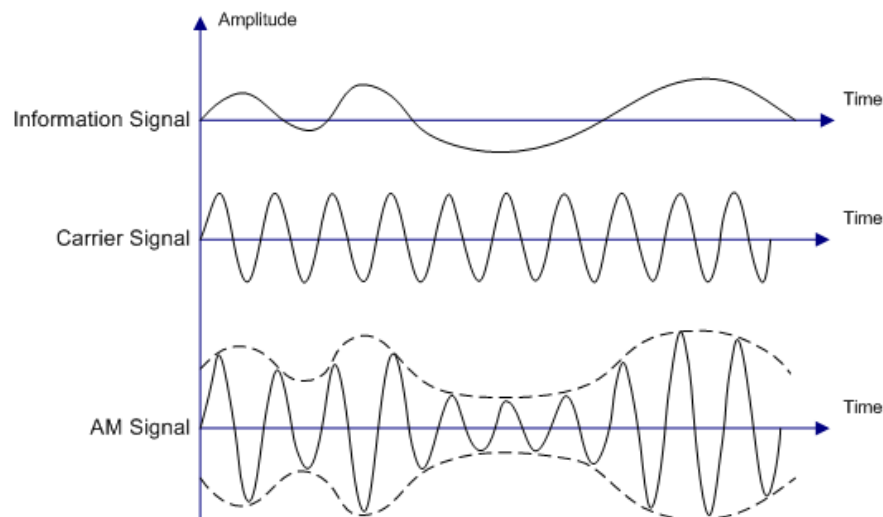


Figure 1: The basic principle of amplitude modulation (AM)¹.

The outline of the project is depicted in the block diagram in Figure 2. First, the input message signal will be mixed with the carrier oscillator signal, generated by a Wien oscillator. A switching modulator will mix the signals by proportionally adding the two signals, relative to a modulation index. Next, a high quality bandpass filter will be used to filter the half-wave output of the modulator, allowing only a narrow band of signals allowed near the carrier frequency. A power amplifier is then employed to buffer the signal and to increase the current driven across the transmission line, a BNC cable.

After transmission through a BNC cable, a combination of a peak detector and a Butterworth bandpass filter will detect and restore the envelope message signal. A comparator using a Schmitt trigger and a diode is used to convert the sinusoid signal into a pulsed waveform. From these pulse waves, a buffer amplifier can drive a speaker to product audible sounds. Verification of meeting the specifications will come through time- and frequency-domain simulations done through LTspice. The output waveforms of each component is captured through the simulations and will be analyzed to determine if the specifications are met.

¹Image is adapted from *Illustration of Amplitude Modulation*, Ivan Akira.

https://commons.wikimedia.org/wiki/File:Illustration_of_Amplitude_Modulation.png

1.1 Specifications

For the project, the following requirements must be met:

1. Components are limited to those in the analog parts kit.
2. Power supplies: ± 12 V DC.
3. Input: Single tone sine wave from a bench generator; frequencies 500 Hz to 4 kHz.
4. Output: Single tone sine wave, displayed on an oscilloscope and played through a speaker.
5. Carrier frequency: between 60 kHz and 80 kHz.
6. Transmitter bandpass filter specifications:
 - (a) Lower stop band: $|H(j\omega)| \leq -20$ dB for frequencies $f < 4$ kHz.
 - (b) Upper stop band: $|H(j\omega)| \leq -210$ dB for frequencies twice the carrier frequency, $f = 2f_c$.
 - (c) Pass band: -1 dB $\leq |H(j\omega)| \leq 1$ dB for frequencies between $f = f_c \pm 4$ kHz.

1.2 Block diagram

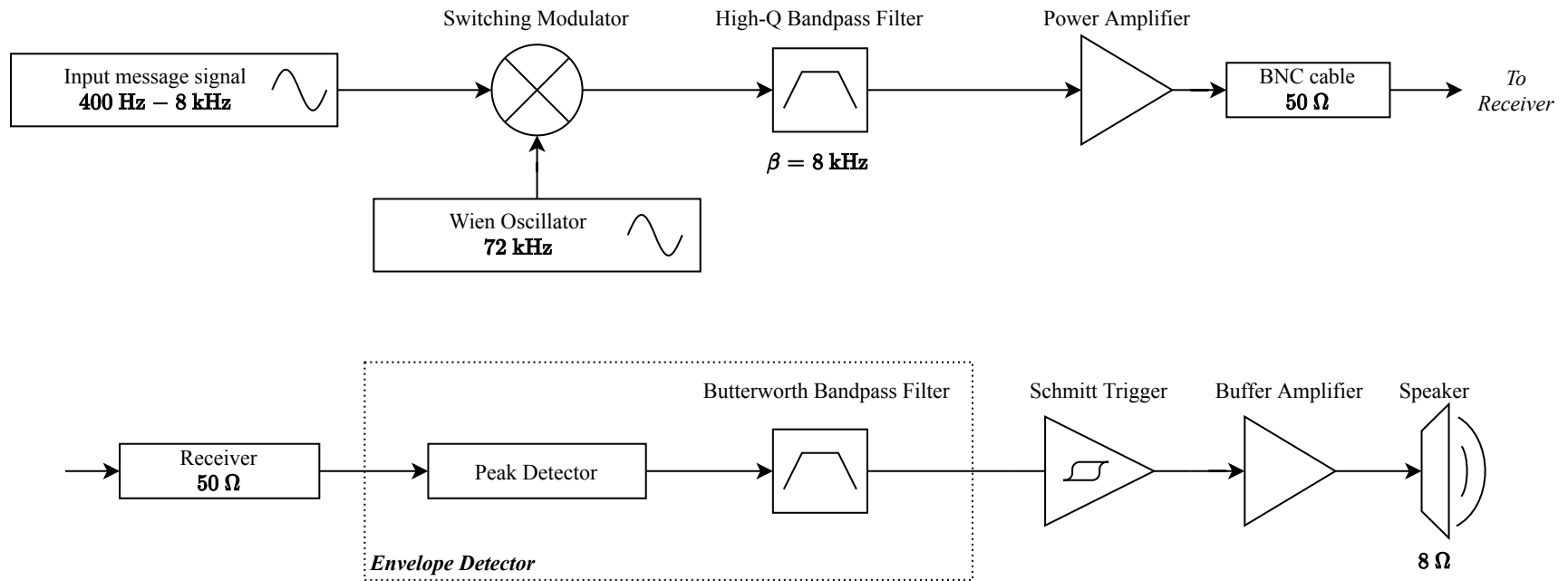


Figure 2: A block diagram of the components used in this AM radio.

2 Design and Simulation Results

2.1 Wien bridge oscillator

The Wien bridge oscillator is a sinusoidal oscillator utilized in the circuit to produce the carrier signal. The basic design of this oscillator uses an op-amp and an RC network. The RC network selects a target frequency and loops back into the non-inverting input of amplifier. Over a short period of time, the oscillator stabilizes around the target frequency with little drift. The oscillator circuit is shown below in Figure 3 with the its RC networks highlighted, Z_s and Z_p .

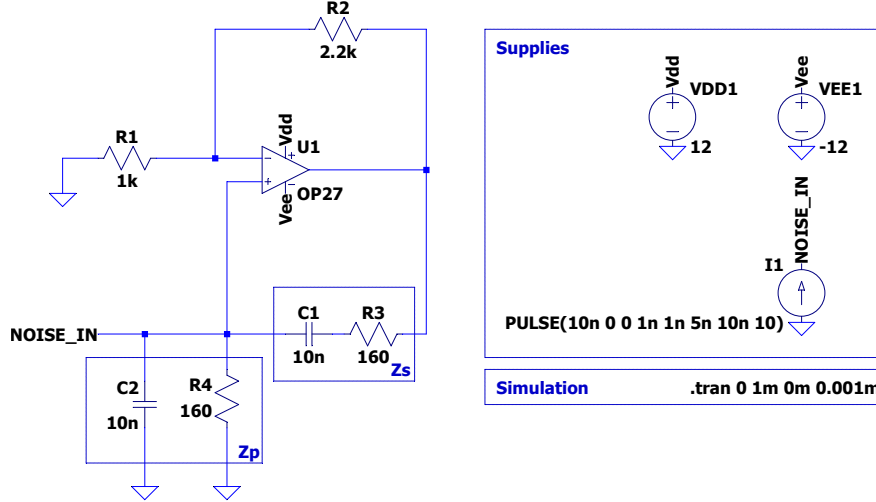


Figure 3: *Left*: the Wien oscillator circuit. *Right*: power supplies and SPICE directives used in the simulations.

This oscillator is characterized by the transfer function [1],

$$\begin{aligned}
 L(s) &= \left(1 + \frac{R_2}{R_1}\right) \frac{Z_p}{Z_p + Z_s} \\
 &= \frac{1 + R_2/R_1}{3 + sRC + 1/sRC} \\
 L(j\omega) &= \frac{1 + R_2/R_1}{3 + j(\omega RC - 1/\omega RC)}
 \end{aligned} \tag{1}$$

From (1), the loop will create gain at a frequency ω_0 with a unity gain G as

$$\begin{aligned}
 \omega_0 &= 1/RC \\
 G &= R_2/R_1 = 2
 \end{aligned}$$

2.1.1 Design

To follow the requirements, the Wien oscillator will be designed to generate the signal for the carrier frequency, between 60 kHz and 80 kHz, while allowing for the range of the input signal, which can reach 4 kHz. The Wien oscillator will be designed to output roughly 70 kHz. To accomplish this, it must be noted the relative ease of finding resistors of ranging values over the limited selection of capacitors. If a capacitance of 10 nF is chosen, then from (1), the resistor in the feedback RC network must be roughly 227 Ω .

For the feedback gain, given by R_2/R_1 , a proportion of 2 is required. For this, two common values were used, which would give an approximate gain of 2:

$$R_1 = 1 \text{ k}\Omega$$

$$R_2 = 2.2 \text{ k}\Omega$$

After testing these values on-hardware, it was quickly realized that additional trimming of the resistor in the RC network. From testing, it was found that 160Ω produced a oscillation at roughly 72 kHz with no load. With additional load, the frequency may drift up to 74 kHz , but that would be within the tolerances of the specifications.

2.1.2 Simulation

Using LTspice, the circuit in Figure 3 was simulated using a transient analysis to 4 ms in steps of $0.1 \mu\text{s}$. From the start, the simulation shows the gradual wind-up of the oscillator until it stabilizes after 1 ms , shown in Figure 4. After the oscillator stabilized, an FFT was generated showing a peak frequency of 72 kHz in Figure 5.

