Crystal Radio and Superheterodyne Receiver

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1 Abstract

The following paper is twofold. The first part is on the design and properties of a crystal radio. The second describes the processes behind a dual-conversion superheterodyne receiver kit developed by David White. It goes into detail concerning each stage and how it functions. The stages are described in the order described in Figures 12 and 13.

2 Conception

2.1 The Big Idea

The overall goal in the project was to construct a dual-conversion superheterodyne receiver capable of receiving audible radio signals on the 17-, 20-, 30-, and 40-meter bands. It will utilize a kit designed by David White (WN5Y) and described on his website. [1] This requires learning about oscillating circuits, amplifiers, and bandpass filters in order to gain a better knowledge of analog circuitry. As an introduction, the first part of the project was to design and construct a crystal radio. This radio is a simple oscillating circuit and provides one with a baseline understanding of how a receiver works before embarking on the more complicated superheterodyne receiver.

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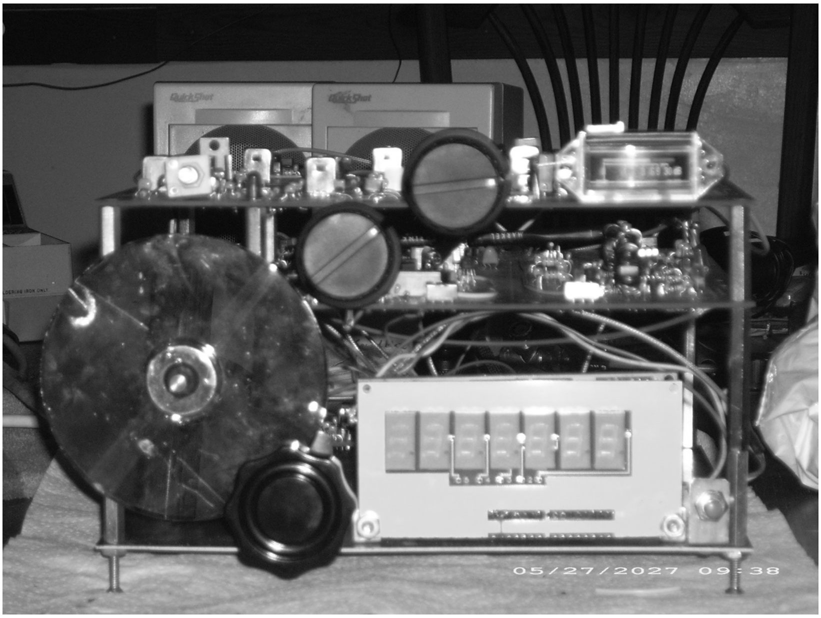

Figure 1: *A superheterodyne receiver*

The conception of this project has been a long time in the making. Since 2007 I have been a ham radio operator. For three years, most of my time has been spent talking to local hams on the N6NFI repeater using a two-meter uniband transceiver. Not only has this become limiting, but also the radio itself relies on digital circuitry, making the individual components difficult to distinguish. The final Applied Science Research project seems a perfect opportunity to take advantage of learning the inner workings of a long-time hobby as well as getting a thorough introduction to analog circuitry.

I decided to focus on analog instead of digital circuitry because digital circuitry represents the turning off and on of switches. That is, building a digital radio involves learning how to manipulate the switches to accomplish a goal. [2] Designing analog circuits, on the other hand, relies on understanding the principles of how the circuit functions and not just on learning how to manipulate it. [3, 4]

Knowing very little about electronics, I decided that a kit would be the best way to proceed. This is because it provides a pre-developed circuit that can be put together with insight on the theory behind how it works. Also, it removes the issue of trying to find and assemble parts by including the parts in a single kit. David White's electroluminescent model was decided on because it provides detailed instructions on the various parts of the receiver and includes two large circuit boards. Also, the large circuit boards allow ample space for modifications. [5]

Even so, the crystal radio first had to be constructed in order to obtain a baseline understanding of what a receiver actually is and how it functions. The radio itself is a simple parallel resistor-inductor-capacitor (RLC) circuit [6] that was assembled and tested using a vertical antenna (piece of insulated wire).

3 Crystal Radio

3.1 Introduction

In 1904 Jagadish Chandra Bose first patented the idea for a crystal radio when he invented a device that would detect electrical signals using a galena crystal. [7] This went largely unnoticed until Greenleaf Whittier Pickard filed a patent for a silicon crystal detector in November 1906. [8, 9] These early crystal radios, called "cat's-whisker detectors," used a thin piece of wire that touched a semiconducting mineral (commonly galena) to rectify the signal, representing an early form of the diode. [10] During the 1940s Allied troops made "foxhole radios" out of readily available parts (old wire, a razor blade, and pencil lead), and similar foxhole radios were also developed by the German anti-Nazi resistance movement. By the 1950s crystal radios had become popular as hobbyist items. [11]

Crystal radios have since been superseded, but their principles have not become obsolete. A crystal radio is a tuned circuit with no external power sources other than the radio waves that the attached antenna picks up. Besides being the backbone of radios today, tuned circuits are used in everything from RF power amplifiers to induction heating by using tuned circuits to maximize the power loss through the heater (coil of wire). [12]

RLC circuits have a great future in resonant energy transfer, which is the basis for wireless electricity transfer. When a current is passed through an inductor, the changing electric field creates a magnetic field, as discovered by Michael Faraday in 1831. [13] Usually this changing magnetic field is used to induce an electric field in another coil. If a capacitor is added to the circuit, it creates a resonant circuit with the magnetic field oscillating back and forth as the capacitor is charged, uncharged, and charged again. This allows transmission and reception at a single frequency. [14]

3.2 CAD Drawing

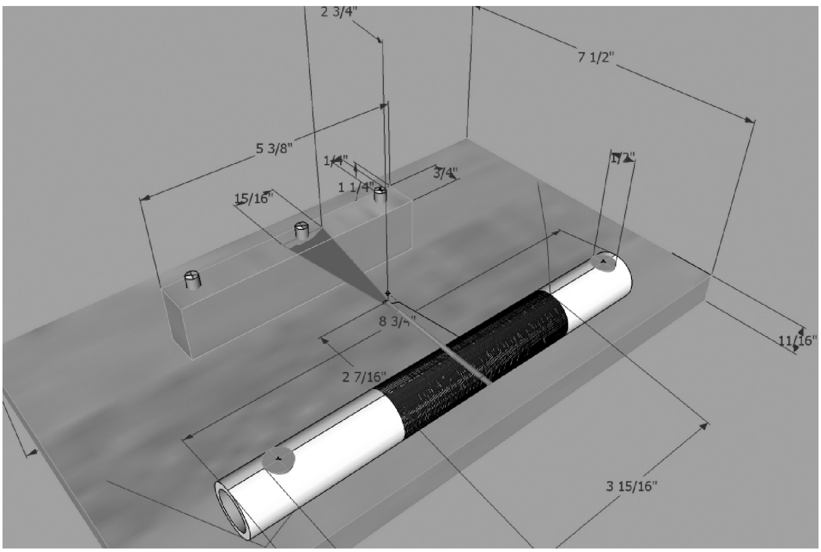

Figure 2: *Inductor, Base, and Tuner*

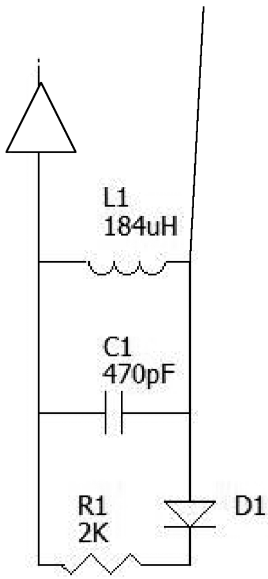

Figure 3: *Circuit Diagram of the RLC Circuit*

3.3 Theory

As noted earlier, the crystal radio is a parallel resistor-inductor-capacitor (RLC) circuit that receives radio waves and turns them into sound waves. Assembling one requires an understanding of what a tuned circuit is. Accordingly, the simpler case of an inductor-capacitor circuit will be examined first.

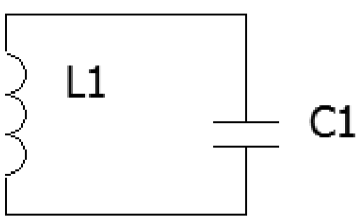

Figure 4: *A simple LC circuit*

Assume that a capacitor has been charged from some external source and placed into the circuit above. At this point all the energy is stored in the capacitor. Positive charge carriers then begin to flow counterclockwise from the top plate to the negatively charged bottom plate through the inductor. Charge flows into the inductor, creating a magnetic field in the inductor until all the energy in the circuit is stored in the magnetic field, although this does not mean that there is no current. (The reason why charge continues to flow is that the inductor resists changes in the electric field and thus in the magnetic field as well, meaning that charge flows from one plate to the other even though the capacitor has equally charged plates.) As charge flows back through the capacitor, eventually all the energy in the circuit is stored in the electric field and charge begins to flow once more from the bottom plate to the top plate. This occurs at some definite frequency, known as the resonant frequency of the tuned oscillator. This frequency can be represented by:

$$f = \frac{1}{2\pi * \sqrt{LC}}$$

(where 'L' and 'C' represent the inductance and capacitance, respectively, of the circuit).

For a long solenoid of length 'l', cross-sectional area 'a', and number of turns per unit length 'n', the inductance of a solenoid can be calculated as:

$$L = \mu_o n^2 Al$$

(where 'μ_o' is the permitivity of free space, equal to $4\pi * 10^{-7}$ henries per meter).

In order for the crystal radio to receive stations in the AM frequencies between around 500 and 1600 kHz, an inductor and capacitor can be made to resonate between these frequencies. [15]

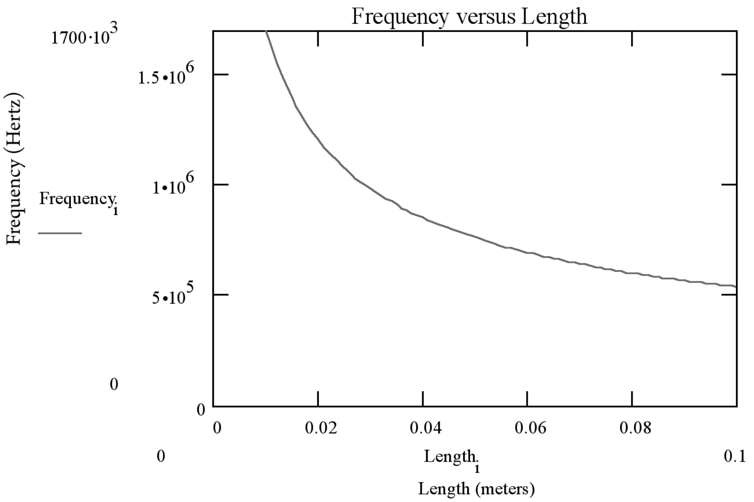

Figure 5: *Frequency versus length of the inductor with a 470 pF capacitor and a coil density of 1700 turns per meter*

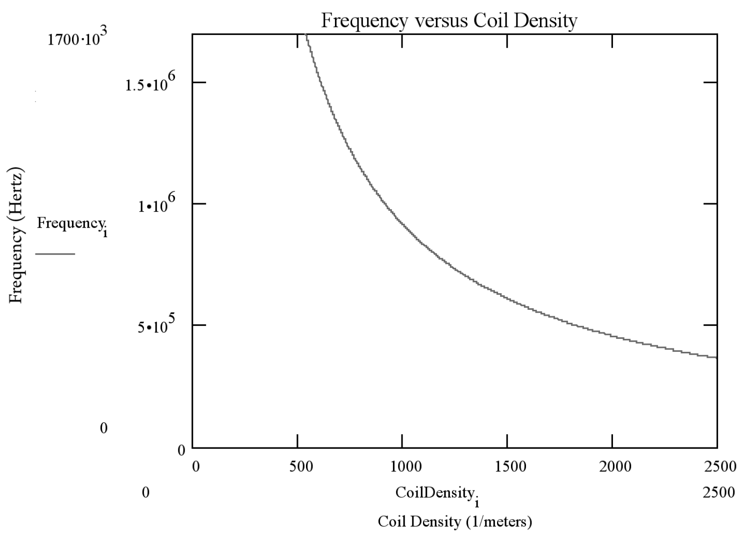

Figure 6: *Frequency versus coil density of the inductor with a length of 10 cm and a 470 pF capacitance*

Still, this does not explain how a crystal receiver works. What makes a crystal receiver unique is that there is no external power source to power it. It functions solely by picking up the radio waves that are already in the air. As the radio waves enter the antenna, they induce a voltage in the antenna and cause current to flow. As current flows, it enters the tuned circuit. The equation for the impedance of the circuit is:

$$Z = \frac{1}{\sqrt{\frac{1}{R^2} + \left(\frac{\omega}{L} - C\omega\right)^2}}$$

(The derivation is shown in Appendix D.) It follows that the maximum impedance will occur at resonance when:

$$\frac{\omega}{L} = \omega C$$

Therefore, at non-resonant frequencies the impedance of the circuit is less than at resonance. Now, charge can flow either to ground or through the diode. Since there is a much higher impedance to get to ground than to get through the diode, most charge will flow through the diode instead of to ground. However, at non-resonant frequencies the exact opposite is true because the path of least impedance is through the ground wire. This highlights the importance of having a good ground. It is necessary to minimize the resistance of the ground in order to make sure that only certain frequencies make it through the diode into the headphones or else nothing will be heard: all the frequencies will pile up and cancel each other out.

