

Design of Simple PLL FM Radiophone

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August 2024

Abstract

This paper describes the design of a custom-built FM radiophone. The topics covered are mainly on the filtering, amplification, and demodulation of FM signals to recreate sound signals.

Acknowledgments

I would like to extend a brief appreciation to Dr. Nutter for his brief yet valuable advice on components of this project.

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1. Introduction

An FM radiophone, a ubiquitous and often overlooked machine in our modern day is a simple yet precise device. Developed in the beginning of the 20th century, it served as a portal into long-distance communication and broadcasting. This is due to the ease of transmission and reception of high-frequency signals, which is simply attributed to component sizes. Firstly and most obviously, for a low-frequency signal to be transmitted and received, the antenna would have to be hundreds of meters long to operate a sinusoidal wave of 1 kHz. So that is a clear reason why we may modulate a signal to higher frequencies (which also ignores the fact we may want to broadcast multiple signals over the same area, therefore simply transmitting multiple 1:1 audio signals is impossible), however why should we use the presently designated FM band of 88 to 108 MHz? Why not simply replace the relatively inferior AM stations at lower frequencies with FM stations? This is where the internal component sizes come into play: To tune into and demodulate a 100 MHz signal, the components (namely capacitors and inductors) are far smaller than a 148.5 kHz to 43.98 MHz. Smaller components are more economical, more accessible, and- naturally- easier to make compact devices with. Furthermore, FM waves are less prone to distortion, use less power, and are statistically perfectly predictable power consumption-wise, hence the modern preference of FM compared to AM. [1]

With the history and justification out of the way, we can delve into the overview of the machine. As seen in Figure 1, it consists of nine stages: the input and output stages, two filtration stages, three amplification stages, the tuning stage, and a demodulation stage. This paper will explain each of these stages in that order.

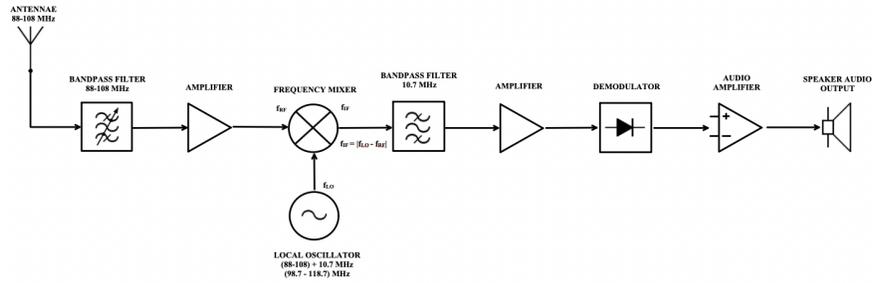


Figure 1: Abstract Diagram of FM Radiophone

Following Figure 1, the signal takes an interesting set of steps to turn from an FM signal into an audio signal. First, the signal that the antenna picks up is filtered to just the FM radio band of frequencies. That signal is then amplified into the tuning stage, where a mixer accepts it and an oscillating signal at the frequency of the desired FM radio channel. That then outputs an intermediate frequency with that does not change station by station, making the rest of the circuitry easy and specific. This intermediate frequency is considerably lower than any of the original radio frequencies, so those are easily filtered out with another filter. The intermediate frequency is amplified and then demodulated from an FM signal into an audio signal. This is once more amplified and then outputted via a speaker.

2. Input and Output

The simplest portions of this project, the input and output stages consist of an antenna and a speaker, respectively. The only real necessity of the antenna is that it connects to the lab's standard connection, a BNC connector. The speaker is equally nebulous in choice, as the radiophone designed only outputs a mono output and is not especially loud. Therefore, any typical 0.5 – 3 W speaker is suitable.

3. Filtration

There are two explicit stages of filtration, the RF and IF filtration stages. To be clear, further filtration occurs within other stages, however that does not pertain to overall signal manipulation and is sometimes not a design goal but a limitation.

The RF (radio frequency) filtration stage aims to isolate the FM radio band of 88 to 108 MHz. This is mainly done so that signals outside that range do not interfere with the processes to process the desired signals. Naturally, the filter used here is a bandpass filter, specifically a passive 3rd Order Butterworth filter. This was used for the “maximally flat” response that a Butterworth design offers us, and that is crucial since we need the amplitude of the input RF signal to be as consistent as possible so that the output signal has minimal distortion that may be caused due to error in derivation of the RF signal by virtue of the waveform slopes not having the appropriate shape. Figure 2 displays the design of this filter, with standard components. Of note is that all the inductors are the same. Since they have to be wound manually, it is a lot easier to try and make multiples of the same specification and gain a consistency than to have to figure out the best possible fit for multiple specifications. However, they are still a bit imprecise, so, as Figure 3 illustrates, some of the capacitors are variable, so that the appropriate characteristics may be realized. In total, this creates a decent filter. Figure 4 shows that this design and implementation results in a slight dip at the middle and an overall loss of about 2.5 dB across the passband. Furthermore, the filtering of the lower frequencies is a lot more effective than the filtering of the higher frequencies.