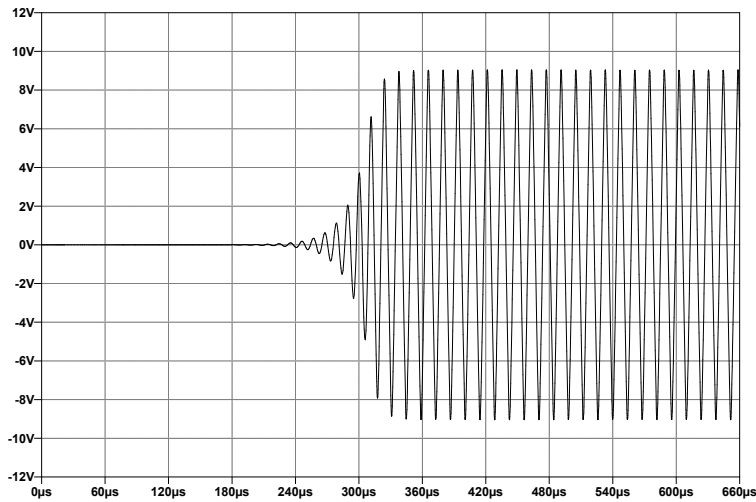


Figure 4: Transient simulation showing the start-up of the Wien oscillator.

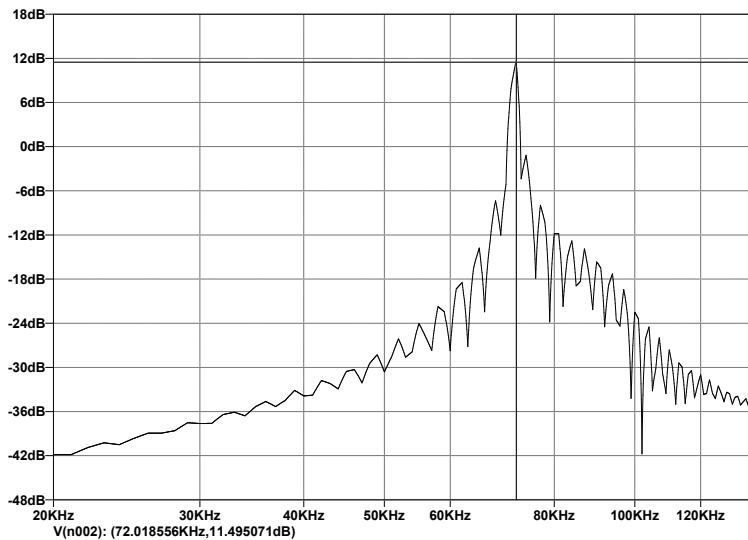


Figure 5: An Fourier transform of the oscillator showing a peak frequency at roughly 72 kHz .

2.2 Switching Modulator

The switching modulator combines the carrier signal and the message signal. This is done simply through superposition of the two signals at the inverting terminal of the amplifier. Once the signals are added, the combined signal is amplified proportional to the input resistances of each signal. Lastly, a diode truncates the signal to the positive half.

The circuit for the modulator is shown in Figure 6 below, where the carrier signal is emulated using a sinusoidal input, `OSC_IN`, and combined with the message signal, `LINE_IN`.

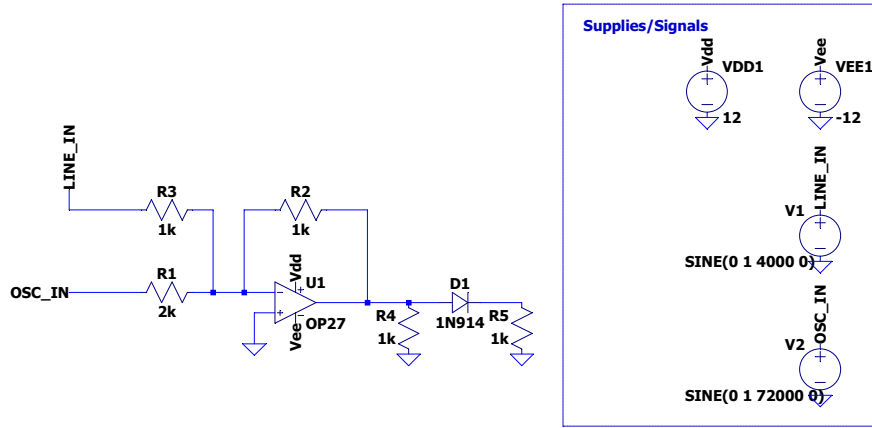


Figure 6: *Left:* The circuit of the switching modulator. *Right:* Power supplies and simulated signals.

2.2.1 Design

In the design shown in Figure 6, the carrier signal will have a half gain, given by the ratio of the resistors, R_2/R_1 . The message signal will have a unity gain, given by equal resistances of R_2/R_3 . These resistor ratios can be changed later on to adjust the modulation index of each input. In this design, the resistors can be chosen as

$$R_1 = 2 \text{ k}\Omega$$

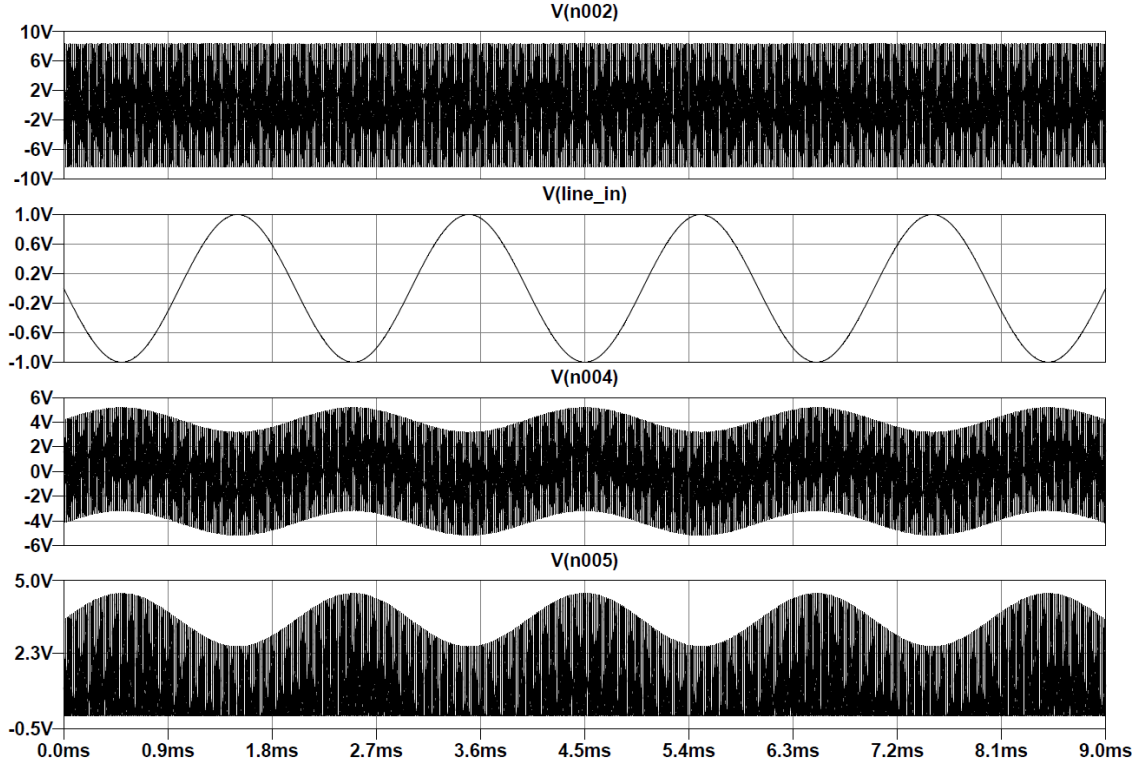
$$R_2 = 1 \text{ k}\Omega$$

$$R_3 = 1 \text{ k}\Omega$$

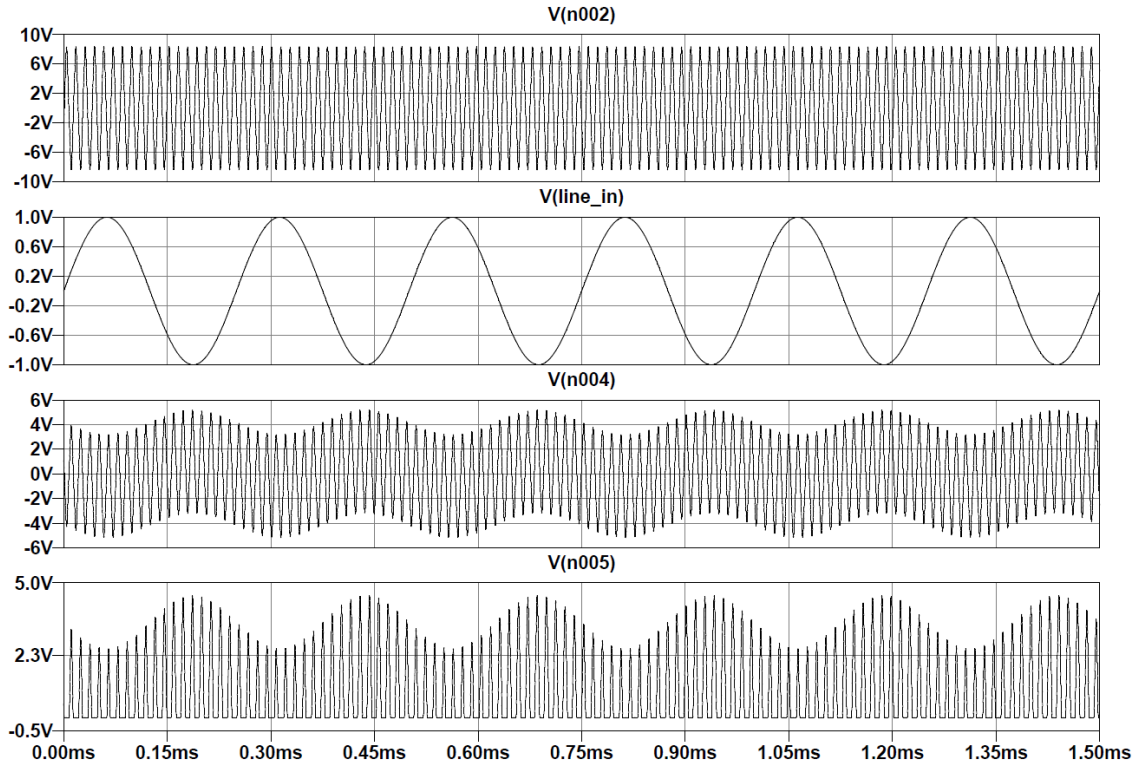
These resistors were chosen for the ease of finding 1 k Ω resistors. Lastly, the signal will be clipped to the positive half using an 1N914 diode in a simple half-wave rectifier.

2.2.2 Simulation

The modulator was simulated inline with the earlier 72 kHz Wien oscillator using an 500 Hz and 4 kHz message signal. The time-domain simulations for both message signals are shown in Figure 7. The Fourier transform of the output (pre-rectification) is shown in Figure 8.