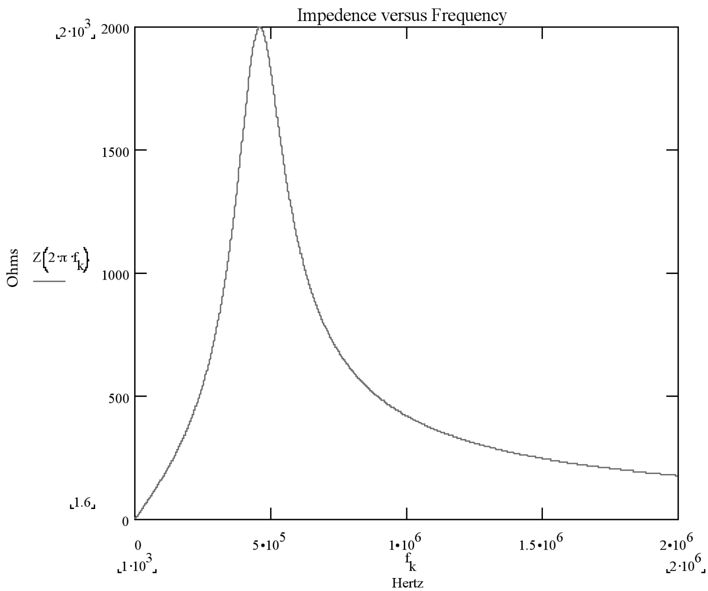

Figure 7: *Impedance versus frequency with the values seen in Figure 3 assuming that the impedance of the headphones is large in comparison to the impedance of the antenna and diode*

The diode is used as a rectifier to convert the AC current travelling through the circuit into DC current that the headphones can convert to sound. Diodes work by only allowing current flow in one direction (thereby cutting off half of the sinusoidal waveform seen in the current-versus-time graph in Figure 8). For the crystal radio, a diode that had a small reverse bias was necessary in order to ensure that the signal was being rectified at a very low voltage. Therefore, a germanium diode was used because it has a reverse bias of only 0.15 V.

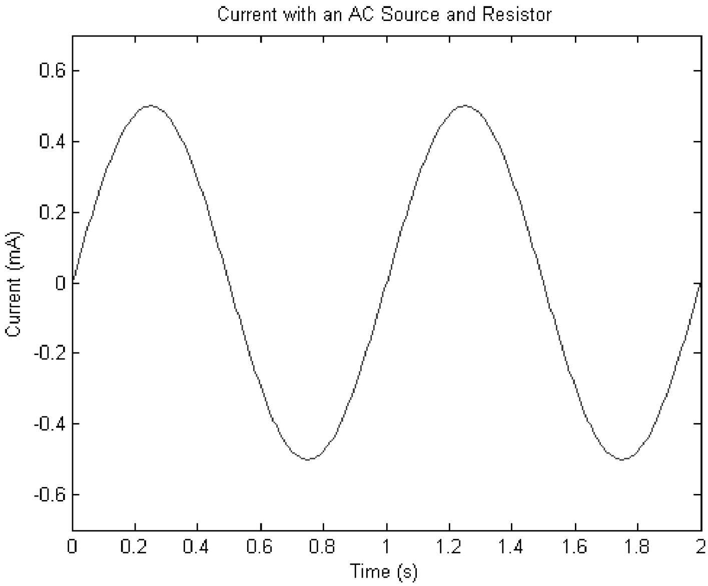

Figure 8: *Current versus time graph. The diode effectively cuts off the bottom or top of the waveform. [16]*

When sound enters the headphones it creates an alternating magnetic field that pushes a plate up and down, causing pressure waves that are heard as the radio station picked up by the antenna. For the purposes of the crystal radio, high-impedance headphones are necessary in order for the circuit to have a sharp resonance and be able to separate closely spaced radio stations. A pair of C. Brande 2000 Ω high-impedance headphones from 1923 was used to maximize the selectivity.

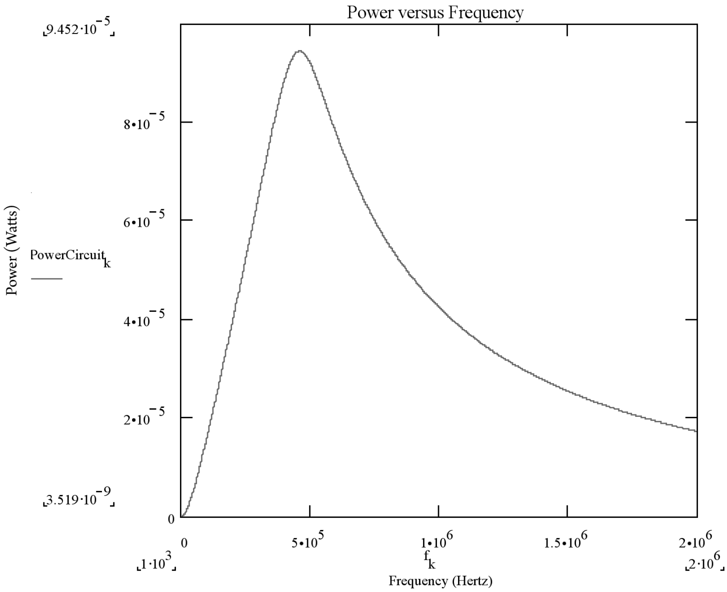

Figure 9: *Power output versus frequency for the headphones using values seen in Figure 3 and a 300 Ω impedance for the antenna*

Figure 9 requires a comment on how the antenna works. The antenna itself has a certain impedance. By Ohm's law (V=IR) it can be seen that there is a linear relationship between voltage and resistance. This means that:

$$\frac{V_{signal}}{Z_{antenna} + Z_{circuit}} = \frac{V_{circuit}}{Z_{circuit}} =$$

$$V_{circuit} = \frac{V_{signal} * Z_{circuit}}{Z_{antenna} + Z_{circuit}}$$

This calculation can be done because the antenna is in series with the parallel RLC circuit, implying that the potential across any one of the three elements is the same. Given this, the power can then be calculated across the headphones:

$$P = IV$$

and

$$V = IR$$

$$\mathrm{P} = \frac{\mathrm{V}^2}{R} =$$

$$P_{headphones} = \frac{V_{circuit}^{\;\;2}}{R_{phones}} =$$

$$P_{headphones} = \frac{\left(\dfrac{V_{signal} * Z_{circuit}}{Z_{antenna} + Z_{circuit}}\right)^2}{R_{phones}}$$

This highlights an interesting point. When connected to the antenna, the loudest station (by what the ear hears) is KNBR radio at 680 kHz. What can be seen in Figure 8 is that 680 kHz is near a resonant frequency, meaning that for equivalently strong signals (in terms of the potential in the antenna), KNBR is one of the louder stations. Combined with a high transmission power (50 kW) and relatively nearby location (Belmont, California), Figure 9 shows why KNBR is the primary station that can be heard on the radio. [17]

3.4 The Next Step

Several problems arose while building the radio, the primary one having to do with grounding. At home, a 20 ft piece of insulated wire served as the antenna with the ground being attached to a water pipe. At school, the antenna was a 40 ft vertical magnet wire grounded to the sink. In either case, the antennas were not long enough to resonate, as the AM wavelengths are between 615 ft and 1,970 ft. However, the antenna and ground system built at home received signals that could be picked up in the headphones while the antenna system at school did not.

This could be a result of a couple of things. For one thing, the antenna at home was stationed at over 700 ft in elevation, while the one at Menlo was at a significantly lower elevation. Also, the antenna at school was near a metal building, which might decrease the potential induced in the antenna. The most likely cause, however, is grounding. If there is not a good ground, non-resonant frequencies will not travel out of the circuit, as the impedance is too high. They instead travel through the diode, causing multiple frequencies to interfere with each other and nothing to be heard. The next step would be to try to connect the radio to a vertical antenna on the roof of Stent Hall that was used as the antenna for the high-frequency transceiver used by the ham radio club.

It is also worth noting here how the radio receives multiple frequencies. As shown in the graphs, at non-resonant frequencies current either runs to ground or is rectified by the diode and goes through the headphones but is too faint to be picked up by the human ear. This could be solved either by changing the capacitance of the circuit or by changing the inductance of the coil. Due to the limited availability of large parallel plate capacitors, the coil is tuned by shorting it at various points along its length with a piece of 18-gauge wire attached to a steel triangle. Therefore, when in operation, the circuit appears differently:

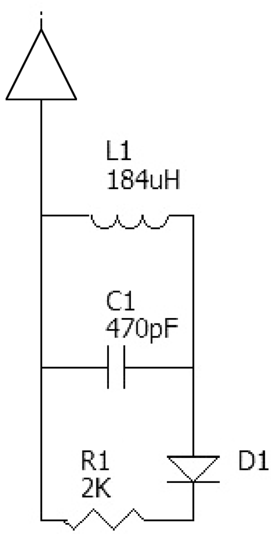

Figure 10: *The circuit with the tuner included*

This allows for a variable inductance, and thus varying resonant frequencies, which allows for the reception of more than one radio station. However, it does not modify any of the aforementioned theory.

There are a couple of things that still can be done with the crystal receiver. The first is to connect it to the antenna on the top of Stent Hall in order to see if the radio picks up any signals. Another step is to add an operational amplifier to the circuit (thereby inserting an internal power source, which makes the receiver no longer a traditional crystal receiver). This would allow faint signals coming through the antenna to be amplified, rectified, and picked up by the headphones.

4 Superheterodyne Receiver

4.1 Introduction

It is first necessary to explain what heterodyning is. When an amplitude-modulated (AM) signal is transmitted, it has a certain frequency corresponding to the frequency of the carrier wave. (Voice frequencies modify the top of the waveform.)

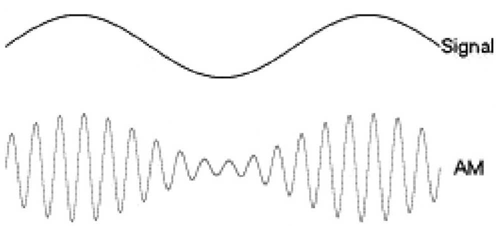

Figure 11: *Amplitude-modulated waveform [22]*

This frequency is combined with a frequency produced in an oscillating circuit in the mixer, which "beats" the two frequencies together. Effectively, the circuit multiplies the two input voltages under the principle that the input voltages can be described by:

$$V(t) = A * \sin(2\pi * \omega t)$$

(where 'A' corresponds to the peak voltage, and 'ωt' yields a constant of the frequency of oscillation multiplied by time)

Given this, the two signals coming in can be modeled as:

$$V_1(t) * V_2(t) = A_1 * A_2 * \left[\sin\left(2\pi * \omega_1 t\right)\sin\left(2\pi * \omega_2 t\right)\right] =$$

$$V_1(t) * V_2(t) = \frac{A_1 * A_2 * \cos\left[\left(2\pi * \omega_1 t\right) - 2\pi * \omega_2 t\right] - \cos\left[\left(2\pi * \omega_1 t\right) - \left(2\pi * \omega_2 t\right)\right]}{2}$$

Note that by multiplying the two input voltages, the outputs are the sum of the two input frequencies and the difference (known as beating the two frequencies together). [23] This "beating" of an incoming signal with a signal produced by an oscillator is what characterizes a superheterodyne receiver.

The idea behind a superheterodyne receiver was first hypothesized by Canadian Reginald Fessenden in 1900, but heterodyne reception remained impractical because of the inability to produce a stable signal. [24] The idea was revisited in 1918 by Major Edwin Armstrong of the U.S. Army in France during the First World War. Armstrong came up with the idea of beating two frequencies together in order to overcome the limitations of vacuum tube triodes (an early amplification device) in radio direction-finding equipment. Due to stray capacitance, negative feedback in the triodes would occur as a result of unwanted resonance. This meant that in order to avoid negative feedback, a hundred or more low-gain triodes had to be linked together in order to provide the necessary amount of amplification, potentially at great expense.