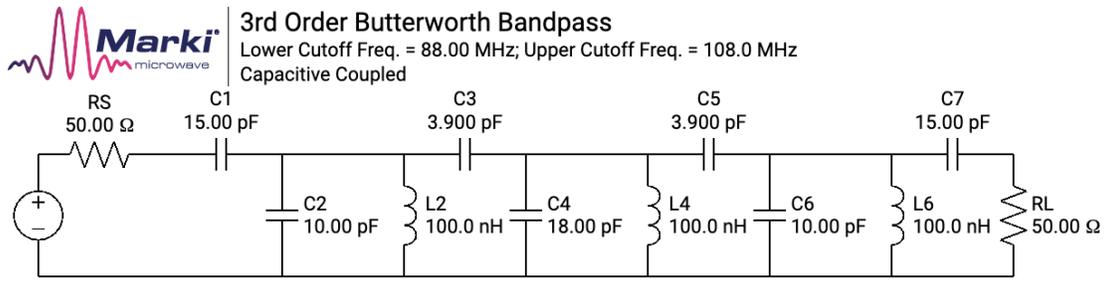


Figure 2: RF Bandpass Filter Design

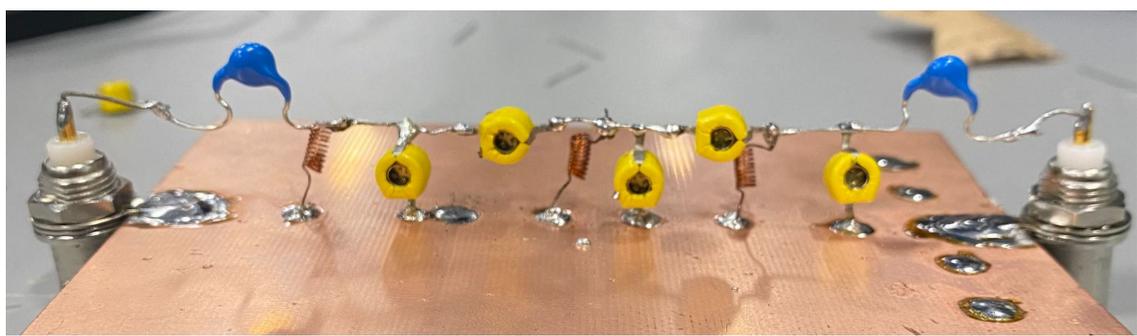


Figure 3: RF Bandpass Filter Hardware Implementation

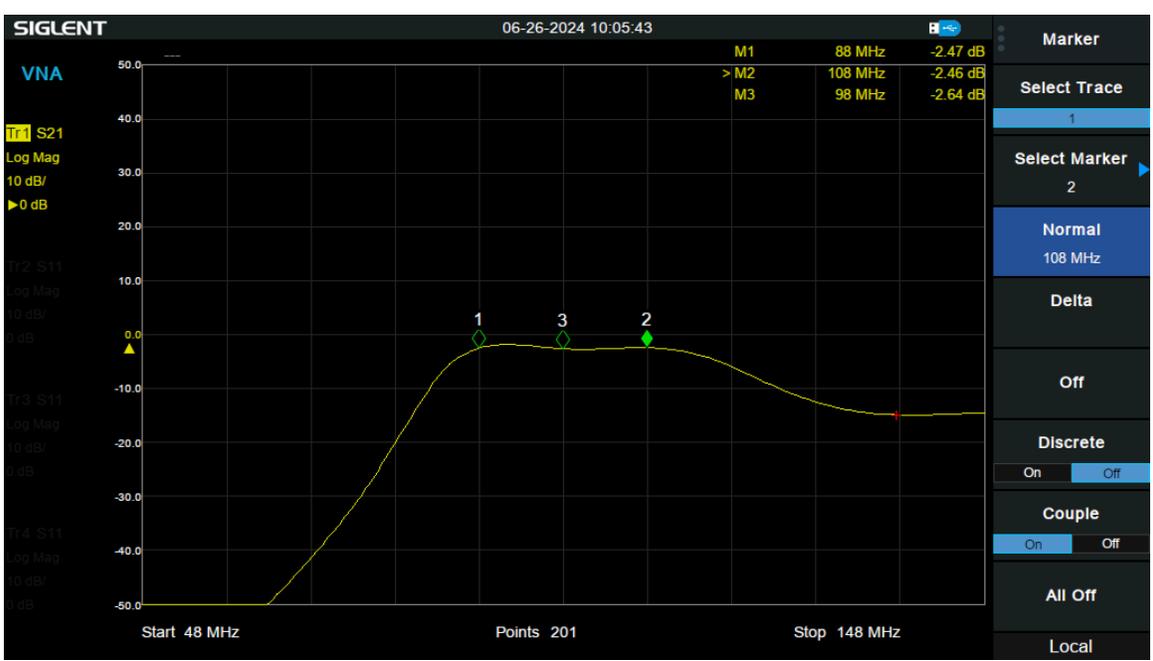


Figure 4: RF Bandpass Filter Characteristics

The IF (intermediate frequency) filter follows a similar path, however with a difference in passband frequencies- it is only across 10.6 to 10.8 MHz. Figure 5 shows how this consideration affects the design, and Figure 6 shows the built implementation. This filter is a 2nd Order Butterworth, as it is found it helps allowing for a wide enough passband. Notice that this time all the capacitors are fixed. It happened to be this time that the variable capacitors were not appropriate characteristically. Figure 7 shows the results of this. Further notice that the peak at the desired center of the passband is at - 8.77 dB. This can be attributed to the poles of the two ends of the filter being closer together (compared to the case of the RF filter), causing the increased passband loss.