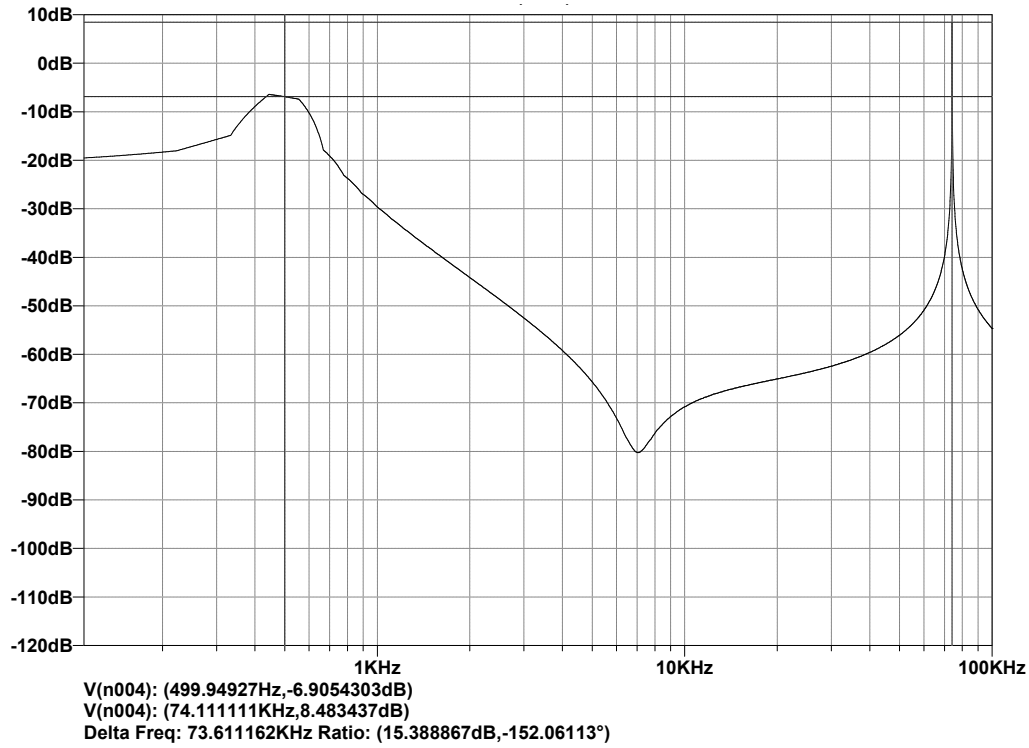


(a) Time simulation of modulator using the 500 Hz message signal.

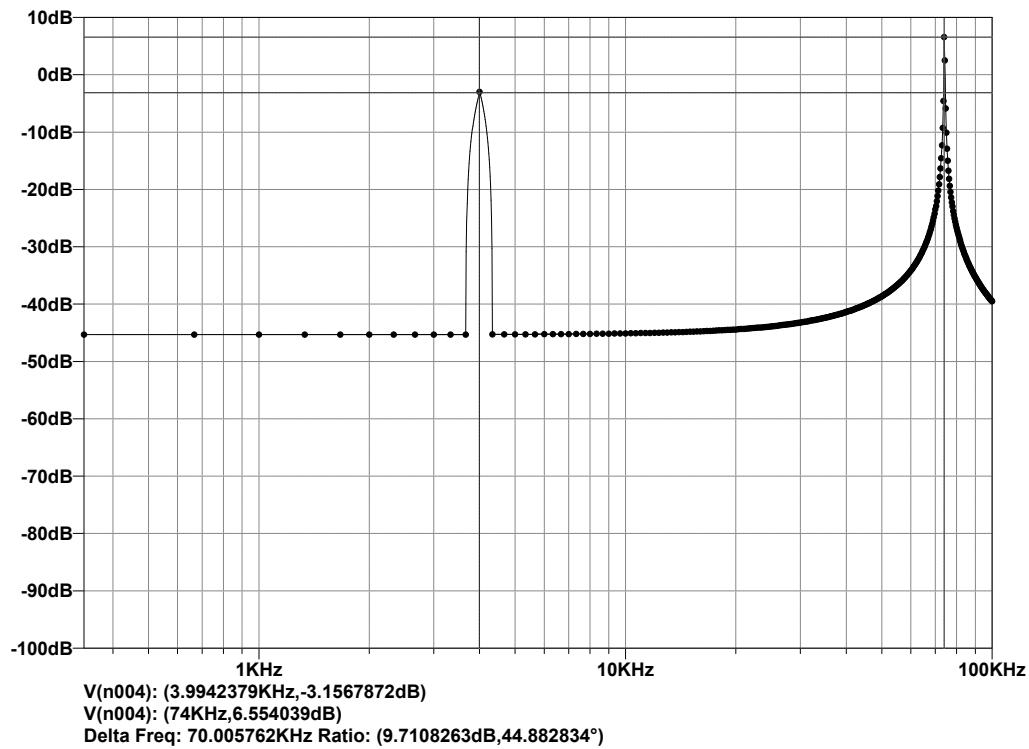


(b) Time simulation of modulator using the 4 kHz message signal.

Figure 7: Time-domain simulation of the switching modulator using two message signals. Each figure contains: *Topmost*: 72 kHz carrier signal input; *Second*: Message signal input; *Third*: Output of the summer; *Last*: Output of the modulator after half-wave rectification.



(a) FFT of the output of the modulator with 500 Hz message signal.



(b) FFT of the output of the modulator with 4000 Hz message signal.

Figure 8: FFT of the output of the modulator for both message signal frequencies, showing peaks at the both the carrier signal and message signal frequencies.

2.3 High-Q Bandpass Filter

After modulation and half-wave rectification, the signal is passed to a high-Q bandpass filter to isolate the range of the combined carrier and message signal. Effectively, the output signal now becomes an amplitude modulated wave with an envelope vertically symmetric. The circuit of the filter used in this project is shown in Figure 9 below.

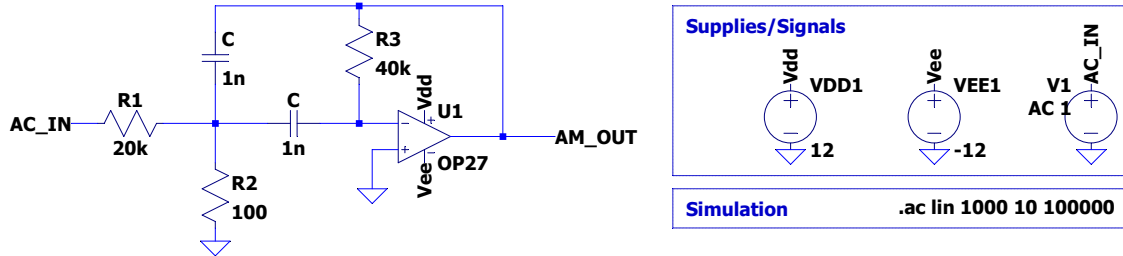


Figure 9: *Left*: The high quality bandpass filter used in the radio project. *Right*: The voltage sources and simulation SPICE directive.

For this filter, its transfer function can be determined by finding the impedances throughout this non-inverting op-amp configuration. It can be shown[2] that the transfer function is

$$H(s) = \frac{-K\beta}{s^2 + \beta s + \omega_0^2}$$

Where the center frequency ω_0 and bandwidth β is given as

$$\begin{aligned}\omega_0 &= \frac{1}{(R_1 \parallel R_2) R_3 C^2} \\ \beta &= 2\pi (2 \times 4000) \\ &= \frac{2}{R_3 C} = \frac{1}{K R_1 C}\end{aligned}$$

2.3.1 Design

For this, a MATLAB script was used to iteratively find potential combinations of component values and is included in Snippet 1 (Appendix A). The capacitances were fixed to 1 nF as there are many ceramic capacitors of this value available. Initially, R_1 and R_3 were calculated to an exact value of 19.894 k Ω and 39.789 k Ω respectively. As there are an abundance of 10 k Ω resistors and multiples, these resistances were rounded to 20 k Ω and 40 k Ω .

After fixing these component values, R_2 was iteratively determined as 119 Ω by testing different R_2 values and calculating the center frequency. After simulating these values, it was realized that R_2 must be trimmed to 100 Ω , likely due to internal capacitance of the op-amp affecting the center frequency.

2.3.2 Simulation

The filter was initially simulated using a linear AC sweep. The frequency response is shown in Figure 10. Next, the filter was placed at the output of the switching modulator and the two message frequencies were tested. The time-domain simulation is shown in Figure 11. For the time-domain responses, the FFT showing the two peaks at $f_c \pm f_m$ is shown in Figure 12.