While watching a night bombing raid, Anderson conjectured that it would be possible to locate enemy aircraft based on the short waves emitted by the planes' motor ignition system. The problem was that at the time there existed no reliable method of amplifying short waves. The amount of power required to support the many amplification devices needed to avoid negative feedback was impractical. Anderson's innovation was the idea of superheterodyning, that is, beating the high-frequency waves with a produced oscillation to create a lower frequency wave that could then be amplified. [25]

The advantage of a superheterodyne receiver is that a single stage can be adjusted to track over the entire tuning range of the receiver. Also, a tuned circuit is much more stable than a tuned amplifier. The latter, a regenerative receiver that relies on positive feedback, risks the loss of power and signal due to negative feedback. In music, heterodyning is the basis of the theremin, whereby a variable audio frequency is produced in response to the position of the musician's hands in relation to some antenna on the instrument. (The space between the hands acts as the "capacitor" for the circuit.) Current research on heterodyning is exploring its possibilities as to higher frequencies, especially of light. This may lead to the ability to accurately measure the frequency of incoming light waves rather than measuring the resulting change in electric field. Light Detection and Ranging (LIDAR), which is like RADAR except at much higher frequencies, would allow for the mapping of non-reflective objects such as rocks at RADAR frequencies. This could also improve the information density of optical cables, as the ability to hyperdyne incoming signals would make it possible to amplify them. Furthermore, televisions use heterodyning in order to amplify incoming signals at a lower frequency so as to decrease the possibility of negative feedback. [26]

4.2 Block Diagram

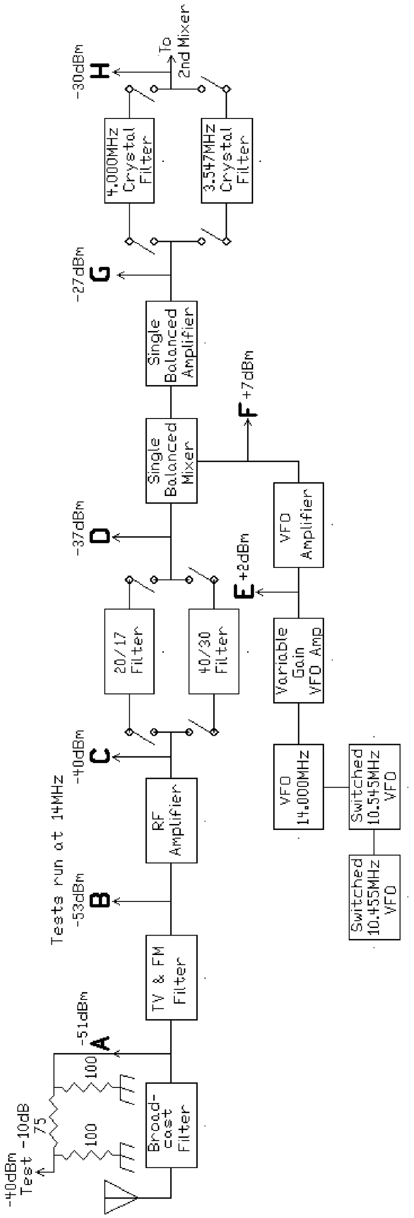

Figure 12: *Block diagram outlining Board 1 [27]*

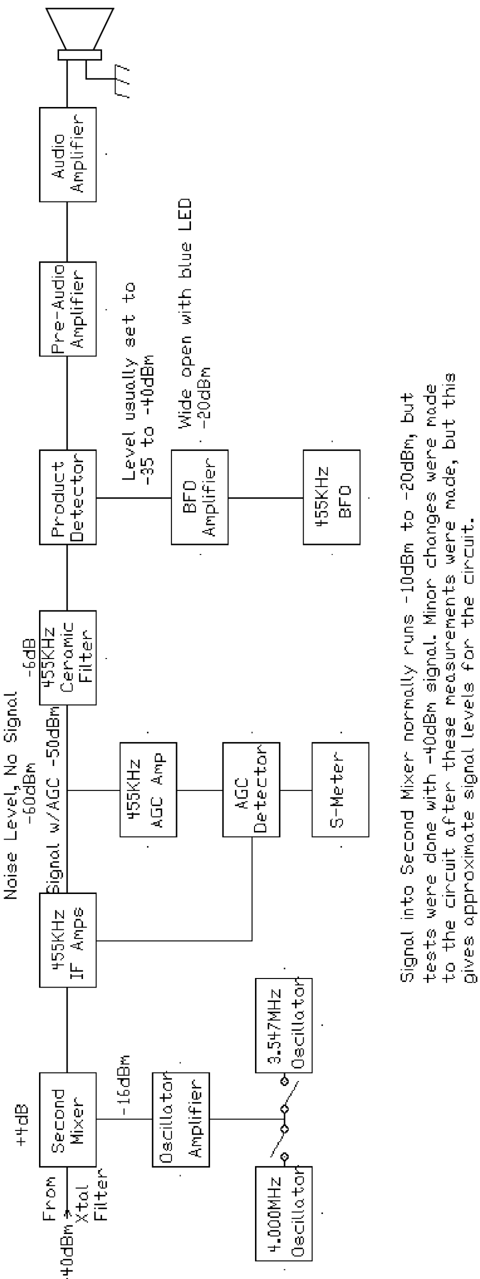

Figure 13: *Board 2 [28]*

4.3 Theory

4.3.1 Broadcast Television and FM filters

As noted on the block diagram (Figures 12 and 13), the first stage of the circuit comprises the broadcast, television, and FM filters that block non-resonant frequencies (for each specific element) from entering the circuit. Like the crystal radio, in their simplest forms the filters can be thought of as parallel LRC circuits in which the impedance increases at non-resonant frequencies, making the path of least resistance to ground.

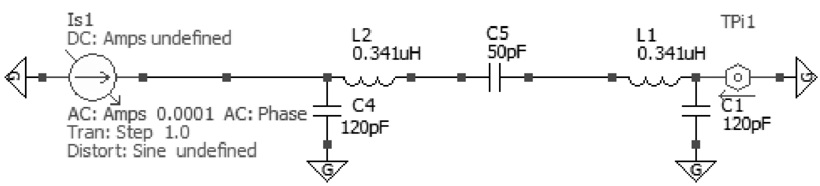

Figure 14: *Low pass filter*

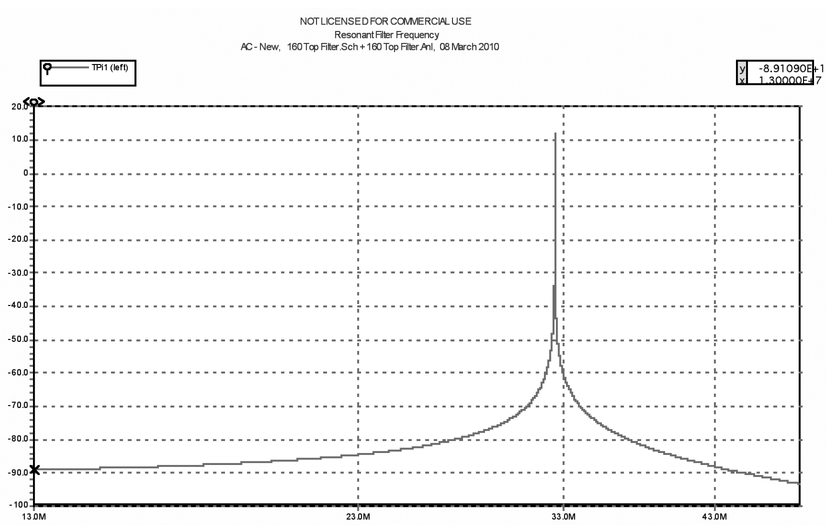

Figure 15: *Frequency versus decibels of 32 MHz filter*

Figure 15 is a simulation showing the intensity of the current out as a function of frequency. Note that at around 32.4 MHz the intensity of the wave actually goes positive, which implies that there is more current coming in than going out. However, at non-resonant frequencies the impedance is much higher, implying negative decibels.

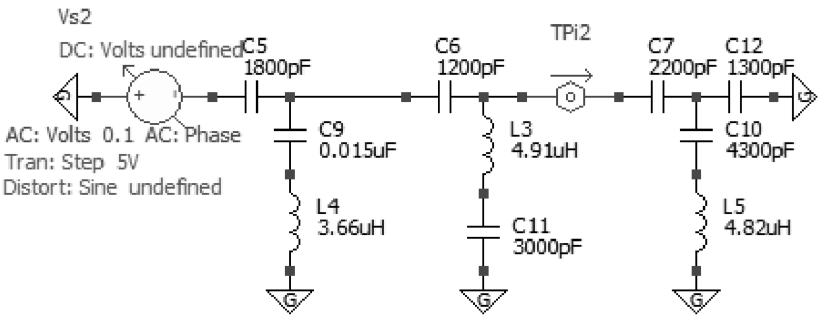

Figure 16: *Broadcast filter*

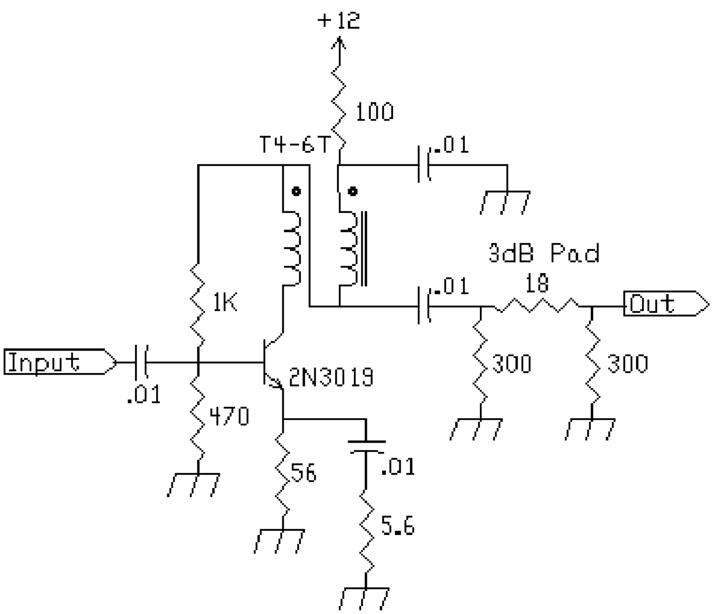

Figure 17: *RF amplifier [29]*

As the name suggests, the RF amplifier amplifies incoming radio signals before they are mixed with the wave produced in the variable frequency oscillator. To analyze this circuit, two paths need to be examined. The first is the 12 V signal that makes amplification possible. To determine the path of the DC current, a calculation can be done to find the potential at the collector of the 2N3019 bipolar transistor (labeled V_1):

$$V_1 = 12 - 100[\Omega]I_1$$

(Note: 'I_1' is the current through V_1)

$$V_1 = V_2$$

$$V_2 = 1{,}470[\Omega]I_1$$

(V_2 is labelled on schematic)

$$\frac{V_{base}}{470[\Omega]} = \frac{V_2}{1{,}470[\Omega]}$$

The current running through the base of the transistor is a voltage divider in which the current running through V_2 can be seen by applying Ohm's law as above:

$$V_{base} = \frac{470 * (12[V] - 100[\Omega]I_1}{1{,}470} =$$

$$I_1 = \frac{V_{base} - 0.6[V]}{56[\Omega]} =$$

$$I_1 = \frac{\frac{470}{1{,}470} * (12[V] - 100[\Omega]I_1) - 0.6[V]}{56[\Omega]} =$$

Note: 0.6 V was subtracted because there is a 0.6 V drop between the emitter and the base.

$$56[\Omega]I_1 = 3.24[A] - 32.0I_1 =$$

$$I_1 = 36.8[mA]$$

$$V_1 = 12 - 100 * 36.8[mA] =$$

$$V_1 = 8.32[V]$$

Thus the potential at the collector of the transistor is 8.32 V while the potential at the base is 3.68 V. This calculation was done to highlight the collector base difference when in operation. (A minor current running through base was disregarded in this calculation, which would slightly change the calculation above as well.) If the input signal is too strong, the collector will get pulled towards ground, implying that the transistor will turn off and not function. This explains the large potential difference between collector and base.

When the radio frequency enters the circuit, a small change in potential creates a change in current in the base of the transistor, which is amplified through the emitter into the transformers. This current amplification is called the β of the transistor and is about 50 for the 2N3019 at 0.1 mA. [26] Now, however, the transformers resist the change in electric field due to the AC current. A large potential is induced, amplifying the radio frequency signal. (The 0.01 mF capacitors are used to keep DC current out of the rest of the circuit).