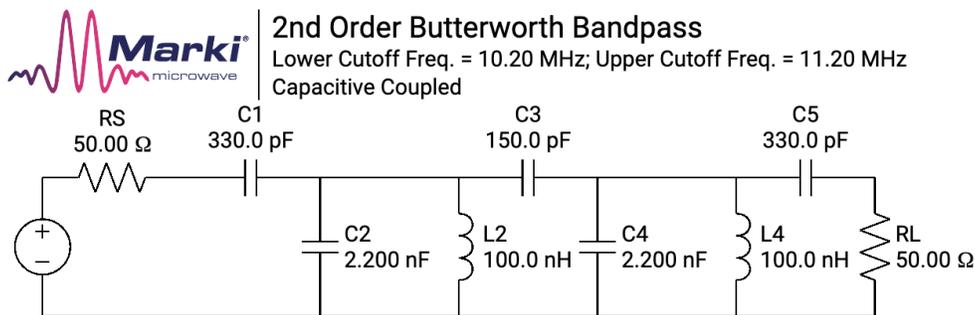


Figure 5: IF Bandpass Filter Design

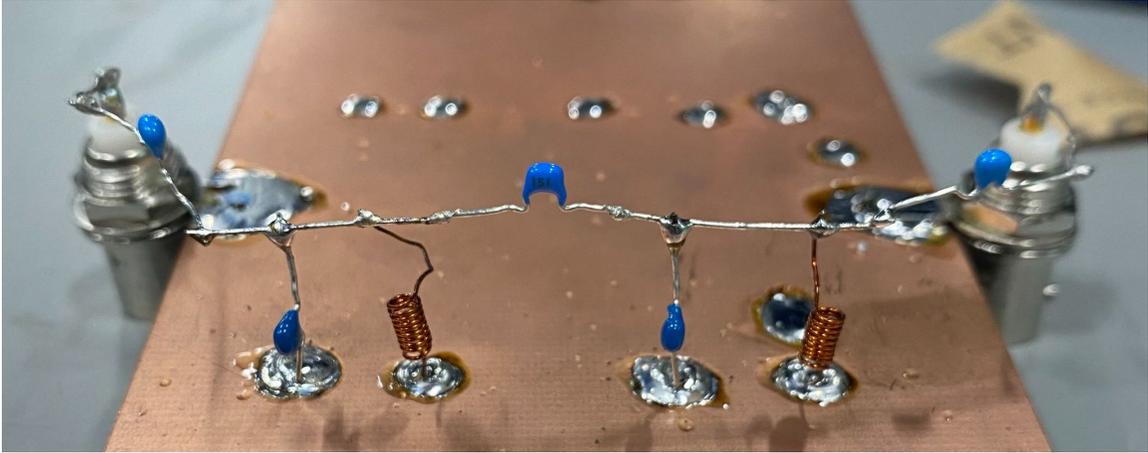


Figure 6: IF Bandpass Filter Hardware Implementation

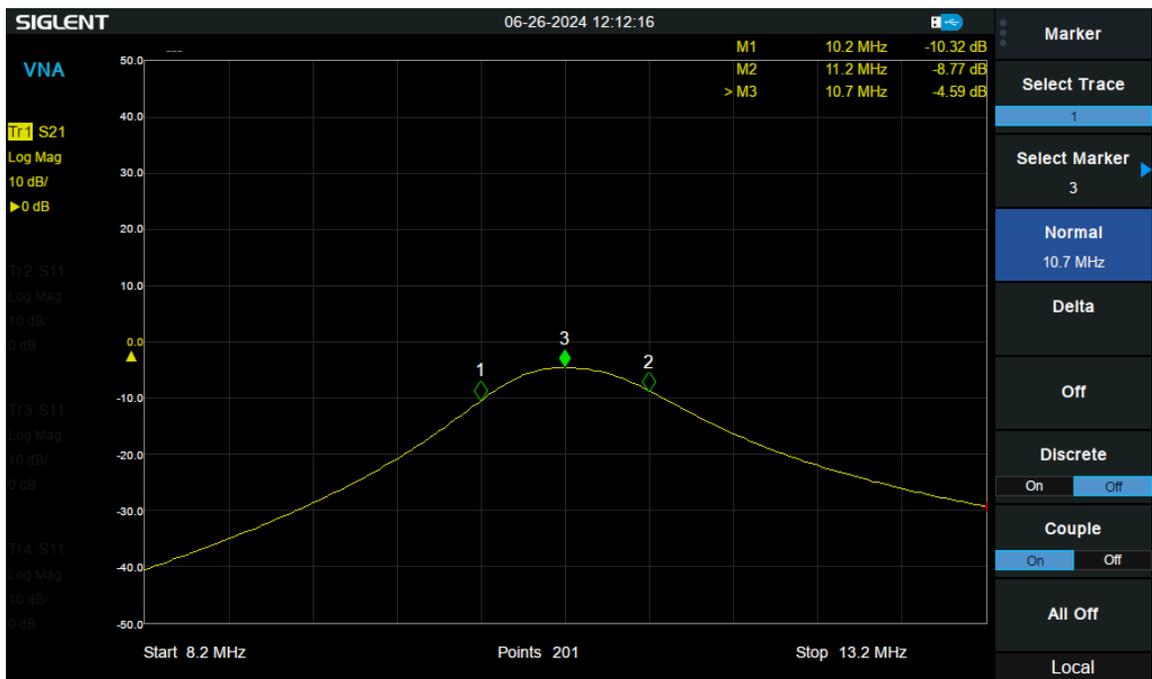


Figure 7: IF Bandpass Filter Characteristics

4. Amplification

The amplification of the RF and IF signals follows a similar path to the filters, in that they are generally of similar architecture and design, simply adjusting for what

frequencies each is meant to operate. Both filters use a common-emitter architecture. The RF stage amplifier utilizes a 2N5179 transistor, which is specifically designed for RF operation. The IF stage can more simply utilize a 2N2222, since the IF signal remains relatively low-frequency in comparison, and does not operate at a wide bandwidth.

The design of a single stage of the RF amplifier is shown in Figure 8. The full amplifier involves three of these amplifiers in series. The best results of the built circuit in Figure 9. This specific example is able to produce about 28 dB of gain at the desired frequencies (original signal was set at -50 dBm).