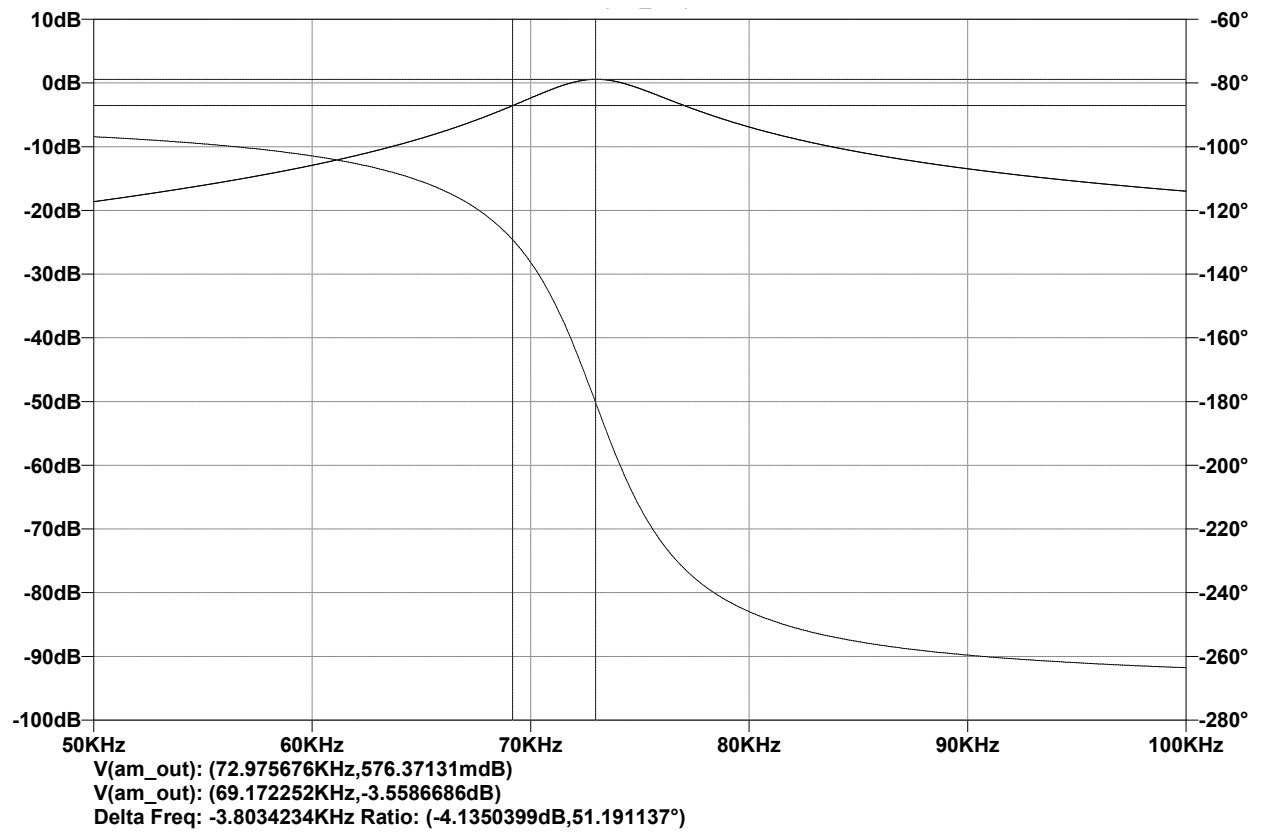
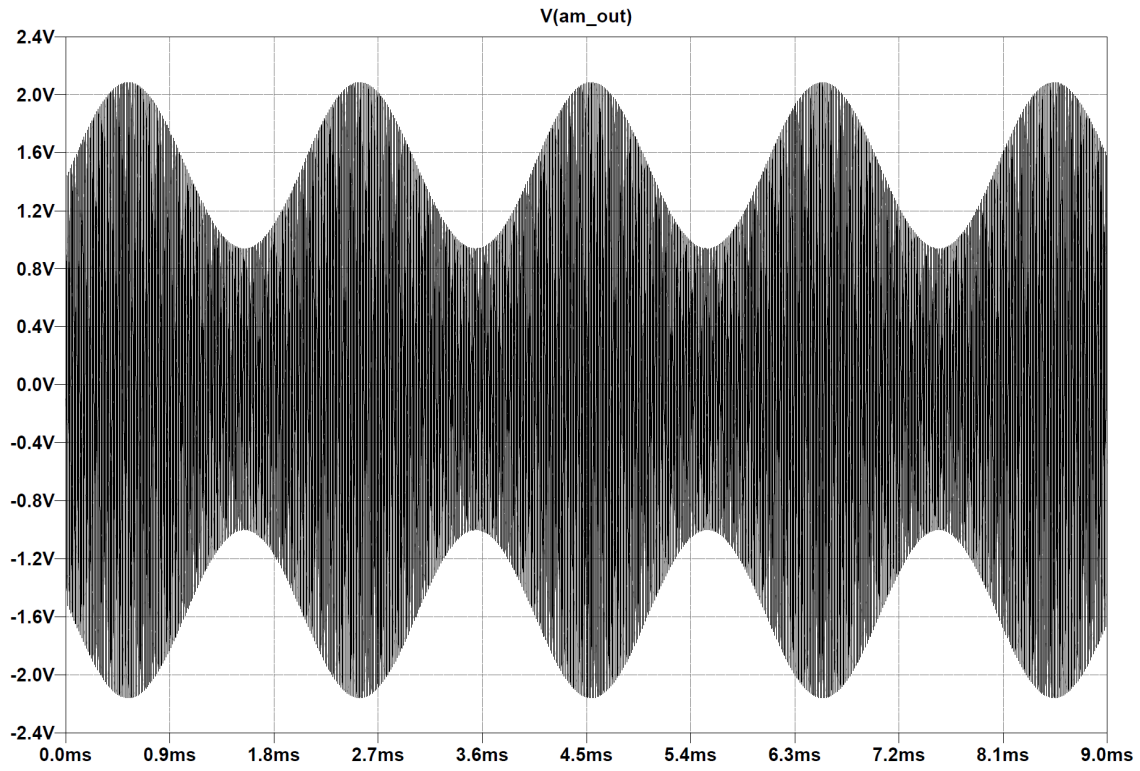
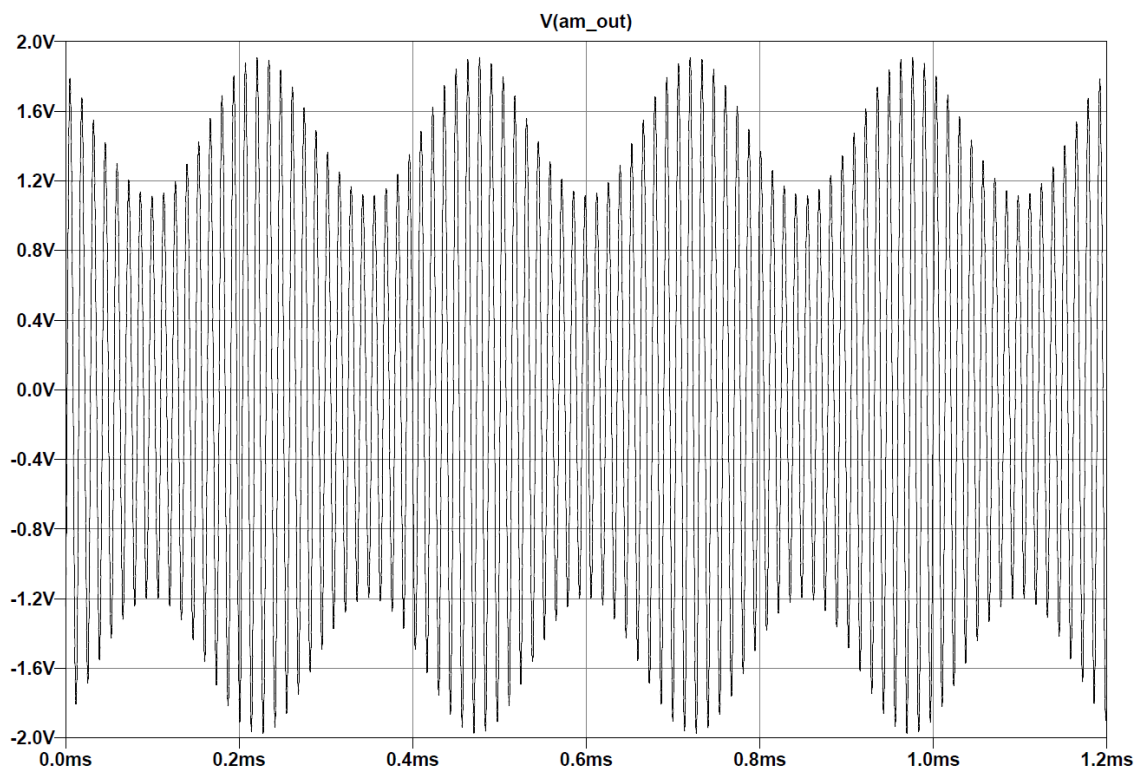


Figure 10: Simulated bode plot of the frequency response of the high Q bandpass filter.

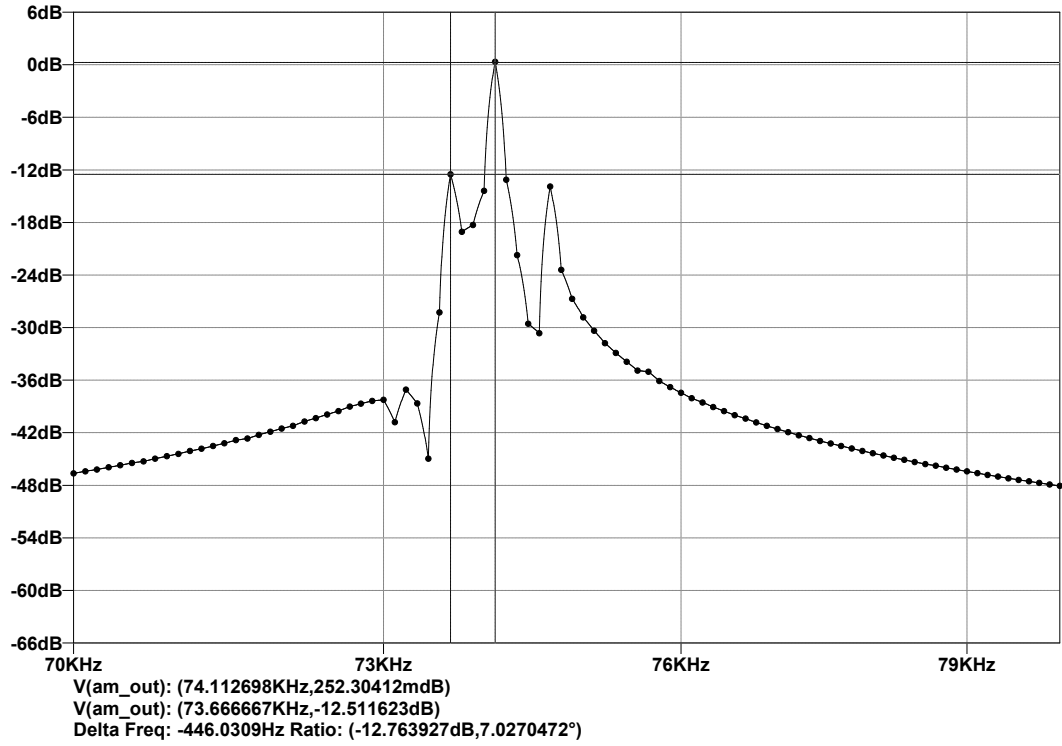


(a)

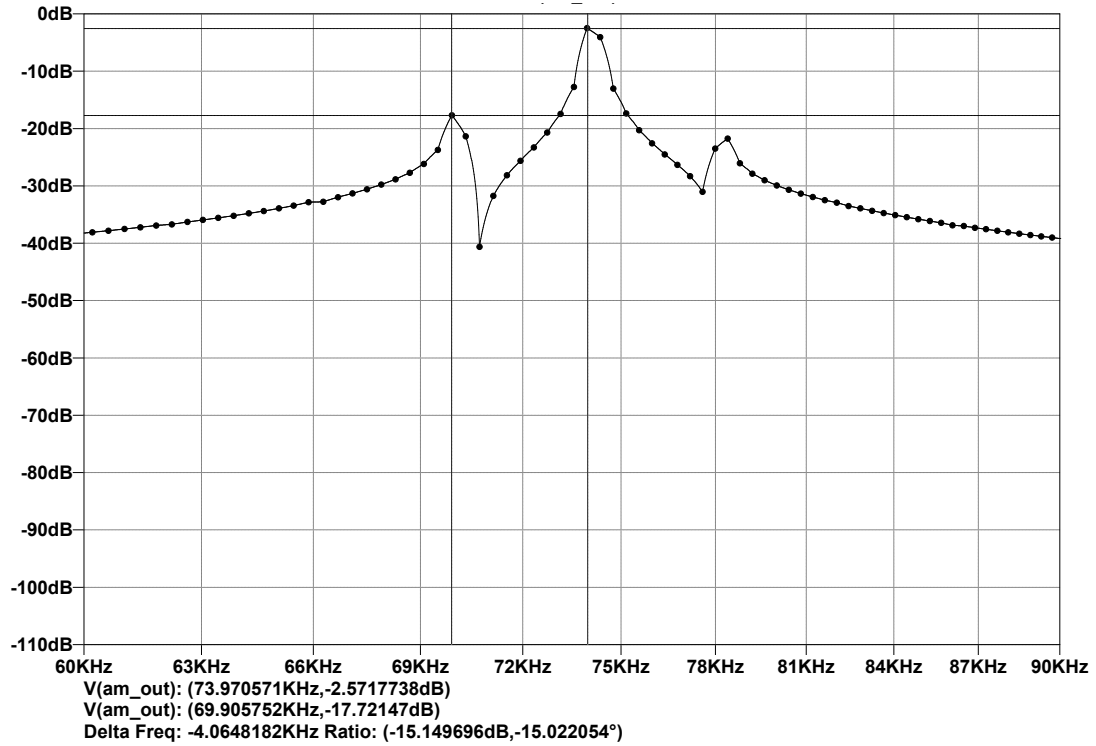


(b)

Figure 11: Time-domain responses of the high-Q bandpass filter for message signals of (a) 500 Hz, (b) 4 kHz.