4.3.3 Bandpass Filters

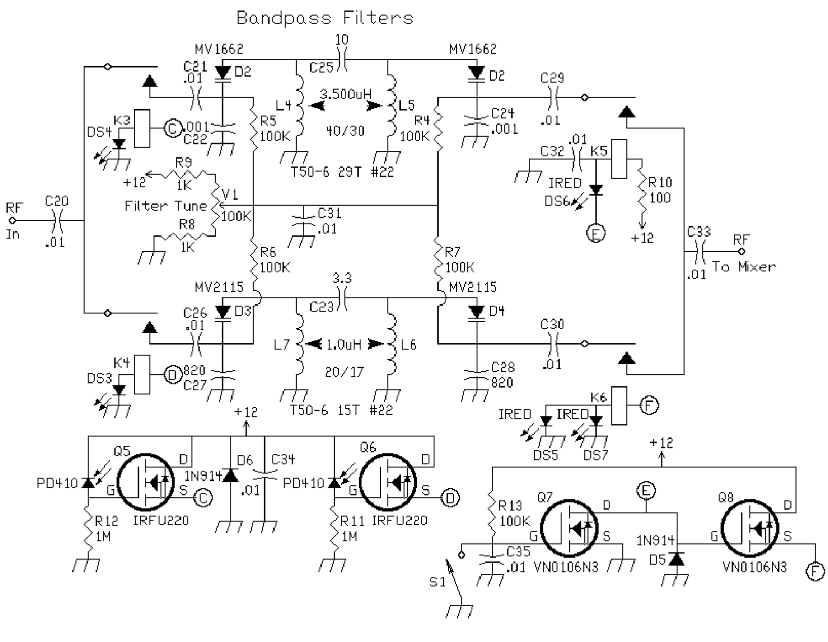

Figure 18: *Bandpass filters [30]*

The infrared diodes prevent the various filters from coming into contact with each other in order to avoid loss of the (relatively) small signals. Each one points to a phototransistor that allows current to flow and turn on the relay, which act as switches turning on the respective filters. Although seemingly more complicated than the initial filters, the bandpass filters also make use of tuned LRC circuits to selectively pick out frequencies at 10 MHz (30 m) and 17.6 MHz (17 m). As before, non-resonant frequencies go to ground while resonant frequencies go to the first mixer.

4.3.4 Variable Frequency Oscillator

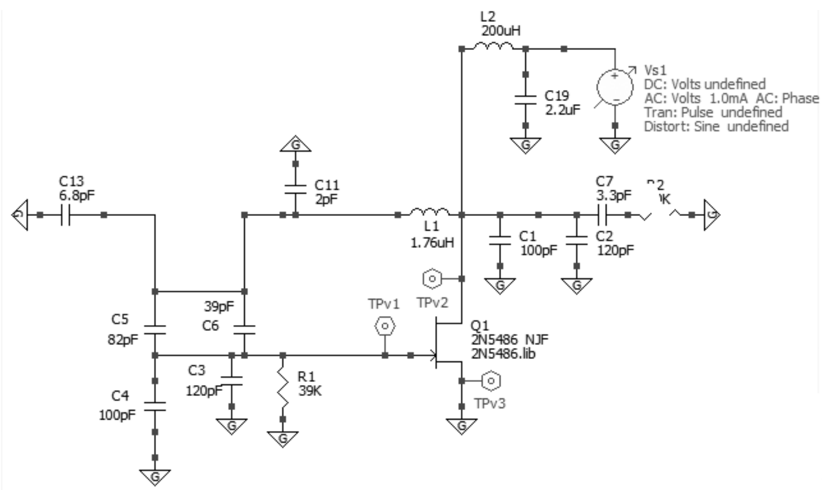

Figure 19: *Variable frequency oscillator*

The variable frequency oscillator creates the frequency that beats with the radio frequency in the mixer, creating the intermediate frequency. The above circuit details how an oscillation is created. Once again, the circuit in Figure 19 is an LRC circuit that oscillates at a certain frequency. In order for the wave not to dissipate, the capacitor needs to be charged at just the right time. The 2N5486 JFET (Junction Field Effect Transistor) acts as this voltage-controlled switch. As the gate is charged it creates a depletion zone between the source and drain, not allowing current to flow. This creates a 180-degree phase shift between input and output as the JFET is turning on and off at the minimum or maximum of the produced wave. The JFET allows the produced potential to keep oscillating through the circuit without dying out.

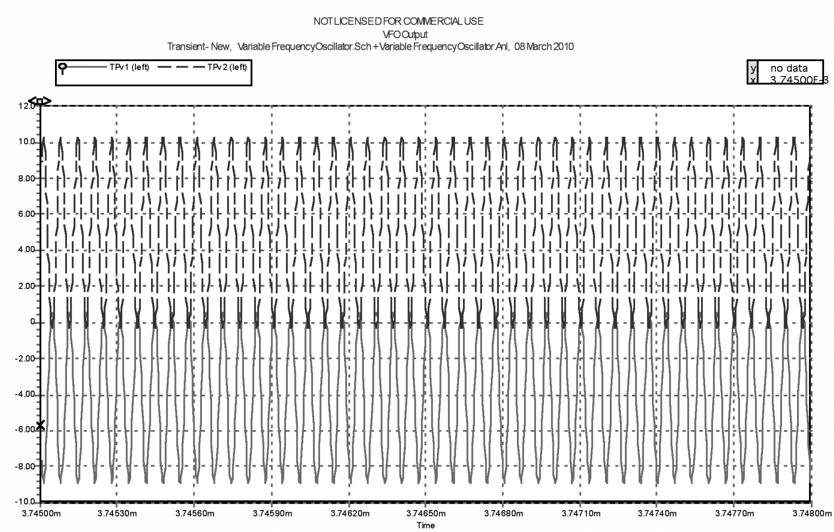

Figure 20: *Potential (V) versus time (seconds) of the gate (bottom line) and drain (top line) on the JFET*

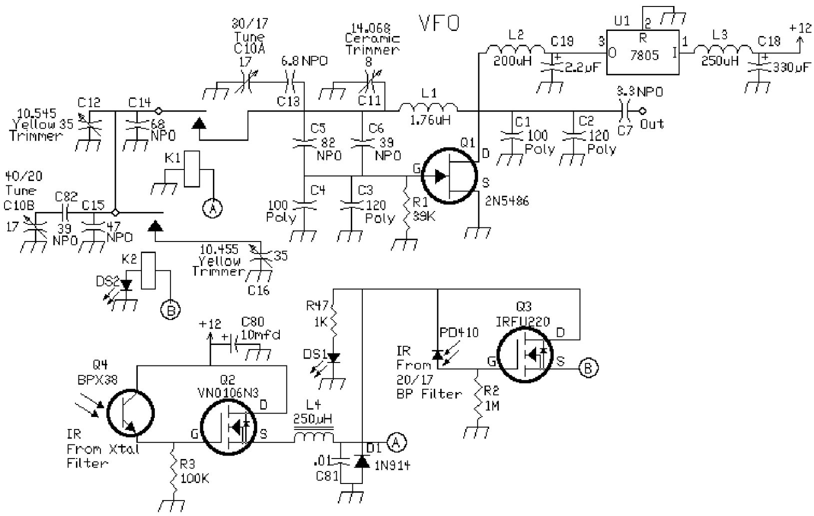

Figure 21: *Circuit used in the radio [31]*

The circuit in Figure 21 details how the variable frequency oscillator produces two different frequencies so that the intermediate frequency is held constant. Each frequency is switched on by a relay (which adds extra capacitance) by using the same method of infrared LEDs as described previously. This in turn selects the trimmer capacitor, which in turn helps set the frequency of the VFO.

4.3.5 First Mixer

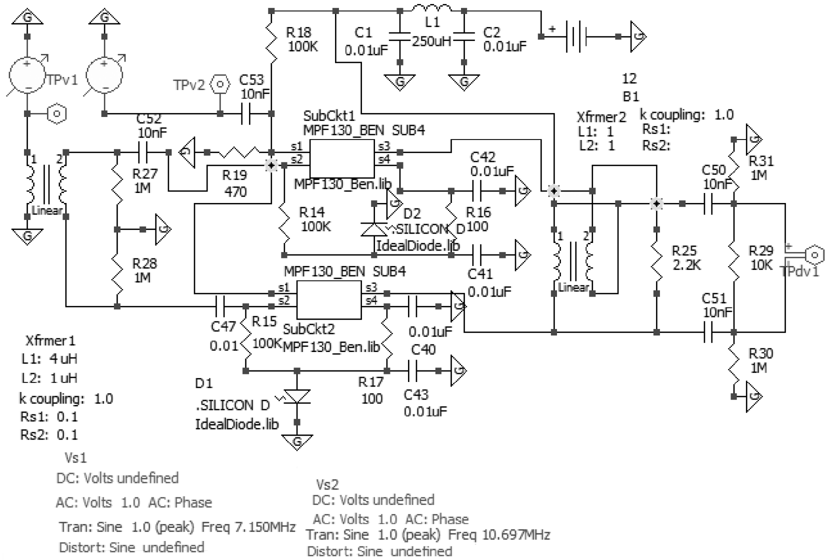

Figure 22: *First mixer circuit used in the receiver (grey squares represent non-connecting wires.) S1 = RF gate; S2 = VFO gate; S3 = drain; S4 = source*

The circuit in Figure 22 represents the first mixer in which the RF and VFO frequencies are combined to create an intermediate frequency (IF). In order to analyze what occurs in the circuit, the RF and VFO paths need to be looked at individually. RF input occurs at the farthest left signal generator (the one connected to the transformer). A changing electric field induces a changing magnetic field in the first coil, which, by Faraday's Law of Induction, induces a voltage in the secondary coil. In order to run the simulation, resistors R27 and R28 were added so that a DC simulation could be run to calculate the potential between the transformer and the capacitor. (5Spice assumes that capacitors have infinite resistance, which makes the calculation of a potential between the transformer and the capacitors impossible.)

From the second coil on the transformer, the RF travels onto the first gate of the MPF130, which is an N-channel, depletion-mode, dual-gate MOSFET. S1 is the gate where the RF goes, S2 is the gate where the VFO (variable-frequency oscillator) frequency goes, S3 is the drain, and S4 is the source. Besides the two gates, the MPF130 is special because it is a depletion-mode rather than enhancement-mode MOSFET. This means that the gate has to be brought negative in comparison to the source in order to pinch the channel from source to drain and turn the MOSFET off. In other words, the MOSFET is always on until the gate is brought negative enough with respect to the source. The resistors are at the gate and source of the MOSFET to ensure proper biasing. This can also be visually checked if the LED turns on, implying a 0.6 V drop across it (implying at least a 0.6 V difference between the source and gate). Note that the power source is on the upper right-hand side of the circuit and is labeled B1.

The VFO frequency goes directly to S1, which is biased at about 0.056 V. This is because the resistors above create a voltage divider such that the voltage drop across the 470 Ω resistor is equal to:

$$V_{gate} = \frac{470[\Omega]}{470[\Omega] + 100{,}000[\Omega]} * 12[V] =$$
$$V_{gate} = 0.056[V]$$

It would seem that if the MOSFET is already turned on it would be unnecessary to bias the MOSFET. However, this is done to make sure that the source gate difference is well above the cutoff threshold (-4.0 V) so that there is no chance that the MOSFET will turn off when the VFO and RF pull this difference down (since both the VFO and RF signals are alternating current).

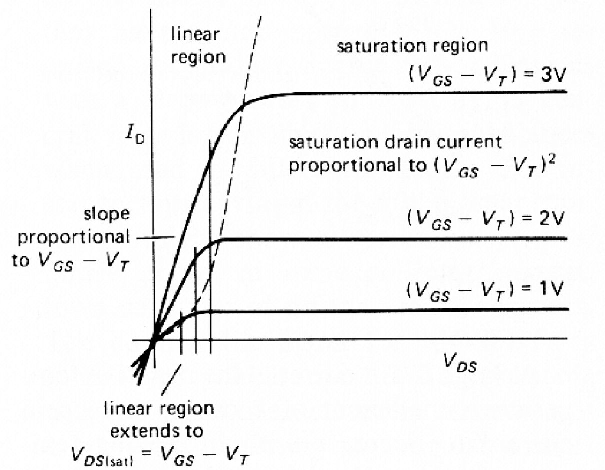

Figure 23: *Saturation current for various $V_{gate\text{-}source} - V_{threshold}$ [32]*

As the graph in Figure 23 shows, there is a certain drain cutoff current regardless of what the drain voltage is. The difference can be calculated if a certain source current is assumed, typically 10 mA according to the datasheet. [33] Therefore:

$$V_{gate-source} = V_{gate} - V_{source} =$$
$$V_{gate-source} = 0.056[V] - 0.01[A]*100[\Omega] =$$
$$V_{gate-source} = -0.944[V]$$

Note: V_{gate} and V_{source} are the operating points
(values before the AC signals are applied) of the MOSFET

$$V_{threshold} = 4.0 - V_{source} =$$
$$V_{threshold} = 1 - 4.0 =$$
$$V_{threshold} = -3.0[V] =$$

$$\Delta V = V_{gate-source} - V_{threshold} =$$
$$\Delta V = -0.944 - (-3.0[V]) =$$
$$\Delta V = 2.056[V]$$

As the graph shows, at 2.056 V (about 2 V), there is some maximum drain-source current that cannot be increased regardless of the potential applied to the drain, which is proportional to $(V_{gate\text{-}source} - V_{threshold})^2$. As $V_{gate\text{-}source}$ (which is the operating point of the gate and source before the RF and VFO signals are applied) has two components (RF and VFO input), it can be modeled as the sum of two varying voltages, which can be described by two sine wave functions. Due to the non-linearity of the cutoff voltage, these two frequencies are multiplied together, which is the mixing process described earlier. (The proof is provided in Appendix B.)