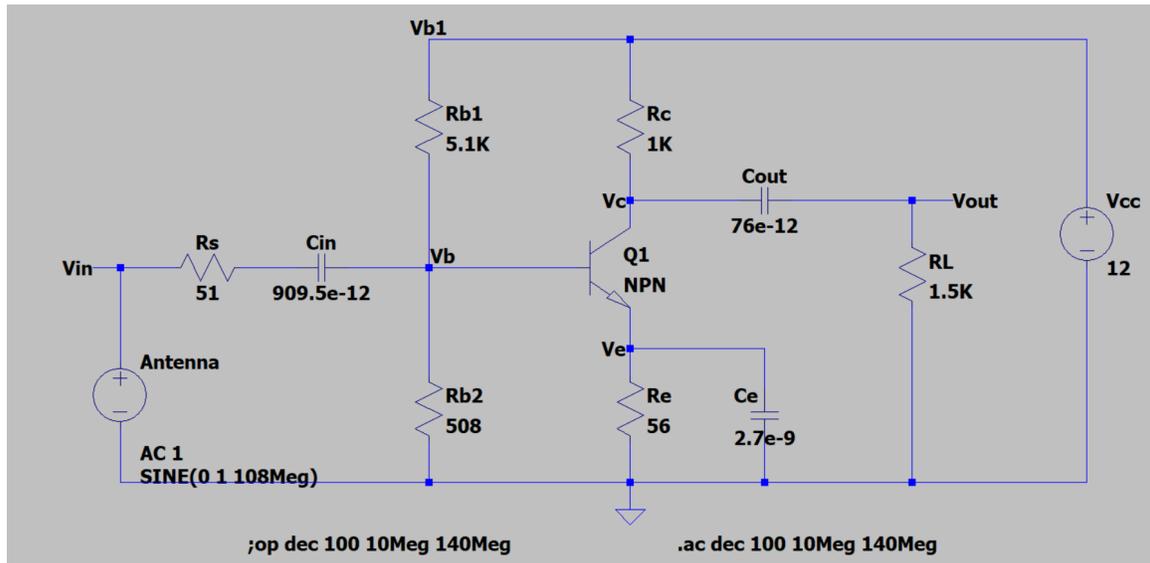


Figure 8: Single Stage of RF Common Emitter Amplifier Design

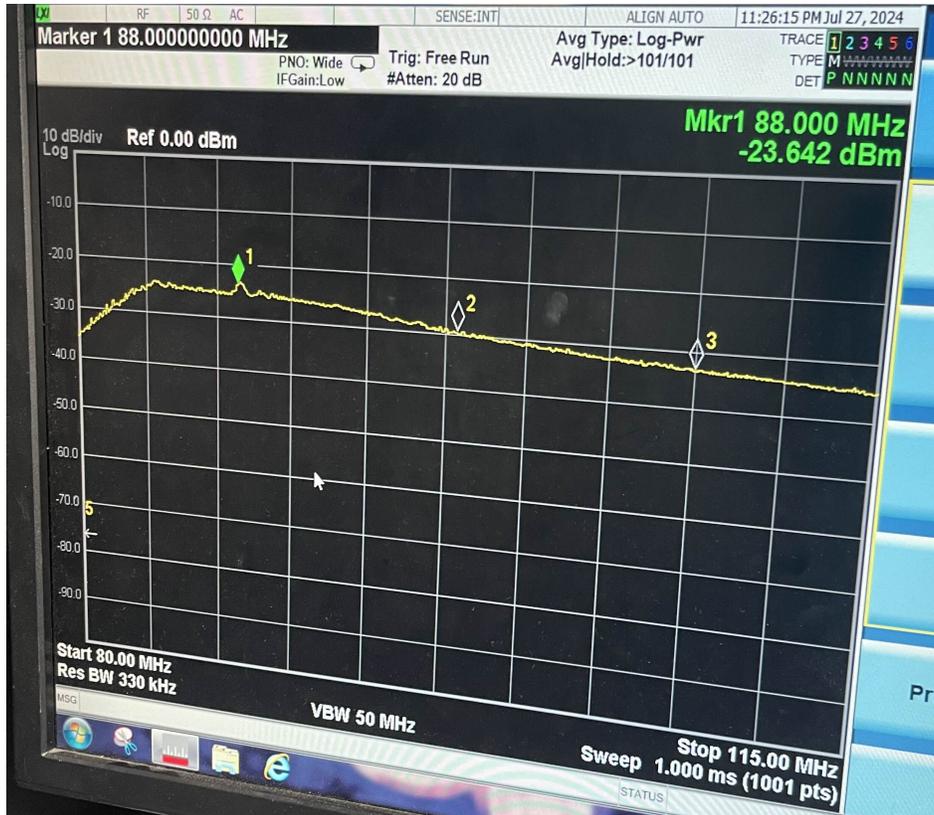


Figure 9: RF Common Emitter Amplifier Hardware Results

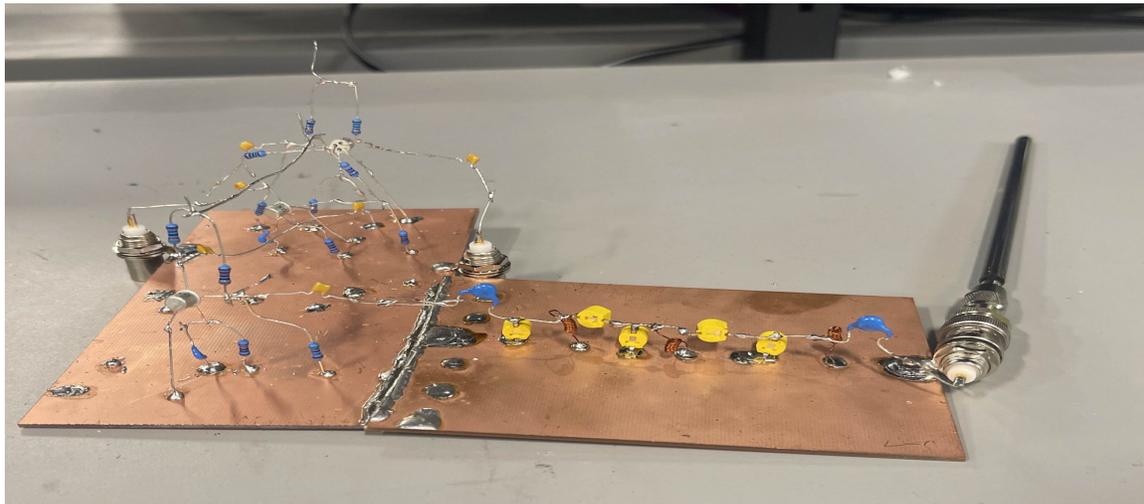


Figure 10: RF Amplifier with Bandpass Filter and Antenna

For the IF stage amplifier, a similar three-stage CE amplifier, as shown in Figure 11, was built. Figure 12 shows the results of this amplifier, being 50dB of gain at the desired 10.7 MHz center frequency (the original signal was -50dBm). The schematic of a single stage is in Figure 13. An interesting part of this amplifier is the high voltage used to drive the circuit, 25 V. This provides the fantastic gain, however also can cause issues with heat. At times, connections can come loose as the solder melts. For short periods of operation, however, this is a non-issue.

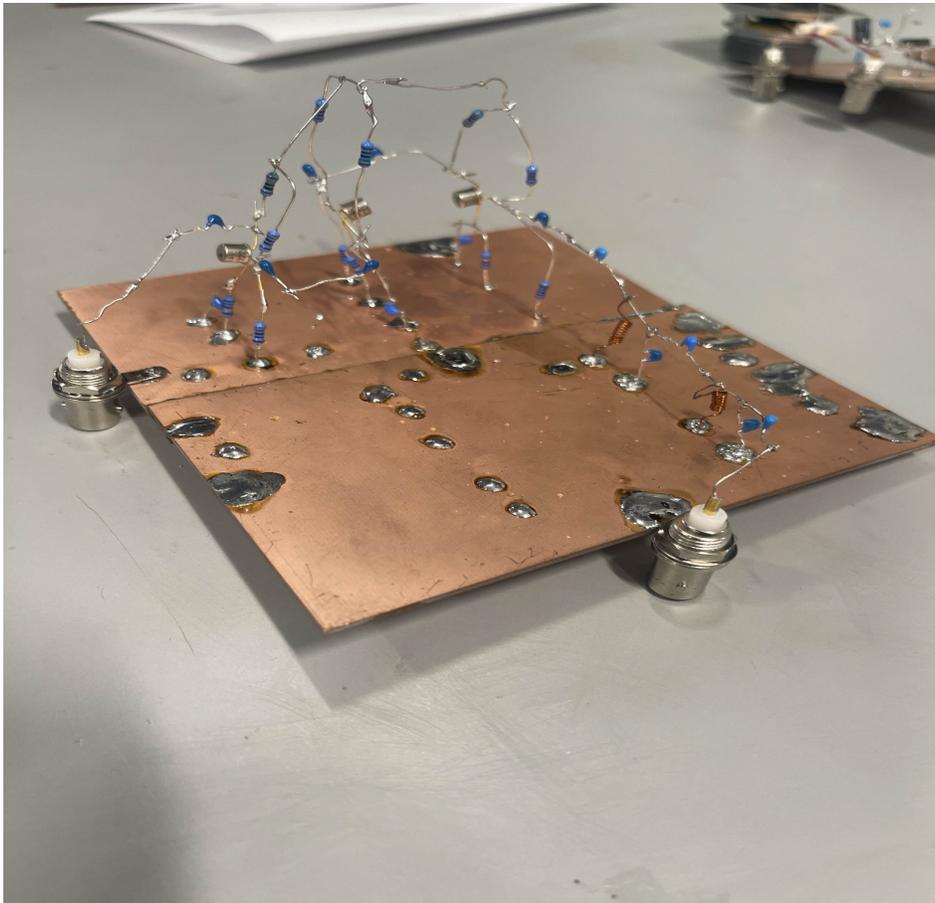


Figure 11: IF Stage Amplifier and Bandpass Filter



Figure 12: Results of IF Stage Amplifier

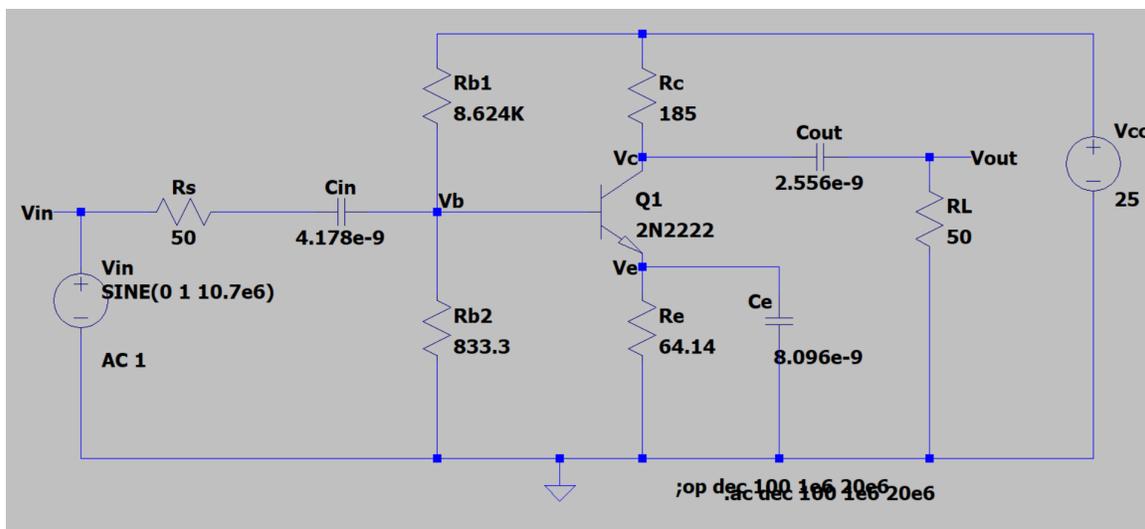


Figure 13: Design of Single IF CE Amplifier

As for the audio amplifier, the conventional solution is to use an LM386 op-amp as shown in Figure 14. Figure 15 shows this circuit built, and it provides a gain of 200 dB.