(a)



(b)

Figure 12: Frequency-domain responses of the high-Q bandpass filter for message signals of (a) 500 Hz, (b) 4 kHz.

2.4 Power Amplifier

The power amplifier in this project amplifies the AM signal and provides a way to drive a high-power output, such as a low-impedance BNC cable and receiver. In this design, an op-amp is used to drive the complementary BJTs with the output providing negative feedback into the op-amp. The circuit is shown below in Figure 13, with the amplification provided by the usual inverting op-amp gain, $-R_2/R_1$.

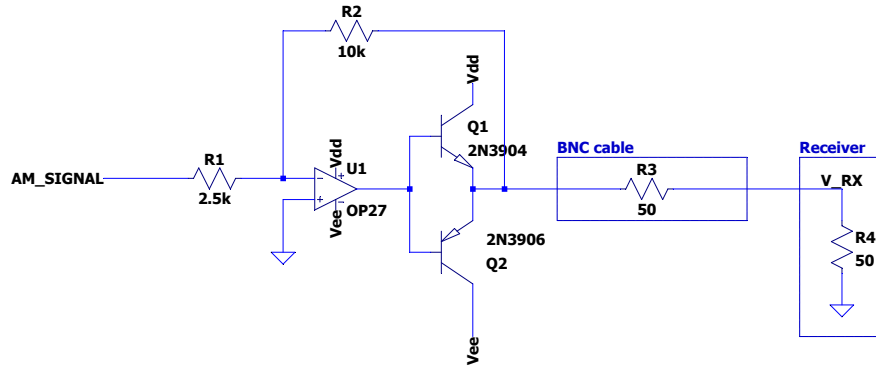


Figure 13: Circuit of the power amplifier used in the AM radio.

2.4.1 Design

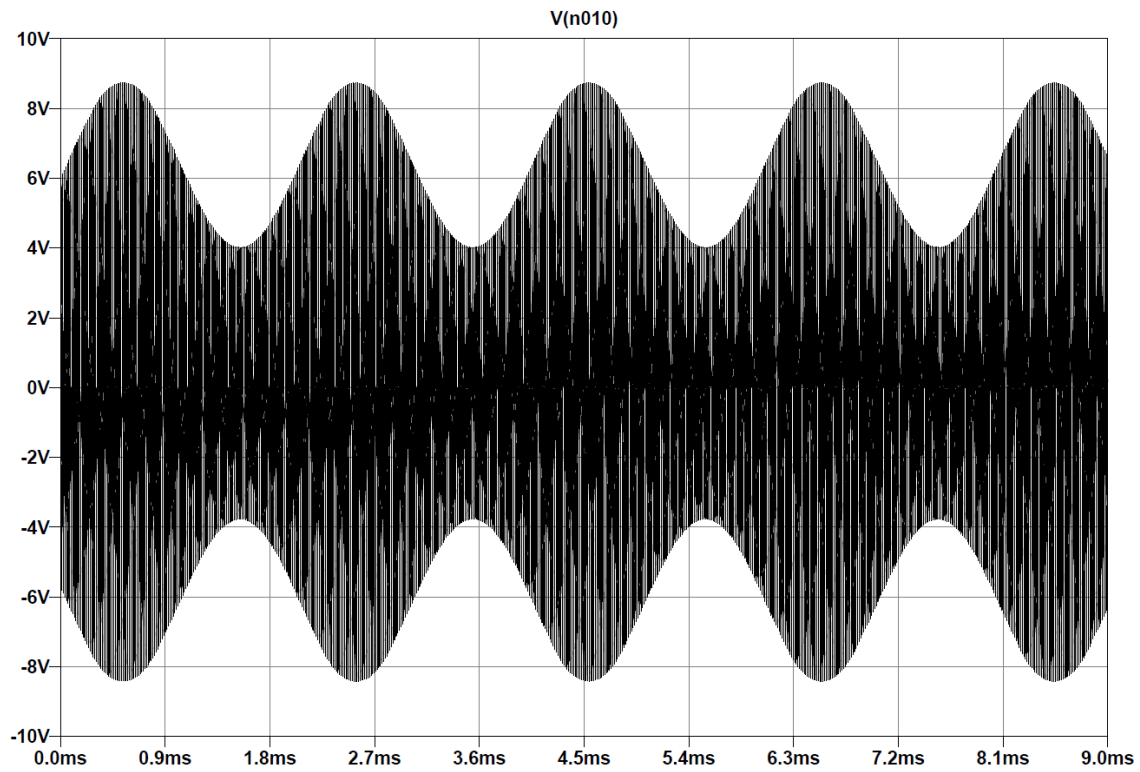
Given the limits of the power supply and the maximum swings of the input signals, a message voltage peak-to-peak 1.5 V will be aimed for. Through several iterations in LTspice, the resistors were chosen as

$$R_1 = 2.5 \text{ k}\Omega$$

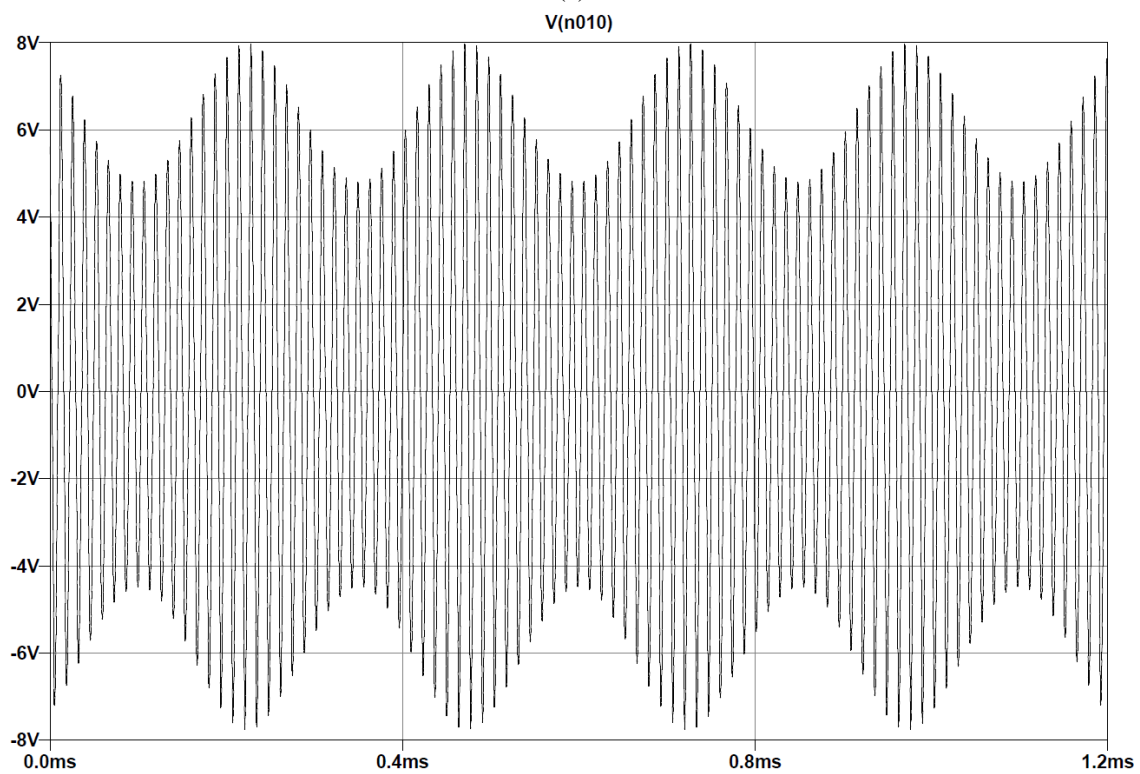
$$R_2 = 10 \text{ k}\Omega$$

2.4.2 Simulation

Simulating this in the time-domain, Figure 14, shows a peak output of roughly 8 V prior to the BNC cable impedance. As the voltage divider of the BNC cable and receiver halves the voltage, the magnitude at the receiver is 4 V. The envelope message signal is then approximately 1.5 V to 2.5 V in magnitude.



(a)



(b)

Figure 14: Output of the power amplifier for message signals of (a) 500 Hz, (b) 4 kHz.

2.5 Peak Detector

After the receiver, the message signal must be separated from the carrier wave. To accomplish this, a peak detector will be used, which will find peaks within the carrier signal, in turn giving a rough outline of the message signal.

A simple peak detector circuit will use a diode and an RC network on the cathode-side. When the input voltage swings upward, current will pass through the diode and will charge the capacitor at an equal voltage. On the negative swings, the voltage is retained by the capacitor and the diode will be reverse biased, and no current will pass through initially. While in reverse bias, the resistor will begin to drain the capacitor until the next peak detection.

The circuit used is shown in Figure 15 with a buffer on its output. Since the time constant of an RC network is given as

$$\tau = RC \quad (2)$$

We can determine an ideal R and C values based on the rise and fall time of the signal peaks. At a maximum potential difference between two peaks, an ideal time constant value can be determined as

$$\begin{aligned} V_1 &= V_0 e^{-\Delta T/\tau} \\ \tau &= -\Delta T / \ln(V_1/V_0) \\ &= -1 / [f_c \ln(V_1/V_0)] \end{aligned} \quad (3)$$

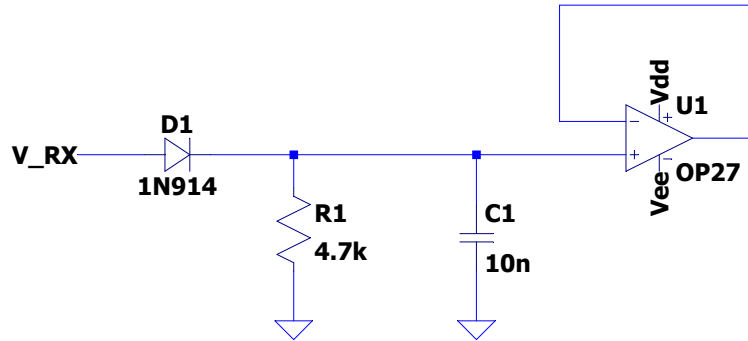


Figure 15: A peak detector circuit and output buffer.