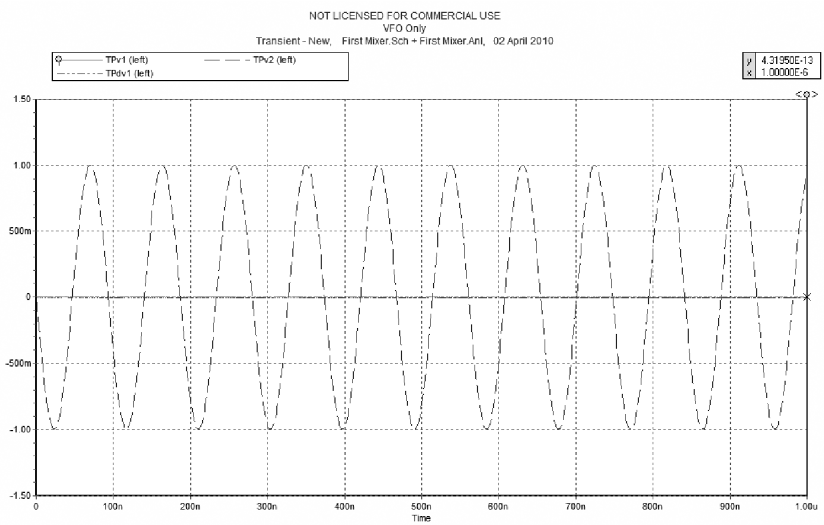

Figure 24: *Voltage (V) versus time (nanoseconds) of only the 10.697 MHz VFO frequency going through the first mixer. Straight lines: RV Waveform and OutputWaveform; curve: VFO Waveform*

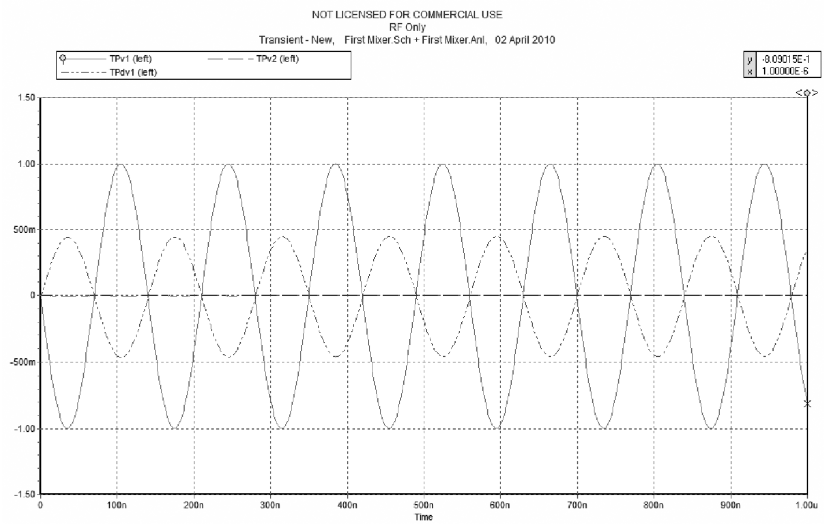

Figure 25: *Voltage (V) versus time (nanoseconds) of only the 7.150 MHz RF frequency going through the first mixer. Large curve: RF Waveform; straight line: VFO Waveform; small curve: Output Waveform.*

What is interesting about Figures 23 and 24 is that when only the VFO frequency passes through the circuit, the output voltage is (about) zero. However, when only the RF frequency passes through the circuit there is a waveform that is phase shifted by 90 degrees. (Note that the resistors R29, R30, and R31 were added so that it was possible to read a DC voltage between the two outputs of the circuit and the capacitors).

For either signal, the varying voltage at the gate pinches and expands the channel from source to drain, allowing more or less drain-source current (as Figure 25 describes). In the case of the VFO input, however, when this current gets to the second transformer, the alternating current creates a changing magnetic field that is opposite the changing magnetic field induced in the second coil, so the signal is cancelled out. For the RF input, the opposite is true because, going from the first transformer, the RF input from both ends of the transformer is phase shifted by 90 degrees. In other words, if the voltage at one end of the transformer is raised, then the voltage at the other end decreases since there is only a certain voltage induced in the transformer. Therefore, since the RF signal is phase shifted by 90 degrees, when it comes to the second transformer the magnetic fields are now in the same direction so the signal does not cancel itself out. The phase shift of the output signal is a result of the transformer coils. For AC, the coils have a certain impedance (resistance to the change in current). As there is a greater change in current, there is a greater impedance, which means a greater voltage drop across the coil. Therefore, the output waveform is phase shifted 90 degrees from the input. This means that an output signal will only be generated when one gate is being pulled down (S1) while the same gate on the other MOSFET is being pulled up with respect to the source. This is most likely done to avoid possible oscillations that could occur due to constructive interference of the two signals.

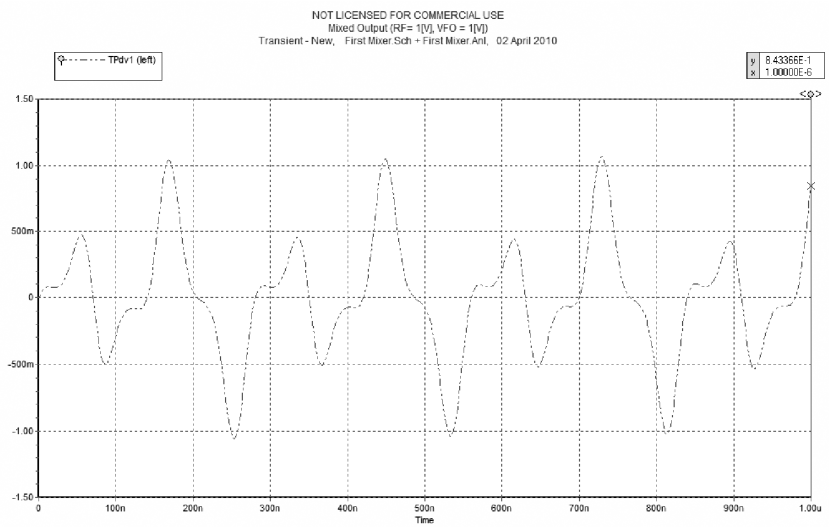

Figure 26: *Voltage versus time of the 10.697 MHz VFO and 7.150 MHz RF frequencies mixed together*

Figure 26 details the output voltage versus time when the VFO and RF are mixed together. In order to see the individual frequencies, a Fourier-transform has to be done.

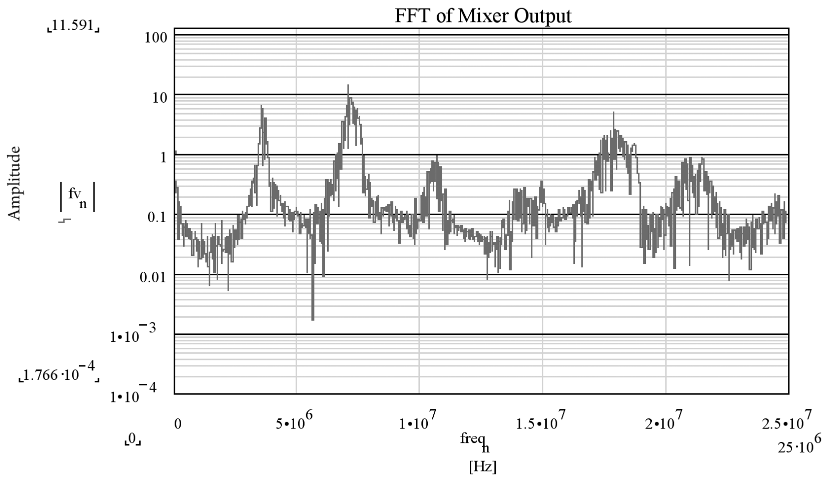

Figure 27: *Fourier-transformation of the data in Figure 26*

The peaks are at around 3.55, 7.407, 10.67, 14.31, 17.83, and 21.01 MHz. These correspond to the VFO–RF, RF, VFO, 2*RF, VFO+RF, and 2*VFO frequencies respectively. Herein lies the proof of the mixing process, in which the sum and the difference of the two input frequencies are produced along with the original two signals and the first harmonic of the two (which is a result of a series expansion of the sinusoidal input frequencies). [34]

4.3.6 First Intermediate Frequency (IF) Amplifier

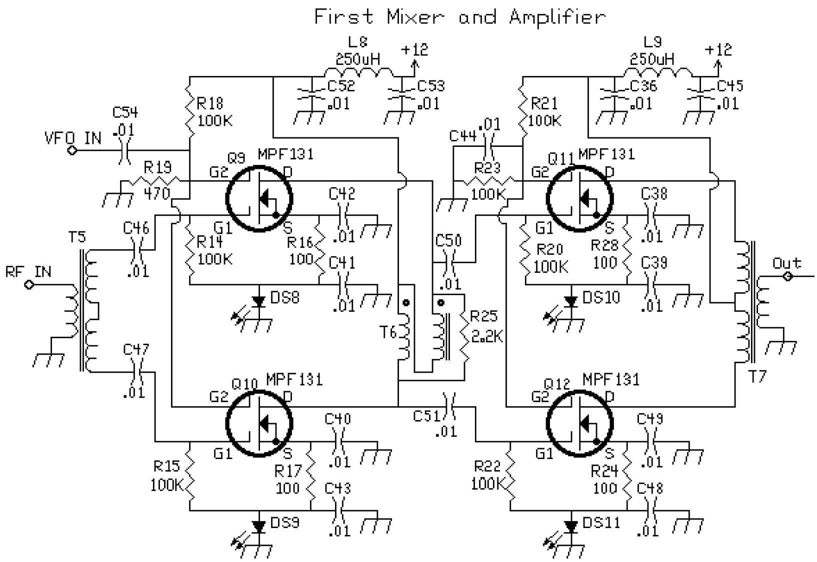

Figure 28: *First mixer and IF amplifier as they appear in the radio*

As can be seen in Figure 28, the first mixer is connected directly to the first IF amplifier. Note that it is very similar to the mixer except that the second gates are held at a constant 6 V (voltage divider between R21 and R23). This effectively assures that the gate source voltage will never drop below –4.4 V. Also, it allows for the IF to swing 6 V, which would be a very large IF frequency. In any case, the amplifier works in a similar manner to the RF amplifier, in which a varying base voltage pinches off and expands the channel from source to drain in the MOSFET, thereby modifying the source-drain current with a small gate voltage (which is solely due to the IF at G1). Also, the same transformer idea applies in which the IF input into the gates have to be phase shifted by 90 degrees from each other or else the flux through the first primary coil in the transformer cancels out the flux through the second primary coil. Once again, this is probably being done to ensure that there is no chance of oscillations if the circuit were to hit a resonant frequency and rob energy from the IF. Therefore, in order for the amplifier to work, one gate has to be brought down while the other is brought up with respect to the source. The change in flux induces a voltage in the secondary coil, which also reestablishes a single wire input.