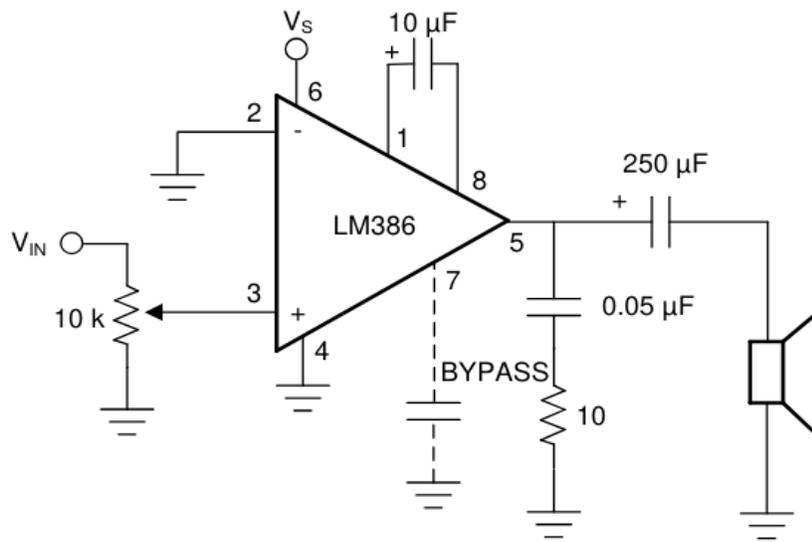


Figure 14: Audio Amplifier Schematic [2]



Figure 15: Built Audio Amplifier with 3W Speaker

An interesting point to note across all of these stages is how gain becomes easier to achieve down the line. This is proof that one trades gain for bandwidth and vice-versa. The RF stage is 20 MHz wide, the IF is 200 kHz wide, and the audio is 20 kHz wide, meanwhile the gain increases in that order with less amplifier involvement.

5. Tuning and IF Generation

The next stage to cover is to tune into the desired radio frequency and to translate that signal into an IF signal. This is done by affecting an oscillator circuit tuned to 10.7 MHz (the standard FM IF). The hardware used for this is an SA602A Double-balanced Mixer and Oscillator chip. Figure 16 shows the logic diagram of the chip. In essence, the tuned FM signal will interact with the oscillator, which is tuned externally to the IF thanks to a Colpitts oscillator circuit (per Figure 17). The mixed signals will be outputted in a balanced manner. At this point, the IF bandpass filter removes the original RF signal that is still present on the mixer output. A built example of this circuit is in Figure 18. The variable capacitor at the top of the photo is how one tunes into the desired RF FM frequency. This process has a loss of about 5 – 10 dB, which is why the IF amplifier follows the mixer.

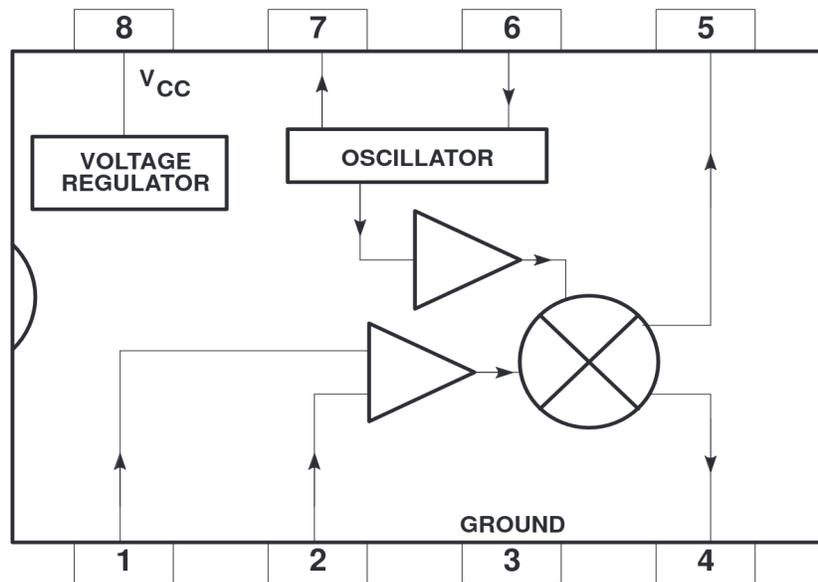


Figure 16: SA602A Logical Diagram [3]

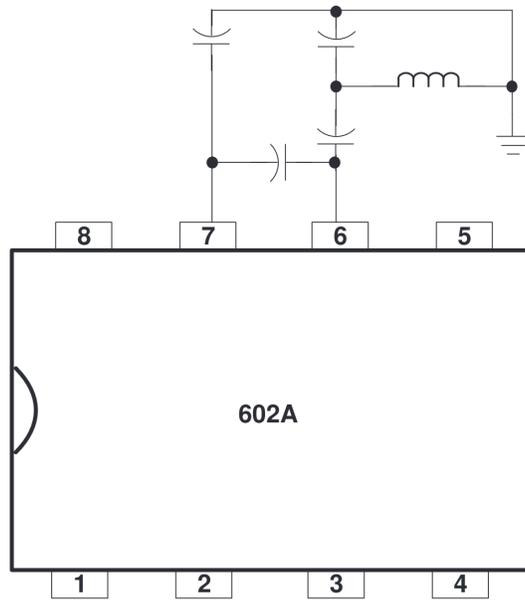


Figure 17: SA602A Colpitts LC Tank

Example Circuit [3]

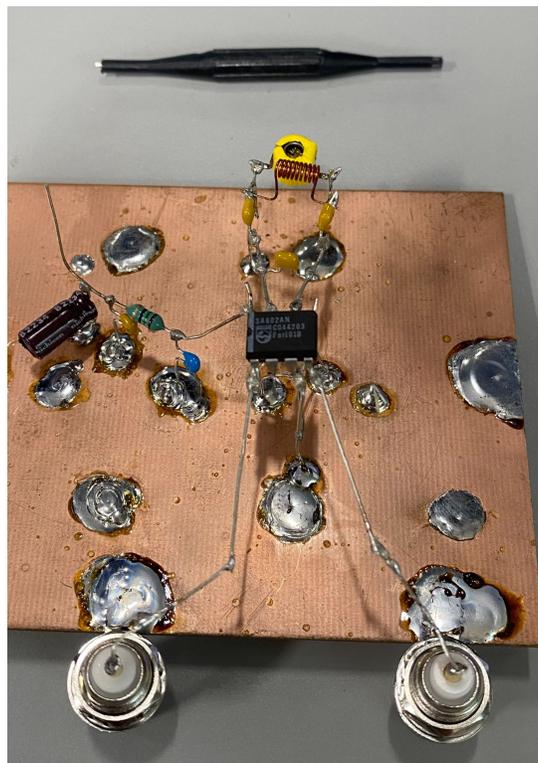


Figure 18: Built IF Mixer

6. Demodulator

The demodulator circuit is based on a PLL (phase-lock-loop) architecture. The simple process of it is that the FM-encoded signal comes into a phase comparator, is filtered with a low-pass filter (often a first-order RC filter suffices due to the distance between the FM and audio signals on the frequency spectrum), and is fed back through a tuned VCO (voltage-controlled oscillator) into the phase comparator. The VCO is tuned in a way that will create a 90° phase-shift compared to the original signal. Figure 19 shows this process graphically. Note that the top-left VCO is instead our IF signal generation, filter, and amplification stages, and that the multiplication and division is implied by the hardware.

