Bacon Radio

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***Abstract*—We built a superheterodyne AM receiver for the 40 meter amateur radio band using hobbyist-accessible parts. Using relatively simple analog circuitry, we constructed a radio capable of receiving transmissions from operators in the local area and broadcast stations as far away as North Carolina. Building the receiver allowed us to explore the history of radio design and how it has driven and influenced the history of electronics. We tested our radio both with actual amateur and broadcast signals on the air, as well as with RF test equipment. The receiver achieved a sensitivity of about $-50\ \mathrm{dBm}$ and a receive bandwidth around $110\ \mathrm{kHz}$ at that power level. While there is certainly room for improvement in RF performance, we came up with a highly understandable and approachable design that includes all the fundamental elements of a modern superheterodyne design.**

***Index Terms*—radio, ham radio, amateur radio, superheterodyne, receiver**

I. INTRODUCTION

Amateur radio is a century-old hobby centered around radio-based communications technology that allows global communication without modern point-to-point infrastructure. Although amateur radio today encompasses a vast array of modern, experimental technologies on frequencies going up to the tens of gigahertz, the core of the hobby and its oldest activity involves communication via the HF (high frequency, also known as shortwave) bands, a set of frequencies ranging from 1-30 MHz, notable because they bounce off a layer of the upper atmosphere called the *ionosphere* [1]. Unlike higher frequencies (such as those used by short-distance devices like cellphones) that radiate in a straight line out into space and can only make direct radio links within line-of-sight, HF allows direct communications globally without towers, repeaters, or satellites relaying the signal [1].

The frequency ranges allocated internally to amateur radio operations on the HF bands are harmonically related and generally referred to by their wavelength (160 meters, 80 meters, 40 meters, 20 meters, and 10 meters) [1]. 60 meters, 30 meters, 17 meters, 15 meters, and 12 meters are also available, but their availability to amateur radio is more recent, so their use is less common. Due to changes in the ionosphere from solar radiation, each band has different propagation characteristics. 160 meters and 80 meters are generally capable of very long-distance contacts at night but perform poorly during the day. During the current high point in the 11-year cycle of solar activity, the 20 meter band has extremely good propagation during the day but drops off quickly as soon as the sun sets [1]. Our radio uses the 40 meter band because it offers a good combination of acceptable short-distance (up to a few hundred miles, generally) propagation during the day and global propagation during the evening and night. Additionally, the frequencies for this band (7.0-7.3 MHz) are low enough that prototyping using breadboards and perfboards is still possible [2].

A. Historical Background and Motivation

Since Marconi invented the radio in 1895, radio design has driven and made use of the latest innovations in electrical engineering. The need for some kind of non-linear device for demodulating RF was what spurred the invention of the first widespread semiconductor device, the diode (see Lecture 2 from [3]). And, as the need for global wireless telecommunication grew, the need for a device that could amplify incredibly weak RF signals to audible levels caused the widespread adoption and development of the first non-electromechanical amplifying device, the vacuum tube (see Lecture 3 from [3]). Today, software-defined radios use some of the fastest and lowest-noise DACs and ADCs available, often on specialty silicon.

The sliding scale of radio design complexity today more or less tracks the history of electronics. The classic DIYer's single-diode broadcast AM receiver with an LC tank circuit closely resembles the very earliest crystal radios from the beginning of the 20th century, which used the diode junction formed by a needle touching a crystal of galena (lead sulfide) to rectify AM signals and a piezoelectric "crystal earpiece" to produce an audible signal using only the RF power from the received signal. At the other end of the scale, modern software-defined radios follow modern electrical engineering's trend of digitization enabling capabilities that were never possible in the analog domain. These radios generally still include fairly complex analog circuitry for pre-filtering and down-converting incoming RF but then digitize the signal, allowing the creation of filters and effects that would be impossible with only analog signal processing.

In exploring the range of receiver architectures available today, we decided to implement a design typical in architecture