2.5.1 Design

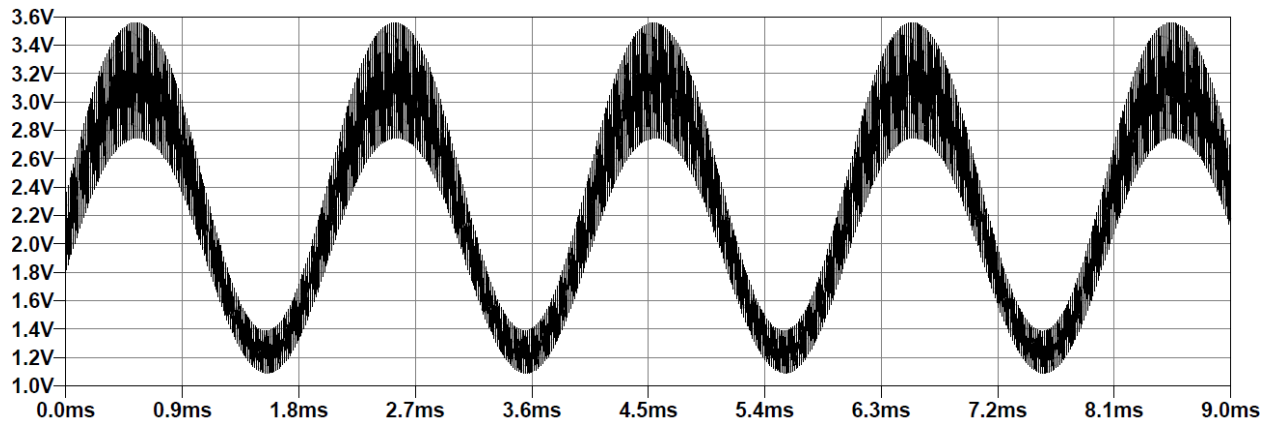
From simulating the power amplifier, the output has the highest difference in peak values of 2.95 V and 2.71 V. If a capacitor value of 10 nF is used, then an ideal resistor value can be found using (2) and (3),

$$\begin{aligned} \tau &= 159.3 \mu\text{s} = RC \\ R_{\text{max}} &= \frac{159.3 \times 10^{-6}}{10 \times 10^{-9}} \approx 16 \text{ k}\Omega \end{aligned}$$

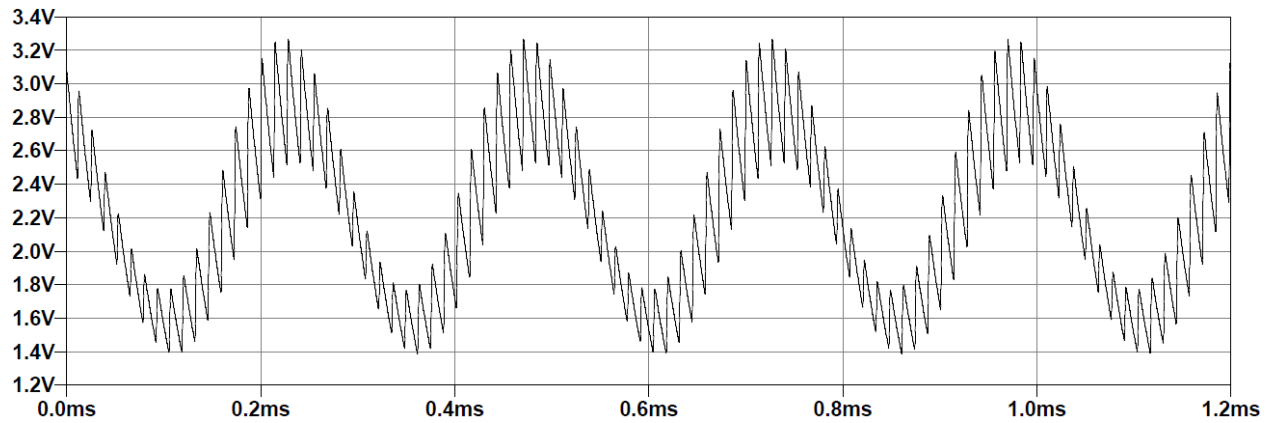
This resistance value gives an estimate of the maximum resistance needed. Any higher will prevent additional peaks from being detected, and lower resistance values will create additional noise to later filter. Here, it is best to err on the side of caution and choose a much lower resistance of 4.7 k Ω . Although doing so will create noise, it can easily be filtered out using a low-pass filter, allowing only the low-frequency message signal through.

2.5.2 Simulation

The peak detector was simulated on the full project circuit with both the 500 Hz and 4 kHz signal in the time domain, shown in Figure 16. For both message frequencies, there is a minimum of 180 mV of allowance as the voltage falls between peaks.



(a)



(b)

Figure 16: Output of the peak detector for message signals of (a) 500 Hz, (b) 4 kHz.

2.6 Bandpass Filter

The peak detector outputs significant noise must be filtered out. A second-order Butterworth low- and high-pass filter will be used to remove noise generated by the peak detector, as well as any other noise on the signal. It can be shown[2] that the transfer function of a Butterworth low- and high-pass filters shown in Figure 17 are given as

$$H_{LP}(s) = \frac{\omega_{c1}^2}{s^2 + 2\zeta\omega_{c1}s + \omega_{c1}^2} = \frac{1/C_1C_2R^2}{s^2 + \frac{2}{RC_1}s + \frac{1}{C_1C_2R^2}} \quad (4)$$

$$H_{HP}(s) = \frac{s^2}{s^2 + 2\zeta\omega_{c2}s + \omega_{c2}^2} = \frac{s^2}{s^2 + \frac{2}{R_2C}s + \frac{1}{R_1R_2C^2}} \quad (5)$$

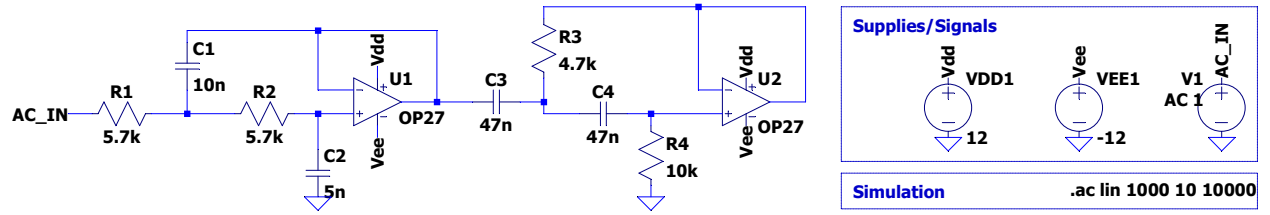


Figure 17: The two Butterworth filters used to filter the output of the peak detector.

2.6.1 Design

As the message signal is limited to 500 Hz to 4 kHz, the capacitor values can be chosen arbitrarily and used to calculate the resistances for those cutoff frequencies using (4) and (5). For the low-pass filter, the cutoff frequency is 4 kHz. Then, choosing 10 nF as first capacitor value, then

$$\begin{aligned} 2\zeta\omega_{c1} &= 2 \times 0.707 \times 2\pi 4000 \\ &= \frac{2}{RC_1} = \frac{2}{R \times 10 \times 10^{-9}} \\ R &\approx 5.7 \text{ k}\Omega \\ \omega_{c1}^2 &= \frac{1}{C_1C_2R^2} = \frac{1}{10 \times 10^{-9} \times C_2 \times (5.7 \times 10^3)^2} \\ C_2 &\approx 5 \text{ nF} \end{aligned}$$

Taking a similar approach for the high-pass filter and the low-frequency cutoff of 500 Hz,

$$\begin{aligned} 2\zeta\omega_{c2} &= 2 \times 0.707 \times 2\pi 500 \\ &= \frac{2}{R_2C} = \frac{2}{47 \times 10^{-9} \times R_2} \\ R_2 &= 9.58 \text{ k}\Omega \approx 10 \text{ k}\Omega \\ R_1 &\approx 4.7 \text{ k}\Omega \end{aligned}$$

2.6.2 Simulation

In this simulation, an AC sweep was used to determine how effective the filter was at removing frequencies outside of the expected bandwidth. The bode plot is shown below in Figure 18. After attaching the filter to the AM radio circuit, a time-domain simulation was done for both message frequencies. These are shown in Figure 19, displaying a sine wave with little distortion near the proper frequencies.