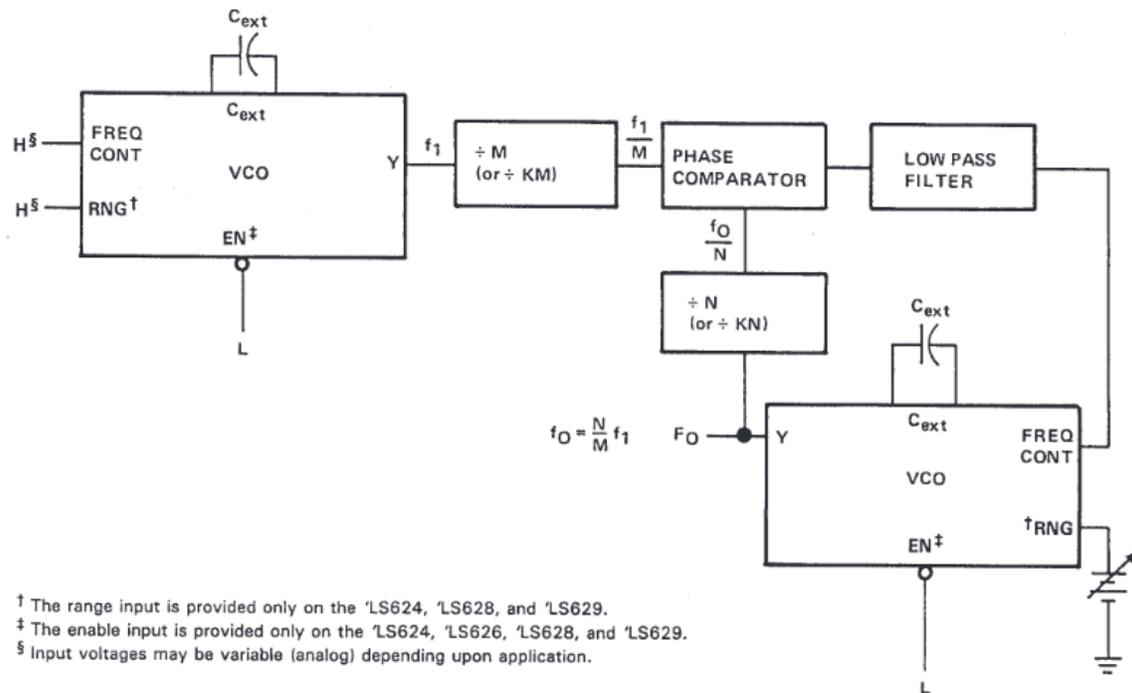


Figure 19: PLL Diagram [4]

The best way to tackle this is to use a PLL demodulator chip, such as the CD74HCT7046AM96, whose logic diagram can be seen in Figure 20. The VCO and phase comparator are built into the chip, and the LPF is added on by the designer of the system. The designer also chooses the capacitor and resistor(s) to tune the circuit to lock onto the appropriate frequency- in this case, 10.7 MHz. How to choose these components is seen in Figure 21. The last thing to consider is which phase comparator to use, as this chip possesses two of different architectures. In this case, the first option, an XOR-network phase comparator is used, as this one's operation is more akin to a Gilbert-cell mixer. With this architecture, the input and feedback signals are at a 90 degree phase difference when locked, allowing for the appropriate demodulation. The other phase comparator meanwhile keeps the two signals in phase, which is not necessarily the best way to go about this topic. [5] Note that Figure 20 shows the second phase comparator being used instead.

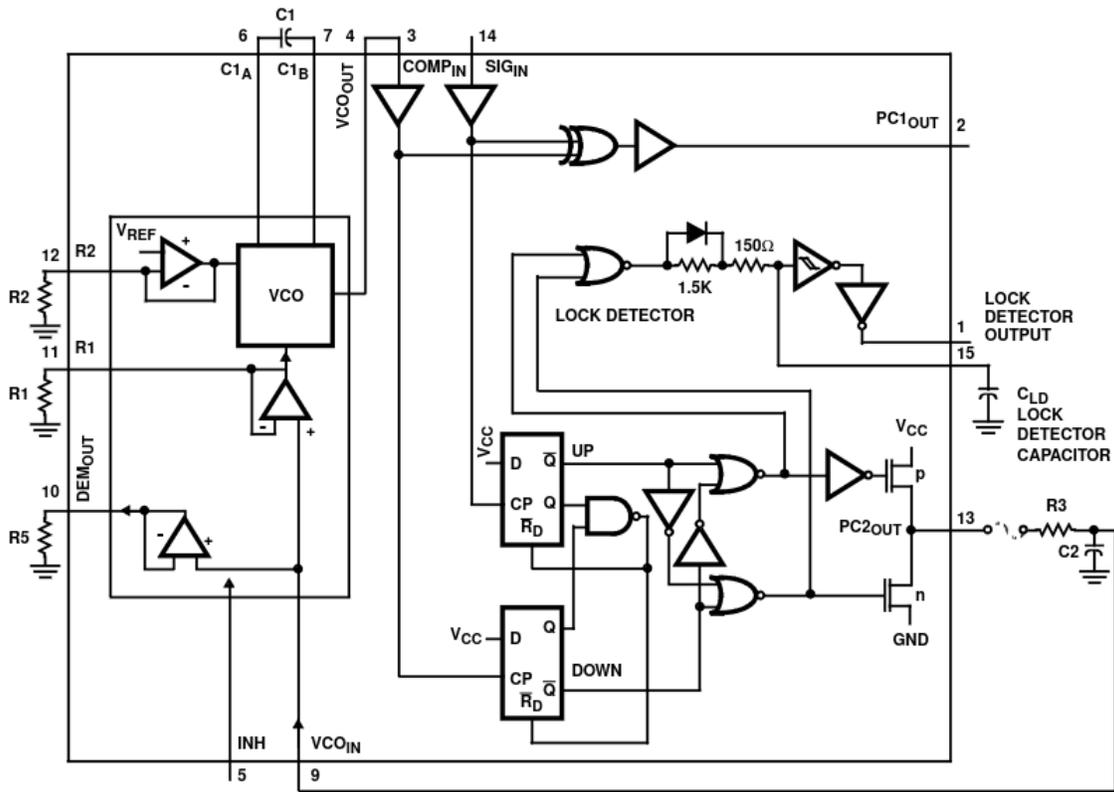


Figure 20: Logic Diagram of CD74HCT7046A Chip [5]

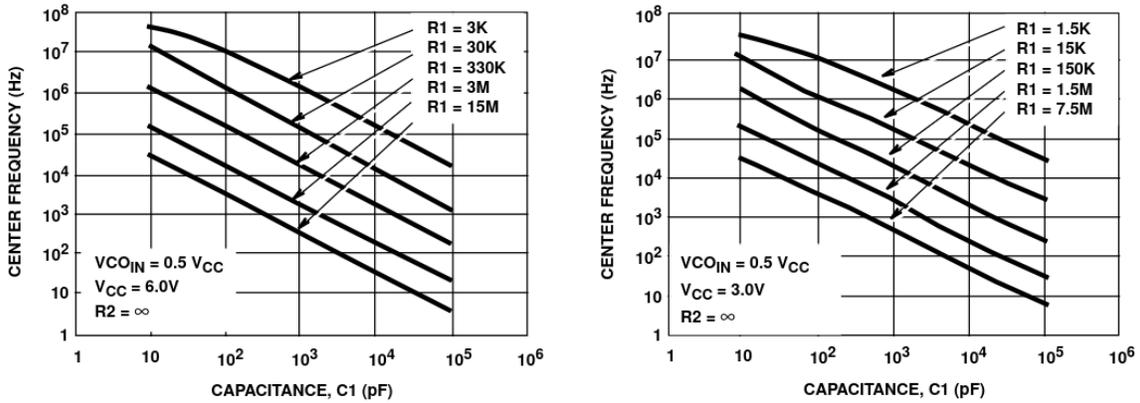


Figure 21: Tuning Characteristics of CD74HCT7046A Chip [5]

Practically, finding the appropriate tuning of this system is an arduous task. Using a 15 k Ω resistor into R1 and a 30 pF capacitor (or rather, a 10 pF and 20 pF capacitor in parallel) across C1A and C1B, the VCO is nearly at the perfect 10.7 MHz. Unfortunately,

the chip itself is small and fragile, and any examples built were damaged before adequate readings were made. Figure 22 shows a couple iterations of the PLL Demodulator system, with the right two using the CD74HCT7046A and the leftmost circuit being an attempt at a custom-built PLL demodulator using a discrete VCO and mixer.