4.3.7 Crystal Filters

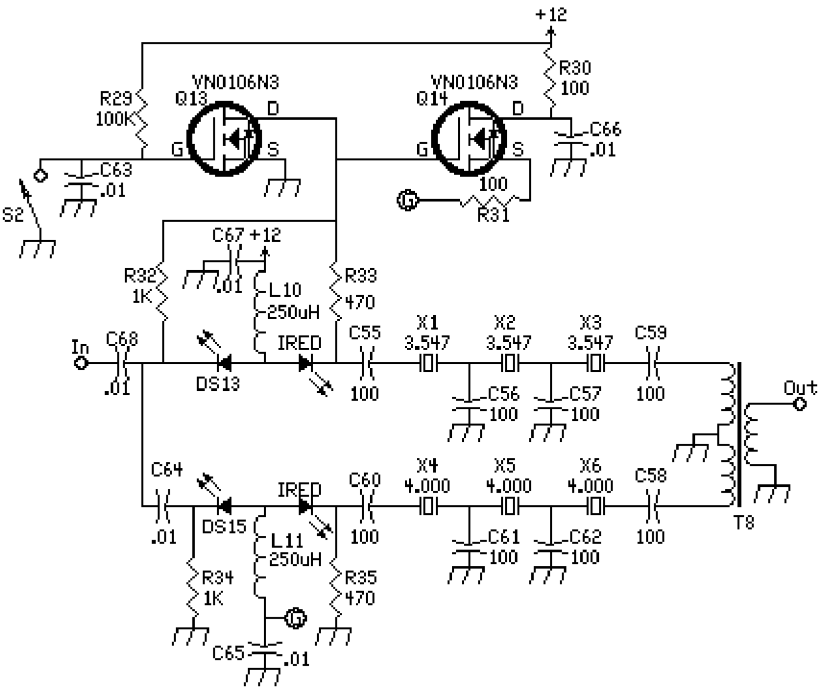

Figure 29: *The crystal filters*

Figure 29 details the crystal filters used to pick out the IF frequency (the difference of the VFO and RF frequencies). Looking at the above position of the switch, there are 12 V at the gate of the leftmost VN0106 (an N-channel enhancement-mode MOSFET). [35] As the gate threshold voltage is at a maximum of 2.4 V the MOSFET is turned on allowing current to flow from drain to source. [36] Since the source is at 0 V, the drain is also at 0 V, which makes the gate of the rightmost MOSFET at 0 V, meaning that it is off. Since the left hand side of DS13 (an LED) is at a lower potential than the right side, and the right side of the infrared LED (IRLED) is at a lower potential than the left side, both turn on. However, since there is no voltage drop across the diodes on the lower half, neither of the diodes turns on. Therefore, the IF frequency travels through the 3.547 MHz crystals, which resonate only at 3.547 MHz, filtering out the other frequencies.

If the switch is turned on, the voltage at the gate of the leftmost MOSFET is now 0 V while the gate of the rightmost MOSFET is now 12 V (note the 12 V by C67). Therefore, the leftmost MOSFET is turned off while the rightmost is turned on. In the circuit, the two circled "Gs" are connected. Therefore, between the bottommost LED and infrared LED there is some potential with no voltage on either side of the LEDs meaning that they are turned on. However, the upper half has 12 V on both sides of both diodes (and therefore no potential drop), which means that they do not turn on. Thus there is no path for the IF to travel on the top half of the circuit. On the bottom half, the IF travels through the crystals, which filter out all but 4.000 MHz. Note that the bottom infrared LED is used to shine onto an infrared phototransistor that sets the oscillating frequency on the variable frequency oscillator stage.

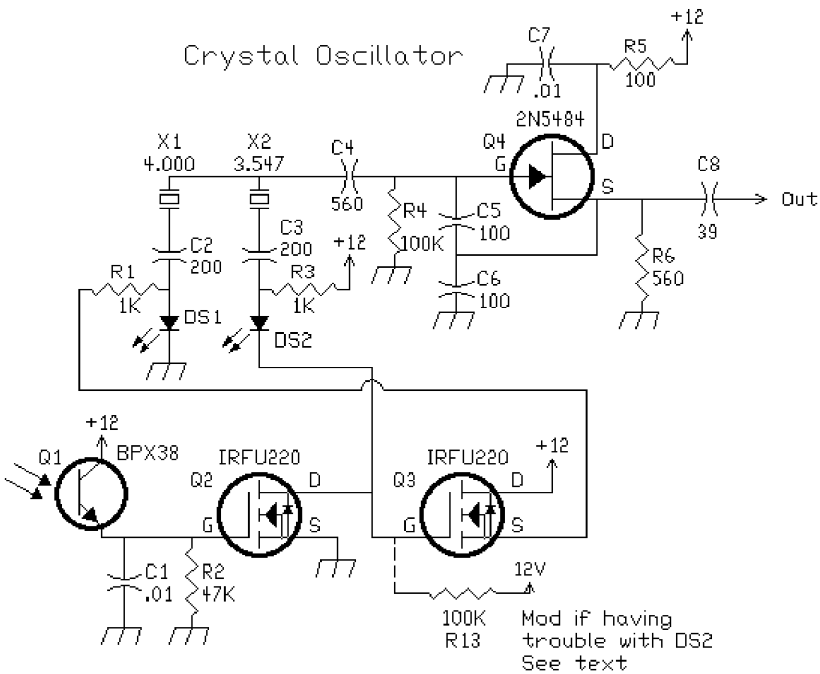

Figure 30: *The crystal oscillator and amplifier [37]*

Figure 30 details the crystal oscillator that creates the second frequency to beat with the IF in the second mixer. In the crystal filters, if the 3.547 MHz stage is turned on, no light shines on the BPX38 phototransistor (Q1), implying that it is off. As such, there is no voltage at the gate of the IRFU220, which is an N-channel, enhancement-mode MOSFET [38]. Since there is no gate current, the potential at the gate is 0 V. Looking at R3, we see there are 12 V across the LED, which is connected directly to the gate of the other MOSFET (Q3). This turns Q3 on, which means that 12 V is applied to the diode through R1, turning DS1 on. However, there is no potential difference across DS2, so it remains off.

If the 4.000 MHz stage of the crystal filter is turned on, it turns on Q1, which in turn means that there is 12 V at the gate of Q2, meaning that it is on. Since the source of Q2 is grounded, the ground of Q3 is at the same potential (0 V), turning it off. This means that there is no voltage drop across R1, which means that DS1 is off. However, since there is now a 12 V drop across DS2, it now turns on. As a voltage is passed through the crystal, it resonates at a certain frequency, which is applied to the gate of the 2N5484 JFET. This gate voltage modulates the current going from drain to source, which can now travel back to the gate of the JFET. This positive feedback modulates the current even more until the gate source power voltage difference is too small (hits the limits of the power supply) and the JFET turns off, allowing the signal to travel through to the output.

4.3.8 Second Mixer

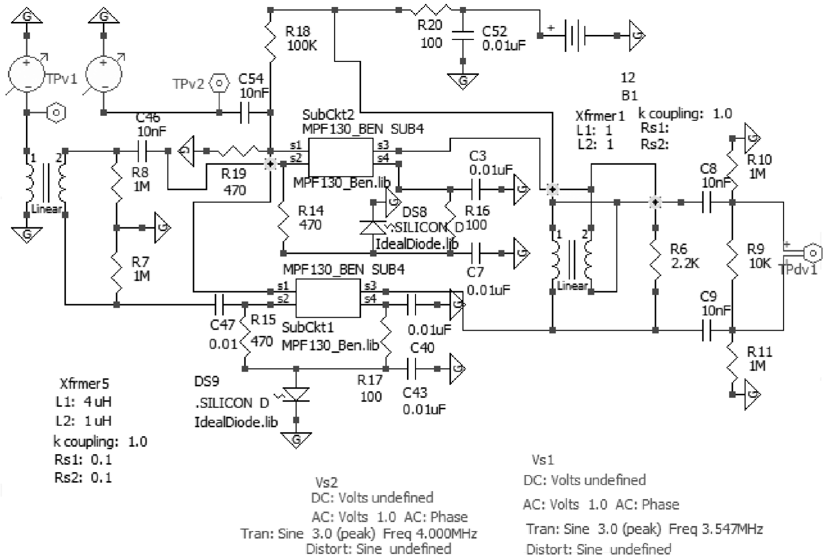

Figure 31: *The second mixer*

The second mixer is equivalent to the first mixer except for the inputs. The RF input (at TPV1) is the IF frequency from the first mixer, and the VFO frequency is the frequency from the crystal oscillator.

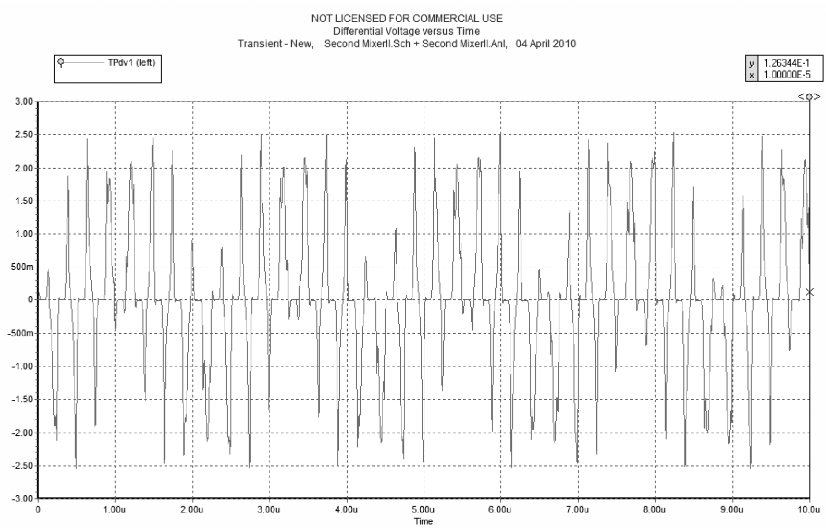

Figure 32: *Voltage (V) versus time (microseconds) for the output from the second mixer*

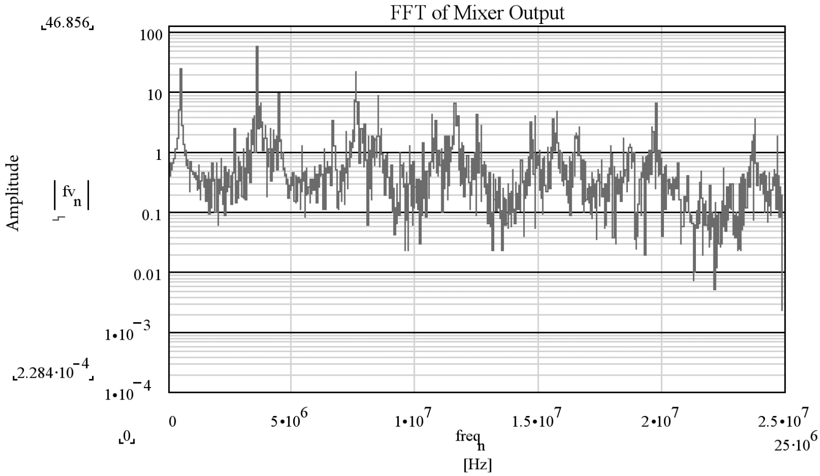

Figure 33: *Fourier transform of the waveform in Figure 32*

The first spike is at around 462 kHz and the third major spike is at around 756 kHz, which represent the difference and sum, respectively. Once again, the relevant IF frequency is the difference spike. The reasoning behind having a two-conversion (two IF stages) rather than a single-conversion (single IF stage) superheterodyne receiver is to ward off against possible feedback. The original RF frequency is much less than a volt, so it needs to undergo two or three orders of magnitude of gain to be audible. If this were done in a single stage, there would be great problems with feedback because any stray signal would get amplified by three or more orders of magnitude. Amplifying in stages makes this less of a problem because the gain at any one stage is a single order of magnitude rather than three or more.

4.3.9 Automatic Gain Control (AGC)

The AGC is tied up into the IF amplifier, so it is necessary to understand how the AGC works before understanding the IF amplifier.

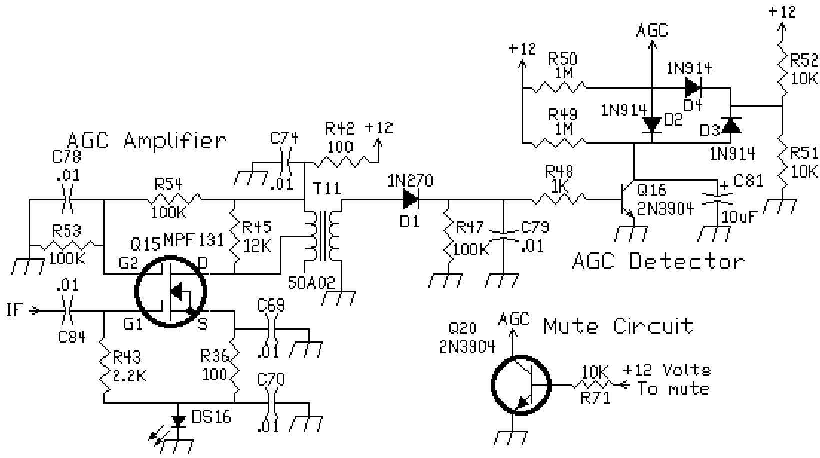

Figure 34: *AGC circuit [39]*

The AGC uses the same MPF131 dual-gate depletion-mode MOSFETs as used in the first and second mixers (at Q15), meaning that, in order to turn off, one gate has to be brought negative with respect to the source. The drain is held at 12 V since the transformer is effectively a wire for DC, and G2 is held at 6 V due to the voltage divider set up between R54 and R53. It is not clear why a dual-gate MOSFET was needed in this situation, as a single-gate FET would seem to work equally well since one gate (G2) is held constant the entire time.