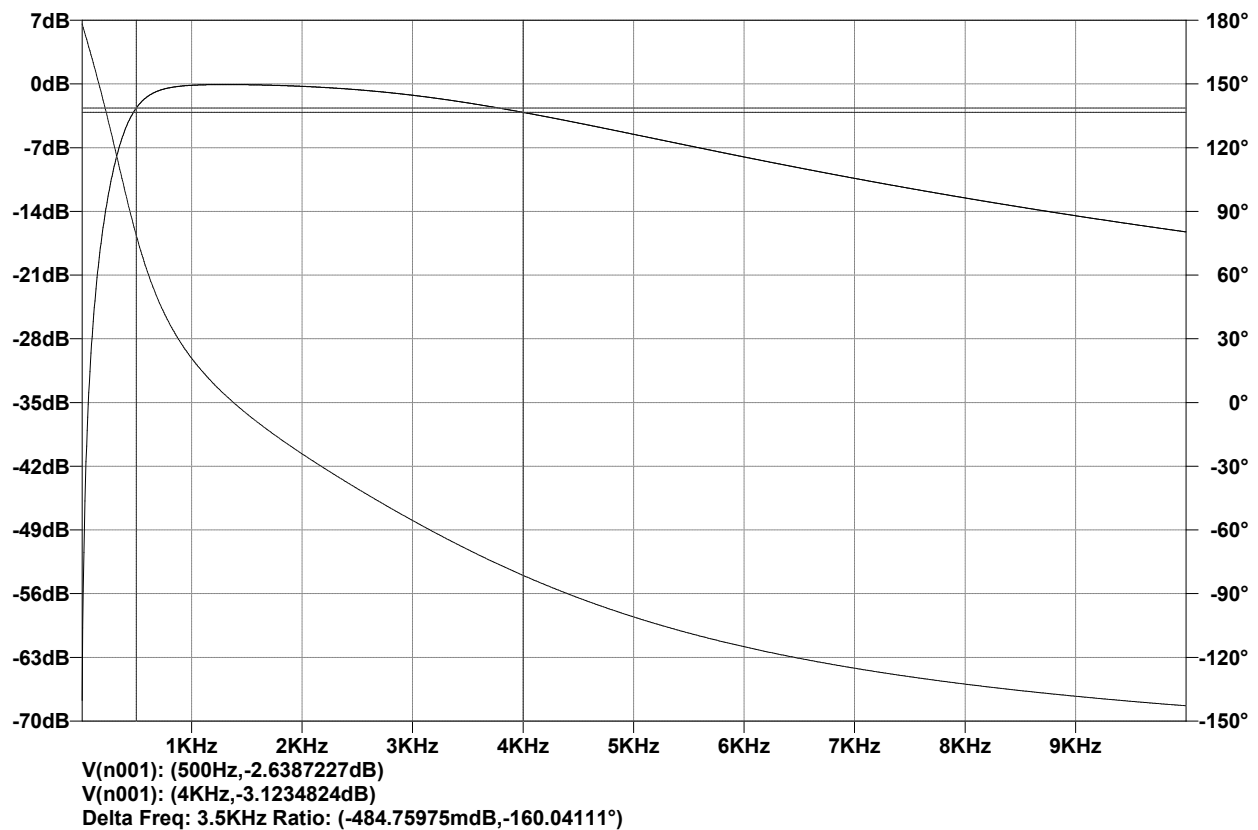
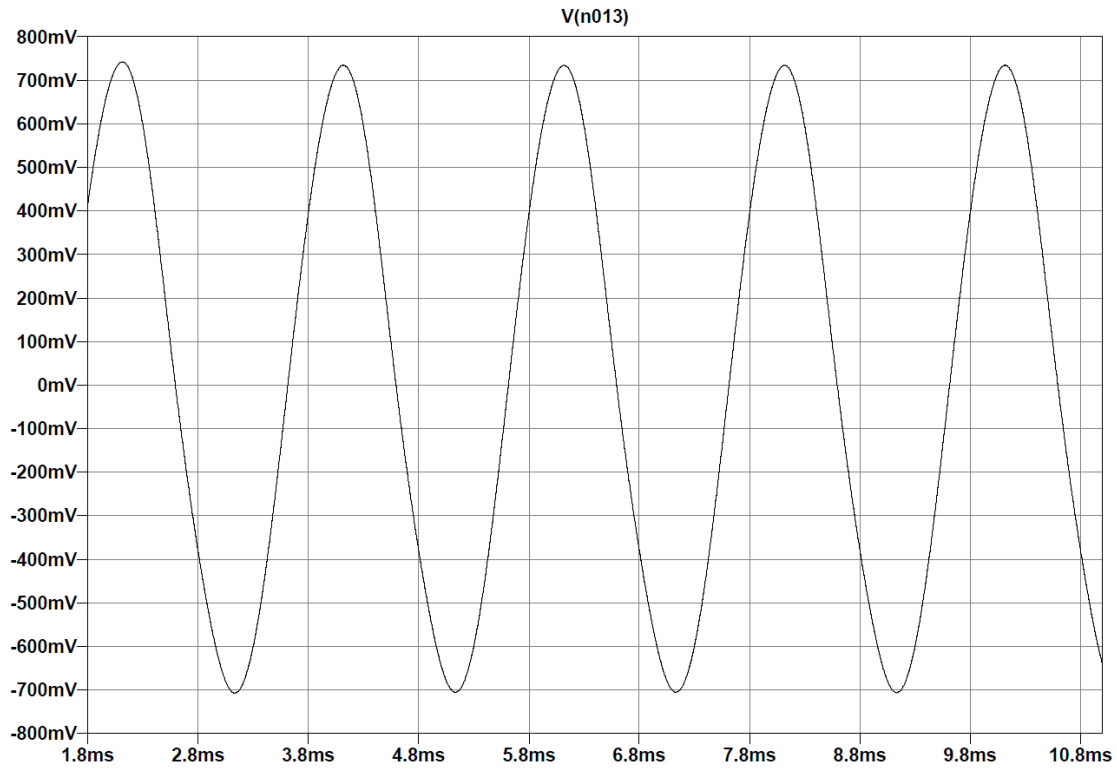
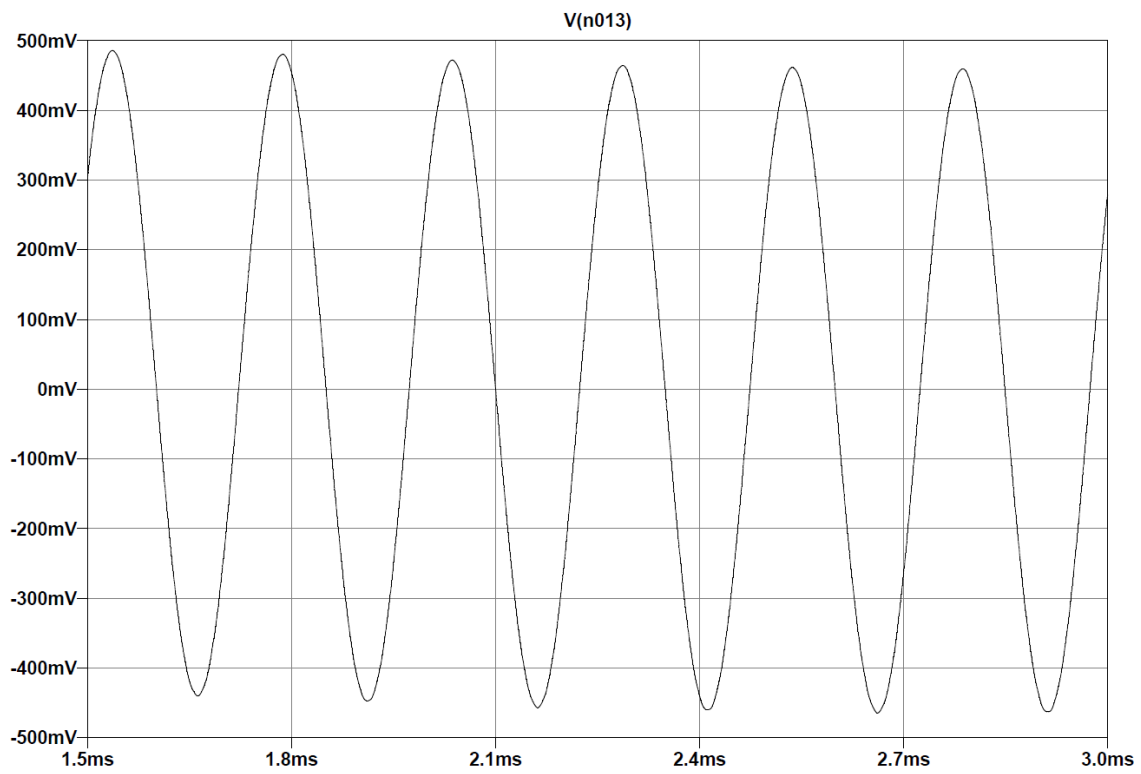


Figure 18: Simulated bode plot of the frequency response of the high Q bandpass filter.



(a)



(b)

Figure 19: Output of bandpass filter for message signals of (a) 500 Hz, (b) 4 kHz.

2.7 Schmitt Trigger

From the output of the bandpass filter, the message signal will be recovered as a sine wave. From this wave, a Schmitt trigger will be used to convert the sinusoid to a square wave, effectively as a comparator. This is accomplished by pulling an op-amp to saturation using the non-inverting input of the op-amp. The minimum voltages required to trigger the jump from each saturation voltage is determined by the resistances,

$$V_{I\pm} = -\frac{R_1}{R_2} (\mp V_{sat})$$

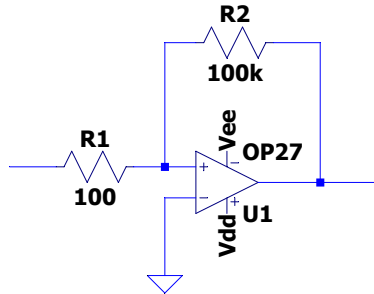


Figure 20: The Schmitt trigger circuit as used in the circuit.

In this circuit, a low threshold will be used in the Schmitt trigger by choosing

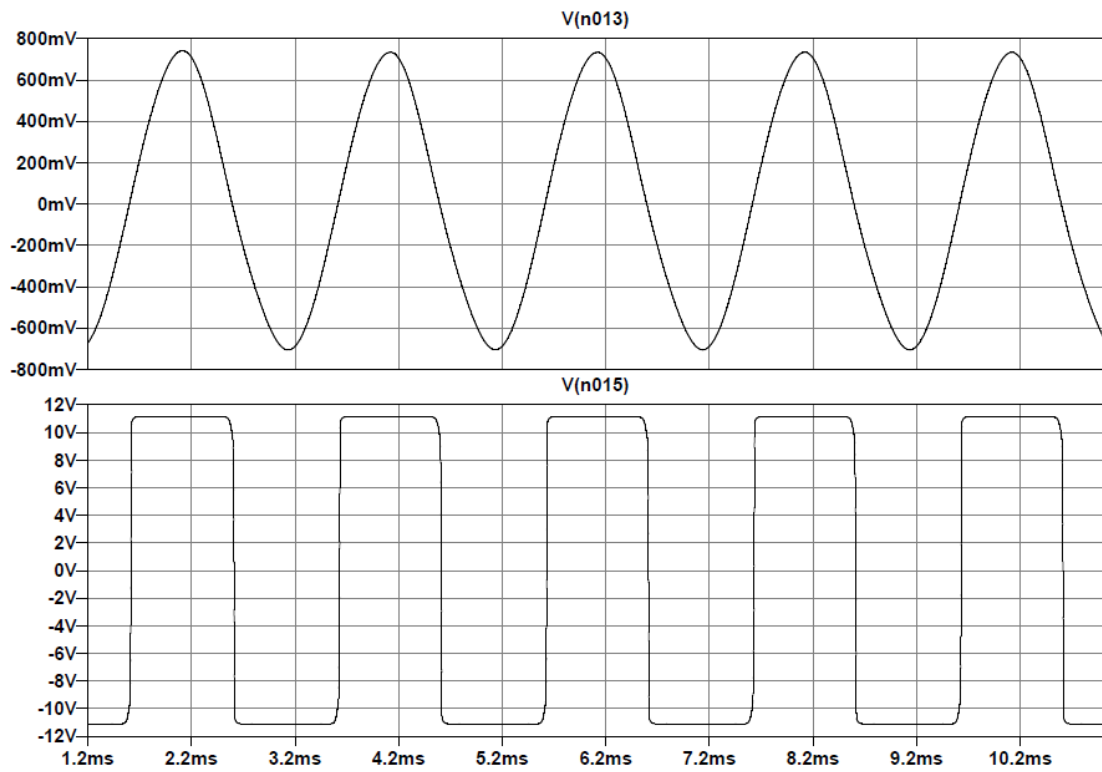
$$R_1 = 100 \Omega$$

$$R_2 = 100 \text{ k}\Omega$$

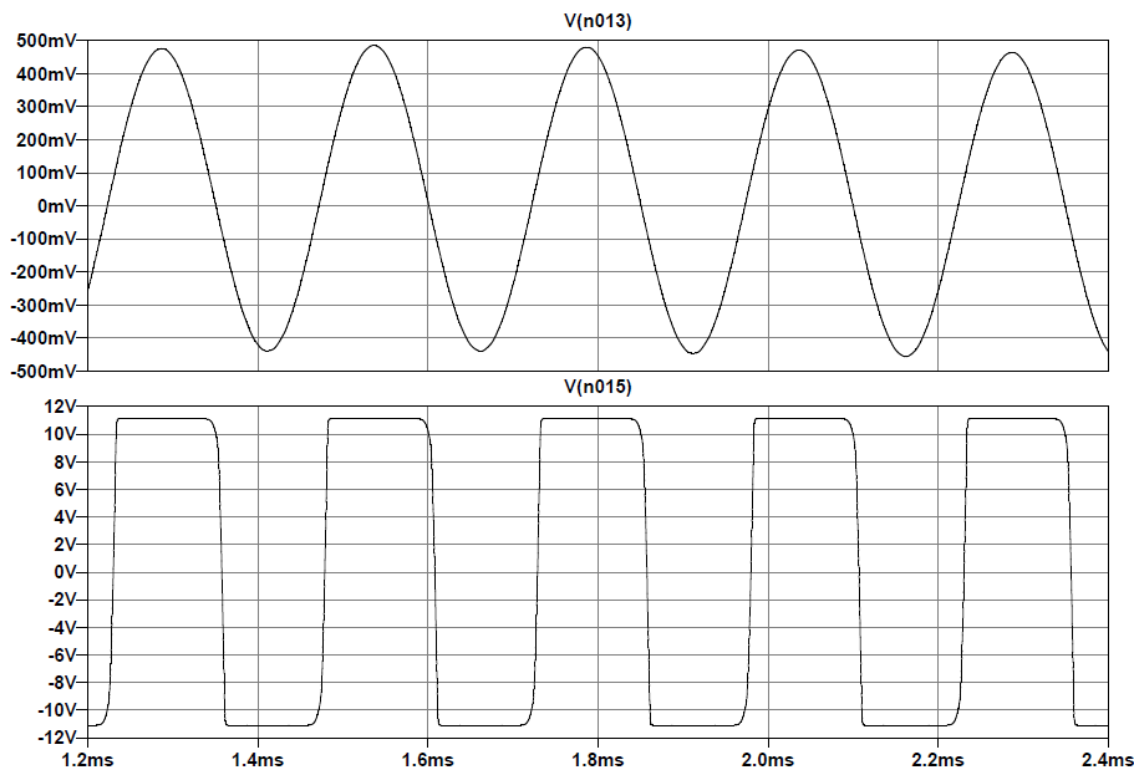
From this, when the input wave cross a threshold of 11 mV, the Schmitt will pull the voltage to the corresponding positive or negative saturation voltage.