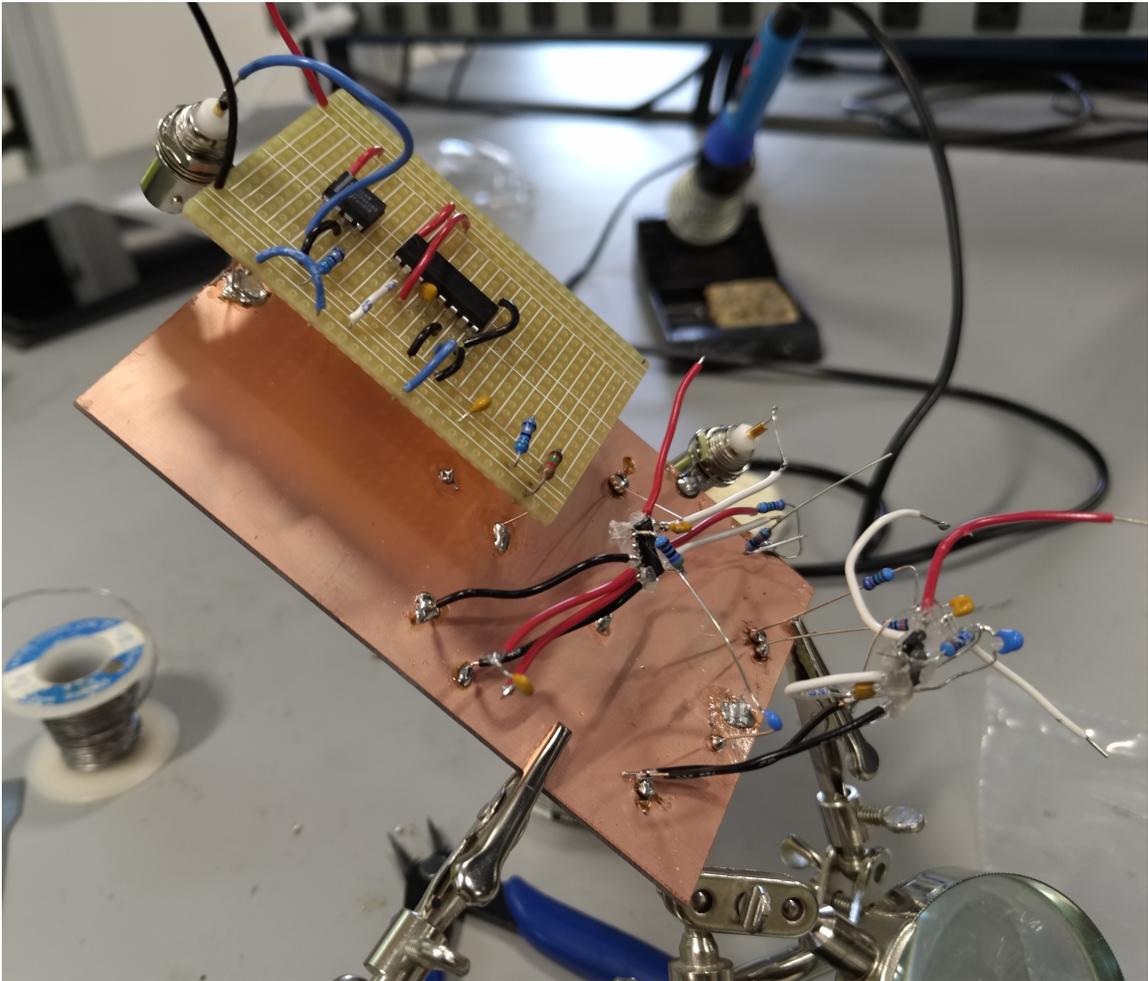


Figure 22: Three Separate PLL Demodulator Circuits

8. Conclusion

Figure 23 shows a rough summation of the hardware. This particular model has trouble with the demodulator, as mentioned above, but otherwise works as expected.

Figure 24 shows the signal entering the demodulator- a clean and loud 10.7 MHz with a peak-to-peak voltage of ~ 15 V.