In any case, if there is IF, then G1 of the MPF131 is at some voltage, which causes drain-source current to flow just as in the amplifiers described earlier, where a small change in base voltage causes a drain-source current. This AC current goes to the transformer where it is stepped up to go through the AGC detector.

The 1N270 diode (D1) cuts off half of the waveform (and R47 and C79 help cut out high frequencies), which is applied to the base of the 2N3904 NPN transistor [40]. In order to turn on, the 2N3904 transistor needs to be properly biased, so the drain needs to be at least 0.6 V above the source (0 V) in order to turn on. Since the voltage drop across the germanium 1N270 diode is about 0.3 V, the signal coming through the transformer has to be at least 0.9 V. [41] If this is the case, current flows from the collector to the emitter. (Note that the collector is around 6 V due to R50 and R49.) This is turn pulls the voltage across R50 down, which could turn off the transistor if pulled low enough, as there is no longer a 0.3 V drop across the diode. Note that the AGC is connected to the IF stage and will be used in the next section.

Figure 35, below, details the mute circuit, which is included if a transmitter is connected to the receiver. In order to transmit without hearing what is being transmitted back in the receiver, the transistor is turned on, which makes the voltage at the AGC on the AGC Detector 0 V. It also turns off the entire IF strip.

4.3.10 Intermediate Frequency (IF) Strip

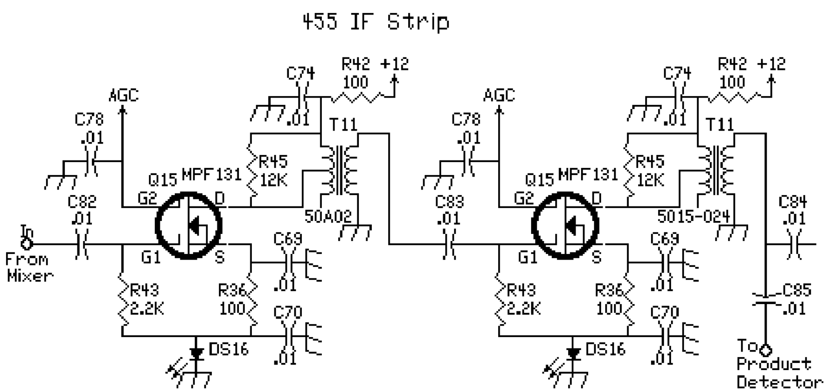

Figure 35: *IF strip [42]*

Figure 35 details the IF strip, which is a near duplicate of the AGC Amplifier. However, if the AGC voltage is 0 V, then the source is biased enough to either turn off or severely diminish the drain-source voltage, thereby minimizing the gain. This is done so as to keep excessively large signals coming through and pulling too much drain-source current, thereby clipping the incoming signal. Also, the IF stage is replicated twice to maximize the gain without pulling too much current.

4.3.11 Beat Frequency Oscillator (BFO) and Amplifier

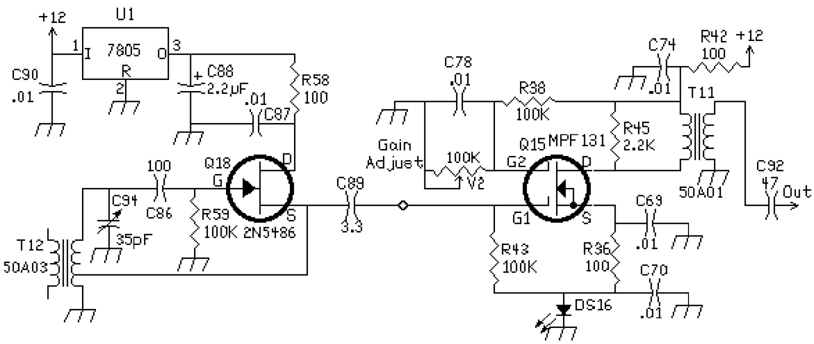

Figure 36: *Beat frequency oscillator and amplifier [43]*

In order to get voice from the IF, it needs to be brought down from the 455 kHz IF. The first stage of this is done in the beat frequency oscillator, which creates a 455 kHz signal to beat with the IF, much as the variable frequency oscillator did.

The 50A03 (T12) is called an IF can. It is effectively a tuned circuit that resonates at a certain frequency, in this case 455 kHz. [44] The oscillator, like the variable frequency oscillator, utilizes positive feedback. A small potential induced in the IF can creates a small change in current (and thus a potential at the gate of the 2N5486) that pulls some drain-source current. This source current ends up back at the IF can, which resonates at 455 kHz and induces a greater voltage at the gate, pulling more drain-source current at the resonant frequency. This continues until no more current can be pulled through and the oscillator hits the rails.

Current then travels through to the same oscillator. The only difference in this scenario is that there is a gain-adjust potentiometer that limits the gate-source current. This is done to limit the BFO signal to prevent possible clipping in later stages.

4.3.12 Product Detector

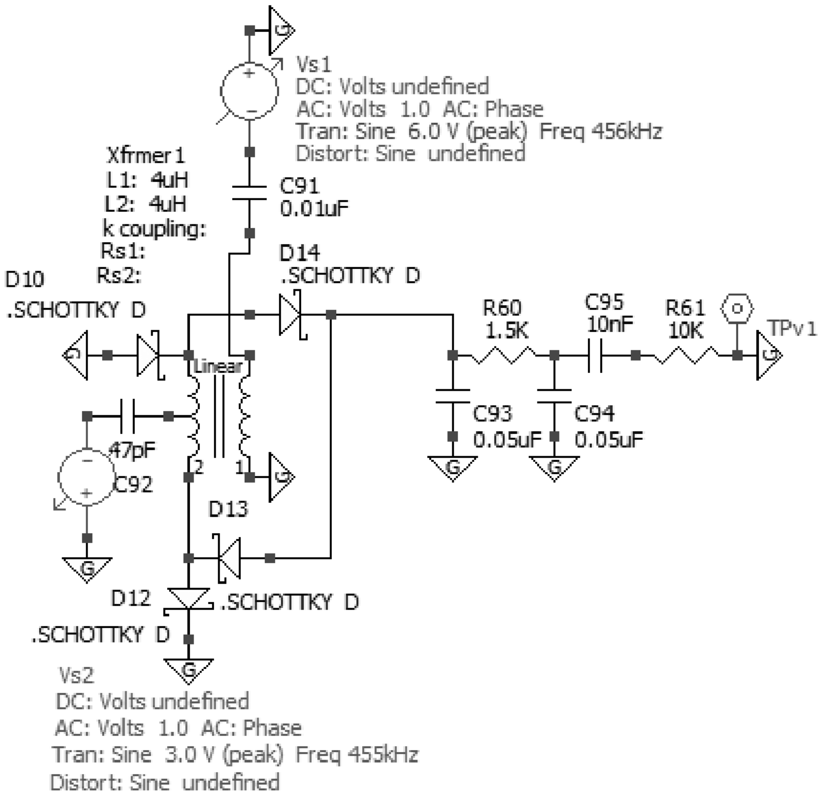

Figure 37: *Product detector*

Like the mixers, the product detector beats two frequencies together in order to produce an audible frequency. It effectively removes the 455 kHz carrier. As shown in Figure 37, the first voltage source is the waveform produced in the BFO while the second voltage source is the IF after it has gone through a 455 kHz filter with about a 6 kHz bandwidth. [47] The BFO frequency and the IF go through the transformer where they are added together. However, since the signals are not quite the same frequency, they destructively or constructively interfere with one another at different spots along the waveform.

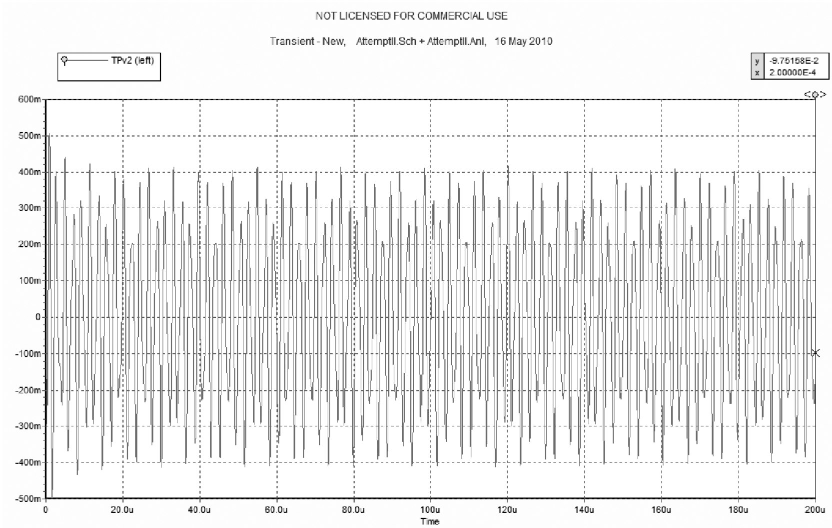

Figure 38: *Waveform when the BFO and IF are 5 kHz apart*

As this waveform comes to the diode, it is rectified due to the reverse bias of the diode, cutting off half the waveform.

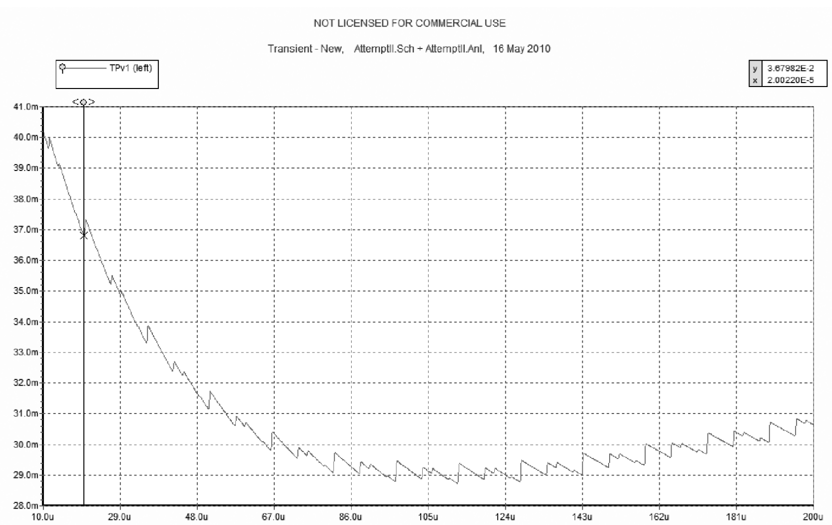

Figure 39: *Rectified waveform*

After passing through the diode, the signal comes to a parallel RC circuit whose time constant is much more than the period of the IF ($1.5x10^{-4}$ s versus $2.20x10^{-6}$ s). This means that the parallel RC circuit acts as an integrator (as defined in Appendix C), meaning that the voltage on the capacitor is proportional to the integral of the voltage applied to it during some time period. In other words, as the voltage of the waveform increases, it charges up a capacitor. As the voltage decreases, the capacitor discharges through the resistor and the diode. Therefore, the 455 kHz carrier frequency is 'integrated out' while the modulation (peaks and valleys) remains. This modulation is the audio on the original RF waveform.