2.7.1 Simulation

This trigger was simulated for both frequencies in the time-domain, as shown in Figure 21.



(a)



(b)

Figure 21: Output of Schmitt trigger for message signals of (a) 500 Hz, (b) 4 kHz.

2.8 Buffer Amplifier

Lastly, a half-wave rectifier and a simple buffer amplifier is used to drive a speaker. Here, a MOSFET is used as a switch to drive a low-impedance speaker. A voltage divider is used to adjust the gate voltage relative to the square-wave signal input—in turn adjusting the amplitude of the output sound waves. The figure for this is shown in Figure 22. In the circuit, the volume is adjusted to 66% of the magnitude of the input waveform.

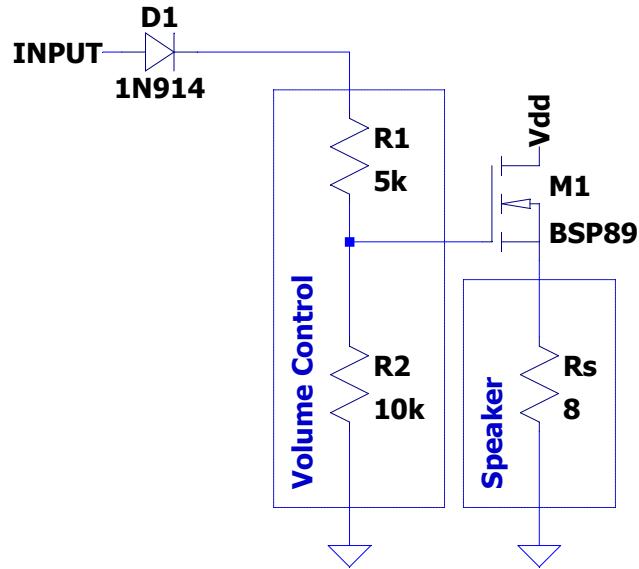
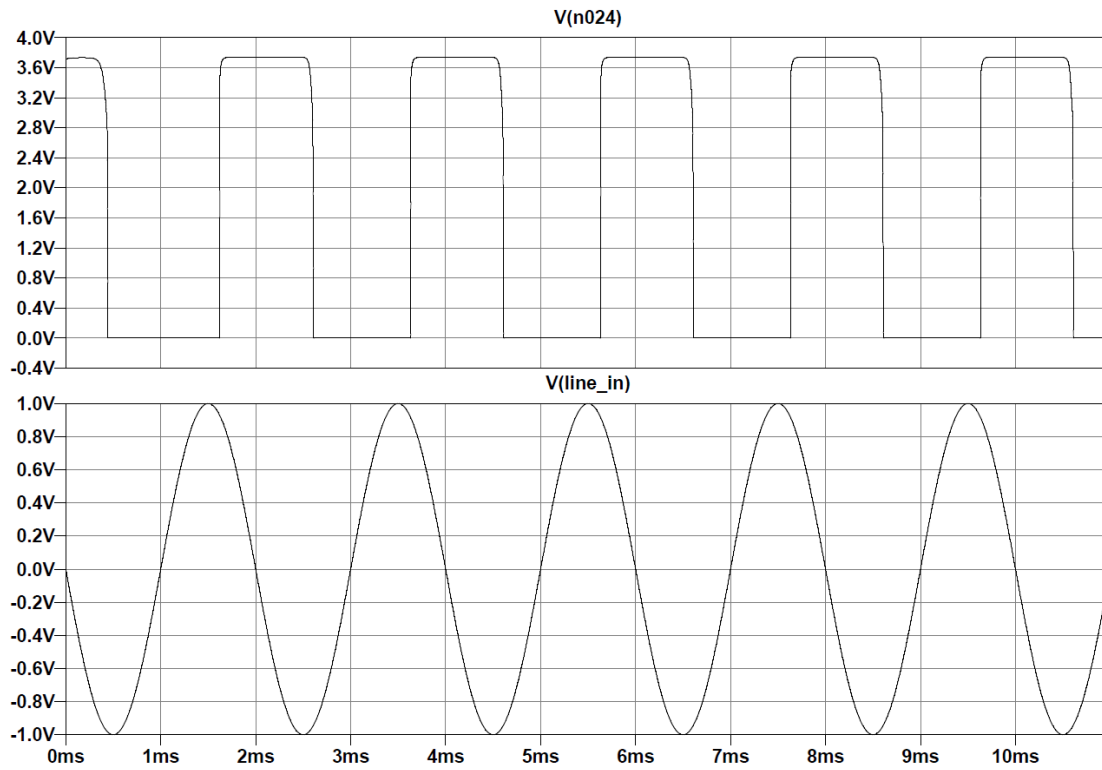


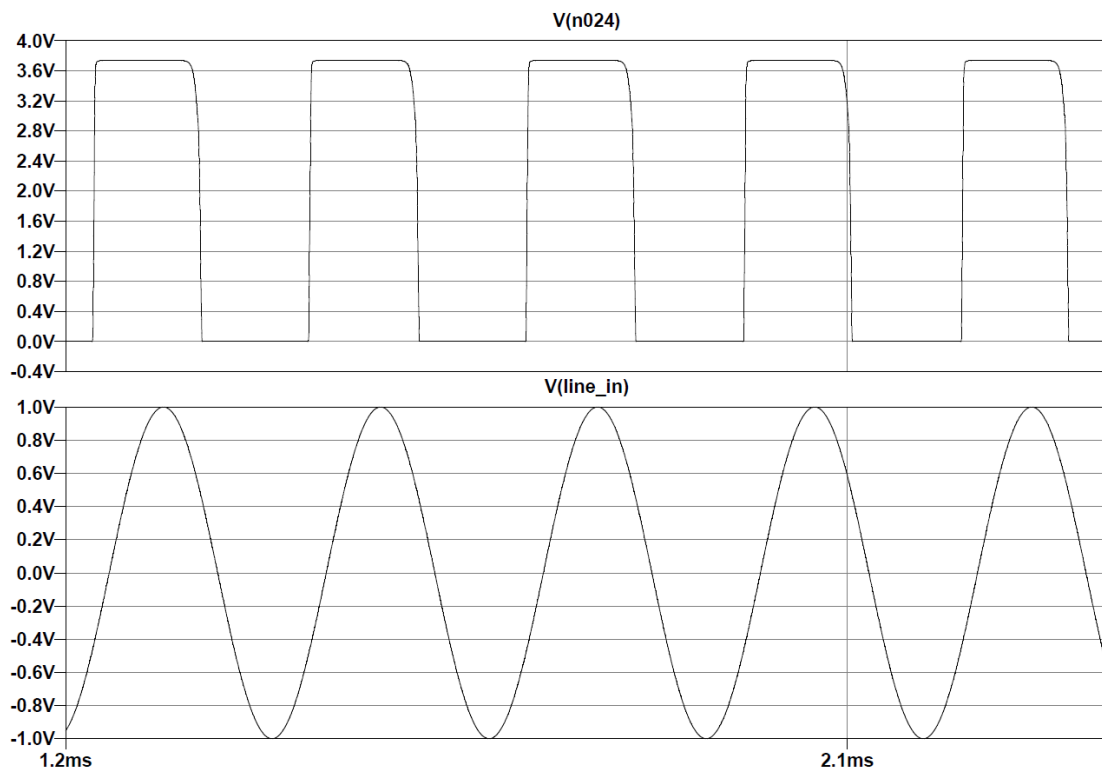
Figure 22: The buffer amplifier and driver for the 8 Ω speaker.

2.8.1 Simulation

At both frequencies, the amplifier was simulated in the time domain, as shown in Figure 23. At this current resistor configuration, the peak voltage seen by the speaker is 3.7 V.



(a)



(b)

Figure 23: Output of buffer amplifier driving the speaker.

3 Conclusion and Discussion

An AM transmitter and receiver was designed and simulated using LTspice. The designed met the required specifications and the outcome of the project was successful. Overall, the design can use several improvements to make the transmission more robust in the real-world. Although the project was simulated, it would be expected to work on a physical system with not many adjustments.

It should be noted that the design has several major drawbacks that could be fixed in iterative versions. First, the carrier oscillator is bound to drift significantly with time as both the resistances and capacitances of are bound to change with temperature. Additionally, there is no feedback in place aside from the RC-network gain. A recommendation would be to implement a crystal oscillator or to use a PLL attached to an external signal source.

Next, both the bandwidth and amplitude of the transmitter and receiver is bound by the limitations of amplitude modulation. Other methods of transmitting signals offer more-robust methods at the cost of higher complexity. One major flaw of this project was the simulation and whether or not LTspice accurately depicts real-world components. It is likely that building this circuit on a breadboard would lead to additional trimming and perhaps a redesign of some components.

References

- [1] A.S. Sedra, D.E.A.S. Sedra, K.C. Smith, and P.E.K.C. Smith. *Microelectronic Circuits*. Oxford series in electrical and computer engineering. Oxford University Press, 1998.
- [2] Susan Riedel James Nilsson. *Electric Circuits*. Pearson, 2015.

Appendix A

Code Snippet 1: MATLAB code for iterating over component values for the high-Q bandpass filter.

```
F_0 = 74000; % (carrier) frequency of the oscillator
W_0 = 2*pi*F_0; % Hz to rad/s
B = 2*(2 * pi * 4000); % bandwidth = 8 kHz
C = 1e-9; % choosing a common cap
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%R3 = 2/(B * C); % to get a perfect value for R3
R3 = 40000; % ~40k
%R1 = 1/(B * C); % similarly for R1
R1 = 20000; %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%R2 = 100 + 10 + 4.7; %
R2 = 100; %

Req = 1/(1/R1 + 1/R2);
W_test = sqrt(1/(Req * R3 * C*C));
F_test = W_test/(2*pi);
```

AM Project Check List1 PSPICE Simulation for Interim Report

Name: Kevin Evans
Partners: Jacob Huthart
Partner: Amir Ahmad al Amadi

- 1- MAH Oscillator Circuit
- 2- MAH AM Modulator (Mixer)
- 3- MAH Bandpass Filter
- 4- MAH Power Amplifier

Each group needs to show progress demo by checking each module.

Items 1-4 are need to be checked by March 13, 2020. This will give you a jump start to finish the project on time and without affecting your study time in other courses.

Figure 24: Sign-off sheet for the interim report.