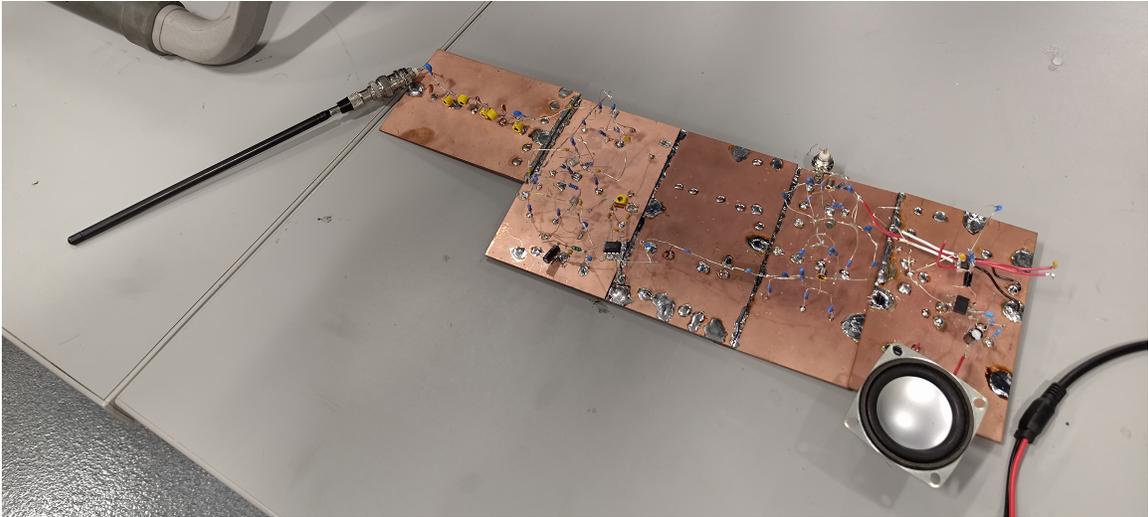


Figure 23: Complete Radiophone

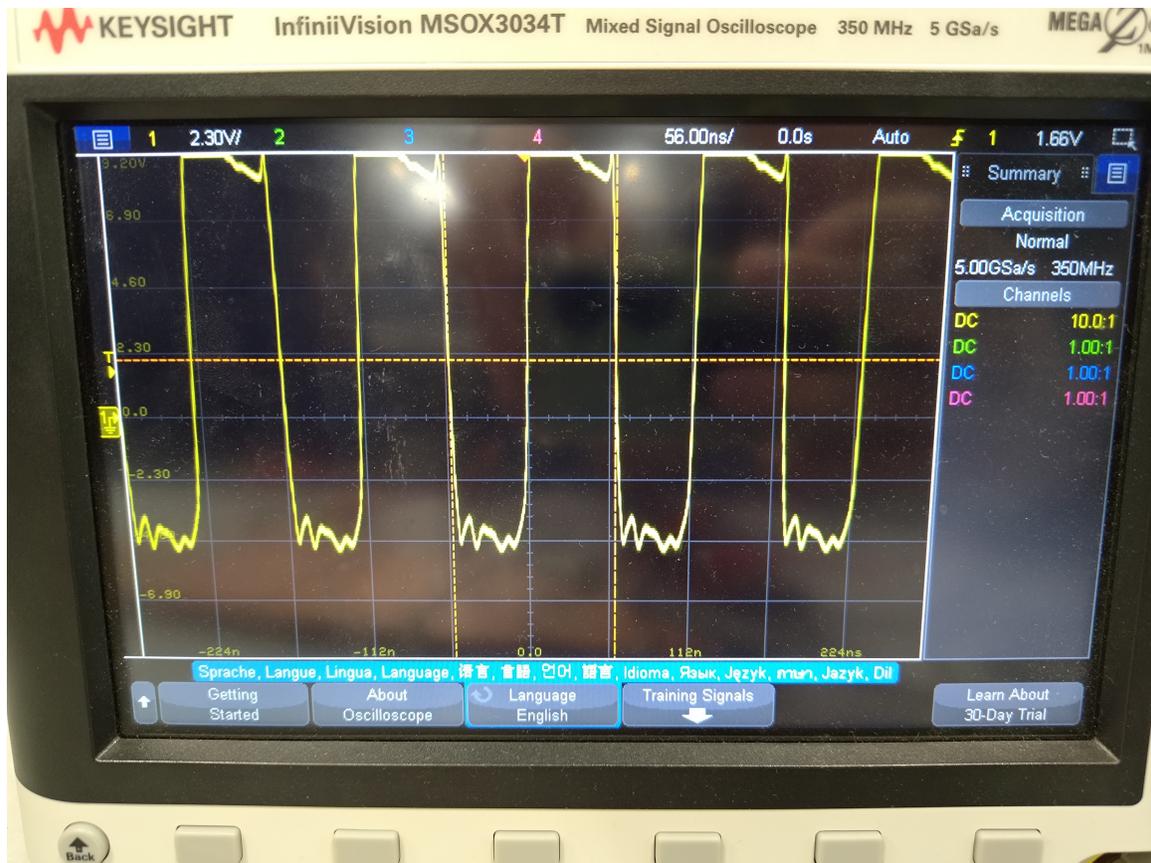


Figure 24: Output of IF Stage with an Input from Antenna

The FM radiophone project is one of surprising challenge. Given the age of the radio, and knowing the lack of refinement that existed in those old days, one would expect this to be a simple project to get right. However, it is now evident that precision is of utmost importance to make a viable radiophone.

The mixture of hand-built components along with well-engineered integrated circuit chips makes this a project of variety and well-roundness. The engineers of an FM radiophone must synchronously be able to design as well as use designed components in a fully understanding way, otherwise the slightest error can cause a complete dud of a machine. Additionally, and most importantly, the engineers ought to experiment with the components at hand, as there seems to be no precisely right answer to this puzzle.

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Appendix A

Our project is a one-off production of a low-power and low-footprint device, and as such there are few considerations we as a group must keep in mind for the safety and well-being of ourselves and others.

A.1 Safety, Public Health, and Welfare Considerations:

The only pragmatically dangerous portion of this project is in the construction of it, since there is plenty of soldering involved. When assembling the radiophone components, the appropriate safety protocols (e.g. glasses, careful operation, appropriate wardrobe) are taken. Past that, all materials are non-toxic and the energy levels of the entire system is well within safe levels.

A.2 Global, Cultural, Social, Environmental, and Economic Factor Considerations:

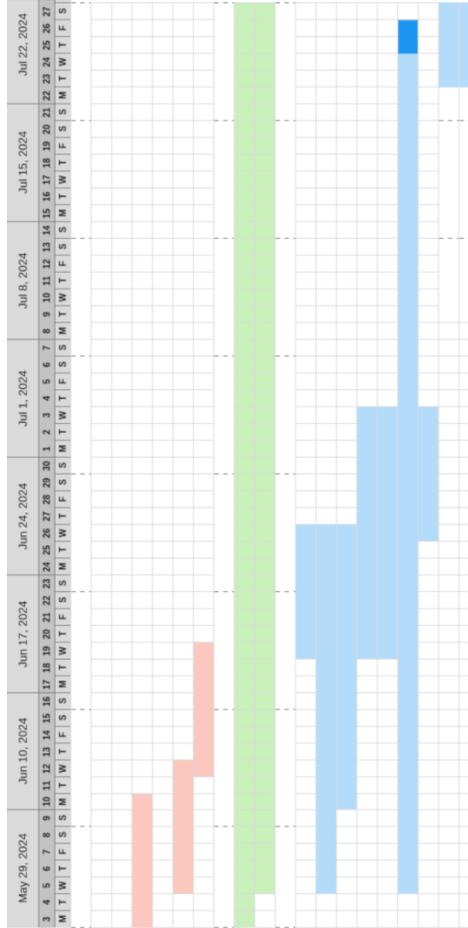
Since the FM radiophone is a receiving system, and one designed to receive public signals at that, there are no real ethical or social concerns. Additionally, due to the previously mentioned small scale of this project, no real economic or global concern is present either.

Appendix B

	Real	Predicted
Labor Cost		
Christopher	1600	2500
Jason	1850	2500
Joseph	1650	2500
Total:	5100	7500
Consulting Fees		
Lab I Student	0	0
Lab II Student	0	0
Lab III Student	0	50
Lab IV Student	0	0
Lab Tutor	0	200
Lab Assistant	0	0
Mr. Woodcock	0	0
Faculty	400	400
Total:	400	650
Direct Labor Cost:	5500	8150
Indirect Labor Cost:	5500	8150
Total Labor:	11000	16300
Supplies and Materials:	104.76	100
Equipment Rental:	946.05	100
Tot. Supplies, Materials, and Equipment Rental:	1050.81	200
Subtotal:	12050.81	16500
Business Overhead:	6627.9455	9075
Total Contract Fee:	18678.7555	25575

Figure 25: Budget Chart

Appendix C



TASK	ASSIGNED TO	PROGRESS	START	END
Initiation				
Safety Topology	Everyone	100%	5/29/24	5/29/24
Stockroom Account	Everyone	100%	5/29/24	5/29/24
Receiv Fm receiver	Everyone	100%	5/29/24	6/10/24
Acquire equipment	Everyone	100%	5/29/24	5/29/24
Confirm design	Everyone	100%	6/5/24	6/12/24
Order Parts	Everyone	100%	6/12/24	6/19/24
Planning and design				
Develop Budget	Jason Bissias	100%	6/3/24	8/2/24
Develop Plan (Sagitt)	Christopher	100%	6/5/24	8/2/24
Execution				
Antennae	Everyone	100%	6/19/24	6/26/24
Bandpass filter for RF	Joseph	100%	6/5/24	6/26/24
RF Amp	Christopher	100%	6/10/24	6/26/24
Local oscillator	Joseph	100%	6/19/24	7/3/24
Bandpass filter for F	Joseph	100%	6/19/24	7/3/24
Demodulate signal	Jason	95%	6/5/24	7/28/24
IF Amp	Christopher	100%	6/26/24	7/3/24
Audio amp	Everyone	100%	7/24/24	7/30/24
Speaker	Joseph	100%	7/24/24	7/30/24

Figure 26: Gantt Chart