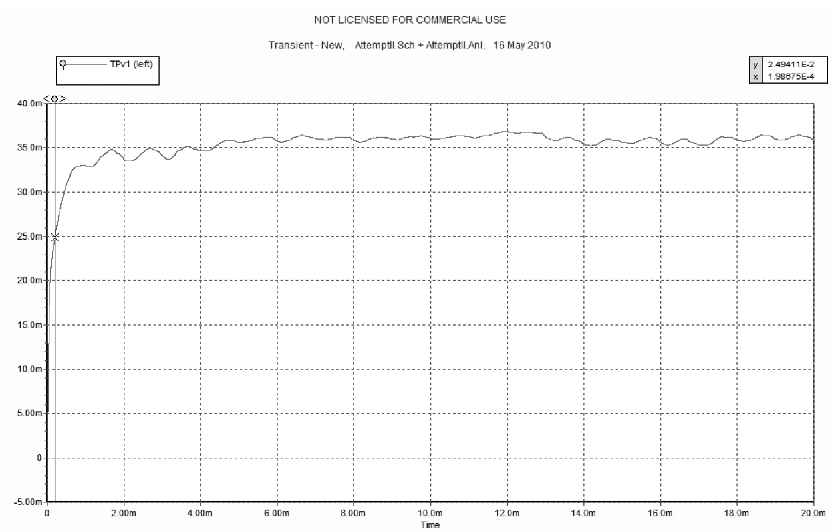

Figure 40: *Output voltage when the BFO and IF frequencies are 1 kHz apart*

4.3.13 Audio Amplifiers

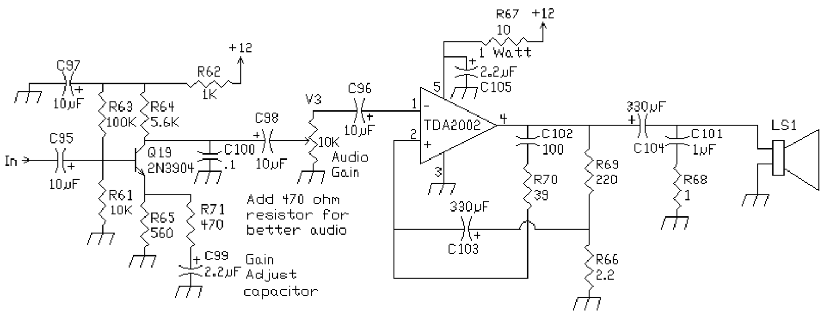

Figure 41: *Pre-audio and audio amplifiers*

Now that the carrier has been removed, the next step is to amplify the audio. The first step is the pre-audio amplifier. This amplifier is similar to the previous amplifiers in which a small base current causes a large emitter-base current. What can be noticed about the amplifier is that Q19 is actually biased at about 1.08 V due to the voltage divider between R62 and R63. This is done to assure that there is current flow for small changes in base voltage. In any case, a small change in base current causes a large change in collector-emitter current, and the change in the current of the audio waveform is mirrored in a change in the collector-emitter current.

The gain of the circuit is calculated in an interesting way. Since the base is effectively tied to the emitter, a change in base voltage is mirrored by an equivalent change in emitter voltage, so that:

$$V_{emitter} = V_{base}$$

The resulting change in current is equal to:

$$\frac{V_{emitter}}{R_{emitter}} = \frac{V_{base}}{R_{base}} = \frac{V_{base}}{R_{emitter}}$$

This change in emitter current is mirrored by a change in collector current equal to:

$$\frac{V_{collector}}{R_{collector}} = -i_{collector}$$

The sign is negative because with a fixed power supply, if more current is getting pulled through the base, less current is getting pulled through the collector. In any case, the change in current in the base is equal to the negative change in current in the base, meaning:

$$\frac{V_{collector}}{R_{collector}} = \frac{-V_{base}}{R_{emitter}} =$$
$$\frac{V_{base}}{V_{collector}} = \frac{-R_{collector}}{R_{emitter}} \qquad [48]$$

Therefore, the gain of the amplifier is equal to:

$$gain = \frac{-5{,}600[\Omega]}{560[\Omega]} =$$
$$gain = -10$$

In other words, the gain of the amplifier is 10, phase shifted by 180 degrees. Note that R62 was ignored because it applies to both the base and the collector, and so cancels out of the equation. Also, R71 is not part of the circuit as put on the board.

The 2.2 μF gain adjust works by changing the RC time constant of the parallel RC circuit, increasing the impedance for different frequency signals. That is, as long as the value of the capacitor is not zero, there is some added emitter impedance, implying a smaller gain.

Finally, the audio goes to the audio amplifier, which is an op-amp biased to filter out high-frequency signals (the various RC circuits). The audio amplifier drives a speaker or headphones to produce a sound.

5 Final Thoughts

Surprisingly, the receiver operates correctly, but a few comments are worth making in closing. An LED frequency display and a frequency stabilizer were added to the above circuit, which came as extras with the receiver kit itself. The frequency display shows the VFO frequency added to the first mixer frequency to display the RF frequency being let in. As a result of thermal inconsistencies and stray capacitance, the VFO can stray from its original position after prolonged operation of the receiver. As a result, the stabilizer is included to keep the VFO from straying.

Also, some debugging was required to make the receiver operational. At first this debugging consisted mostly of getting the LED frequency display to work by removing traces left by poor soldering and unsoldering.

Once the LED frequency display was operational, the next step was to apply power and see which LEDs were turned off. (The LEDs proved extremely helpful in the debugging process.) When first powered up, no LEDs turned on, due to incorrect soldering of the input power to ground and the ground to the input power. Many of the connections between boards (for example, from the crystal filters on Board 1 to the second mixer on Board 2) were connected using mini Teflon coaxial cable. Unfortunately, due to separating too little of the braid from the central core, it ended up shorting together, which necessitated covering it with insulation from some low-gauge insulated wire.

The next problem arose from a hairline crack along the trace next to the pre-audio amplifier. Not only was there no sound coming through, but the pre-audio transistor appeared to be biased correctly when the op-amp had one pin correctly biased but the other pin was held at zero. This was fixed by creating a solder bridge across the trace.

Other problems included an incorrectly placed 7805 voltage regulator next to the VFO amplifier, which became apparent when the LED not only failed to turn on but began to heat up and smell. It was indeed blown out, but a new Radio Shack part filled in well. Also, an FET on the second mixer was acting strangely, as indicated by an LED not lighting up. It was later found out that the source-drain resistance in the working one was around 200 Ω but infinite in the non-working one. Finally, the BFO filter potentiometer was not soldered correctly to the board, preventing any audio signal until it was shifted back and forth some to create a better connection.

The next step will be to actually make modifications to the original design. A couple of modifications have already been done as relate to the frequency range. Originally, the receiver had a bandwidth of about 150 kHz, which was not enough (especially on the 40 m band) to receive voice. As suggested by Mr. White, increasing the tuning range required adding another section on the main tuning capacitor, which was done by adding a jumper between two sections. Also, a capacitor was changed near the VFO to increase the capacitance enough to get a wider bandwidth. This unfortunately raises the capacitance, implying that everything is shifted down: RC has gone up, meaning that the frequency has gone down. The next step is to bring the receiver up by 200 kHz, which involves removing capacitance.

The second modification was to increase the bandwidth of the radio to receive single side band (voice). The receiver was designed for receiving Morse code (CW). As such, the crystal filters filter out much of the voice signal, leaving the remainder distorted. Increasing the capacitance lowers the "q" of the circuit and increases the bandwidth. [49]

At present the receiver receives Morse code very well. However, the lack of a proper antenna has caused some signals to be lost. When that is hooked up, it will probably be able to receive for hundreds of miles.

6 Conclusion

Overall, I have learned an immense amount about not only radio operation but the basics of circuit design. It is astonishing how a simple tuned circuit can transform itself into such an amazing piece of equipment as the electroluminescent receiver. It took much more time than I had originally envisioned, but it was an incredible pleasure when everything finally came together.

7 Appendices

7.1 *Appendix A: Parts List*

Part Description	What needed for	Cost($)	Location
470 pF capacitor	tuned circuit crystal radio	0.20	HSC Electronics
220 pF capacitor	tuned circuit crystal radio	0.20	HSC Electronics
100 pF capacitor	tuned circuit crystal radio	0.20	HSC Electronics
PVC Pipe	inductor crystal radio	0.00	Dr. Dann
Sheet-rock Screws	crystal radio	0.00	Dr. Dann
PVC Pipe	inductor crystal radio	0.00	Dr. Dann
27 gauge wire	inductor and circuit crystal radio	0.00	Dr. Dann
18 gauge wire	antenna, ground, and tuner	0.00	Dr. Dann
Insulated wire	circuit crystal radio	0.00	Dr. Dann
Slimfast can	tuner crystal radio	0.00	Dr. Dann
Wood	radio base and tuner base	0.00	Dr. Dann
Electroluminescent Receiver	Superheterodyne receiver kit	170.00 + shipping	Amateurradio receivers.net
TOTAL COST = 170.60 + shipping			

7.2 *Appendix B: Proof of the Mixing Process*

$$\sin A \sin B = \frac{\cos(A-B)-\cos(A+B)}{2}$$

Using addition and subtraction of cosine rules, this expression can be simplified down to :

$$\sin A \sin B = \frac{\cos A\cos B + \sin A \sin B - [\cos A \cos B - \sin A \sin B]}{2} =$$

$$\sin A \sin B = \frac{\cos A\cos B + \sin A \sin B - \cos A \cos B - \sin A \sin B}{2} =$$

$$\sin A \sin B = \frac{2\sin A \sin B}{2} =$$

$$\text{sinAsinB} = \text{sinAsinB}$$

7.3 Appendix C: Proof of an Integrator Circuit

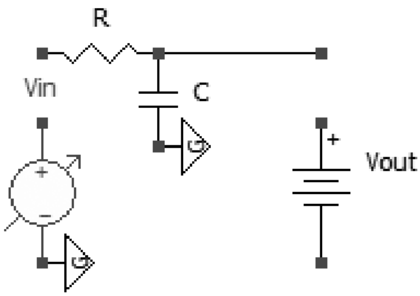

Figure 42: *Parallel RC circuit*

The voltage across 'R' is V_{in} - V implying:

$$I = C\frac{dV}{dt} = \frac{V_{in} - V}{R}$$

If V << V_{in} then:

$$C\frac{dV}{dt} = \frac{V_{in}}{R} =$$

$$V(t) = \frac{1}{RC}\int_0^t V * dt + \text{ constant}$$

Note, however, that this only applies while V << V_{in}, which is about one time constant $\left(\frac{1}{RC}\right)$. [45]

7.4 Appendix D: Solution to the Differential Equation for Impedance in the Circuit

$$I = I_1 + I_2 + I_3$$

$$I\cos(\omega t) = \frac{1}{L}\int V * dt + C * \frac{dV}{dt} + \frac{V}{R}$$

Take the derivative to get rid of integral

$$-I\omega\sin(\omega t) = \frac{V}{L} + C * \frac{dV^2}{dt^2} + \frac{dV}{dt} * \frac{1}{R}$$

Judging by how similar this equation is to simple harmonic motion presume its solution to be :

$$V(t) = A\cos(\omega t + \phi)$$

$$-I\omega\sin(\omega t) = \frac{A\cos(\omega t + \phi)}{L} + -CA\omega^2\cos(\omega t + \phi) - \frac{A\omega\sin(\omega t + \phi)}{R} =$$

Since this equation is true at all times 't' make 't' equal zero to make the problem simpler

$$0 = \frac{\text{Acos}(\phi)}{L} - CA\omega^2\cos(\phi) - \frac{A\omega\sin(\phi)}{R} =$$

$$0 = \frac{\cos(\phi)}{L} - C\omega^2\cos(\phi) - \frac{\omega\sin(\phi)}{R} =$$

$$0 = \frac{1}{L} - C\omega^2 - \frac{\omega\sin(\phi)}{\cos(\phi)} * \frac{1}{R} =$$

$$\boxed{\tan(\phi) = R\left(\frac{\omega}{L} - C\omega\right)}$$

Once again, choose 't' such that $\omega t + \phi = \frac{\pi}{2}$

$$-I\omega\sin\left(\frac{\pi}{2} - \phi\right) = 0 - 0 - \frac{A\omega}{R} =$$

$$-I\sin\left(\frac{\pi}{2} - \phi\right) = \frac{-A}{R} =$$

$$A = RI\sin\left(\frac{\pi}{2} - \phi\right) =$$

$$A = RI\cos\phi$$

$$A = RI\frac{\cos\phi}{\sqrt{\cos^2\phi + \sin^2\phi}} =$$

$$A = \frac{RI}{\sqrt{1 + \tan^2\phi}} =$$

$$A = \frac{RI}{\sqrt{1 + R^2\left(\frac{\omega}{L} - C\omega\right)^2}} =$$

$$A^2 = \frac{R^2 I^2}{1 + R^2\left(\frac{\omega}{L} - C\omega\right)^2} =$$

$$\boxed{A = \frac{I}{\sqrt{\frac{1}{R^2} + \left(\frac{\omega}{L} - C\omega\right)^2}}}$$

Since $V(t) = A\cos(\omega t + \phi)$, and '$\omega t$' is unitless, 'A' gives a voltage, meaning that the above is a form of Ohm's Law V = IR, meaning :

$$\boxed{Z = \frac{1}{\sqrt{\frac{1}{R^2} + \left(\frac{\omega}{L} - C\omega\right)^2}}}$$

7.5 Appendix F: Mathcad calculations

The Mathcad documents used to do the calculations are available online at http://roundtable.menloschool.org.

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