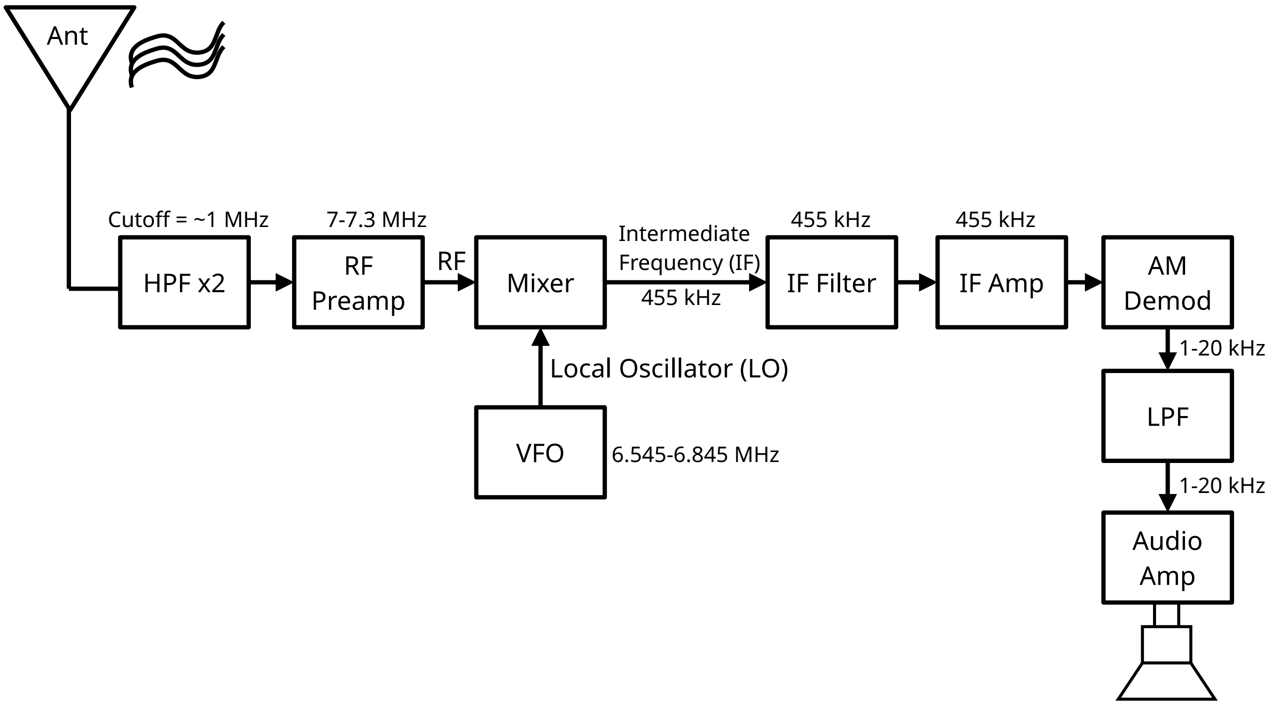

Fig. 1. Block diagram of the full receiver architecture, with a signal path going from left to right, then down. Shows the critical stages of how very weak RF gets turned into strong audio through down-conversion and demodulation.

of the 1970s or 1980s (and still common with hobbyists today). This choice allowed us to explore the heyday of fully-analog radio design while still using an architecture that remains very applicable to modern radios.

1) Historical Architectures: The low transmit power levels and poor-quality amplification devices available for most of the early history of radio, coupled with the enormous demand for long-distance communication without wires, resulted in many inventive architectures for receivers.

The first device that could be called a radio receiver used a “coherer,” a now-forgotten rectification device that changed conductivity when RF signals were present using iron filings that would stick together [3]. These were quickly replaced with diodes as soon as natural crystal diodes were discovered.

The very earliest crystal receivers mentioned before contained no amplification and used mechanically-tunable LC tank circuits for filtering. They worked by directly demodulating the incoming RF signal with no frequency conversion [3].

As soon as active amplification devices became available (vacuum tubes), a new class of receivers called TRFs (Tuned Radio Frequency) receivers became common. TRFs used resonant amplifiers very carefully biased so that they would resonate at the desired frequency enough to achieve some kind of feedback amplification but not enough to oscillate forever [4]. The “regenerative receiver” was the most common TRF design until the 1920s, but they suffered from unwanted oscillation [3]. Slightly later iterations on this design like the “neutrodyne receiver” became more stable, but the TRF family of architectures is essentially dead today. They were a useful workaround for achieving very high gain with relatively low-gain amplification devices (early tubes). Notably, however, these architectures pioneered positive feedback, which remains very common in all kinds of analog circuit designs (including radios) now [3].

The invention of the superheterodyne receiver architecture (explained in the next section) in the 1920s rapidly ended the era of complex, unstable receiver architectures. It remains the dominant receiver architecture to this day.

In terms of project motivation, building an analog superheterodyne radio offered the best combination of exploring radio’s history and building something with principles applicable to modern radio.

II. CIRCUIT DESIGN

The two fundamental performance metrics of a radio receiver are *sensitivity* and *selectivity* [2]. These metrics define the main challenges involved with building a receiver, so discussion of the circuit design of the receiver will center around them. Sensitivity measures how weak of a signal the receiver can successfully detect, and selectivity measures how well the receiver can select the signal of interest while rejecting other signals. Conveniently, these two goals roughly correspond to the two types of circuits that comprise a receiver;

sensitivity comes from the amplifiers, and selectivity comes from the filters.

The main challenge of building a good receiver is that achieving good selectivity can worsen the radio's sensitivity (and, to some lesser extent, vice-versa). A receiver with very good selectivity will have very narrow filters with sharp passbands–in analog signal processing, creating such filters generally involves introducing some amount of attenuation even in the passband. A receiver with very good sensitivity will have very high-gain amplifiers, which entails introducing non-linearity that can result in *intermodulation*–unwanted frequency mixing producing interfering signals within the radio (note that intermodulation is also its entire own category of performance metrics).

A net gain of $124\ \mathrm{dB}$ from the initial RF to the final audio output is typical of good amateur receivers, although $80\ \mathrm{dB}$-$90\ \mathrm{dB}$ is usable [2]. An amateur AM signal is about $10\ \mathrm{kHz}$ wide, but there is no channelization or enforced channel separation on the amateur bands, so receiver selectivity should ideally be good enough to reject very closely-spaced (sometimes even partially-overlapping during contests) signals.

A. Architecture (see Fig. 1)

The bacon radio uses a superheterodyne receiver architecture with an intermediate frequency (IF) of $455\ \mathrm{kHz}$. The full block diagram in Fig. 1 shows the signal path all the way from from antenna to speaker. Signals begin as RF in the microvolt range ($-50\ \mathrm{dBm}$) at the antenna, a Yagi beam 110 feet above sea level on a tower on MIT building 50. RF travels down the coaxial feedline from the antenna and through the station's low-loss switching setup until it reaches two off-the-shelf, high-pass filters designed to block the AM broadcast band.

RF then travels to the RF preamp circuit, which amplifies the unfiltered RF enough to drive one input of the mixer. The other input of the mixer is driven by a variable frequency oscillator.

The central problem of creating an *tunable* receiver is that physically constructing the very high-quality factor filters necessary to achieve good selectivity is already quite difficult, and adding the requirement that the resonant frequency of those filters be variable makes it almost impossible. Crystal filters cannot be re-tuned without physically grinding (or adding material to) the piezoelectric crystal. For LC filters, making good mechanically-variable capacitors is expensive and can consume a lot of space (and mechanically-variable RF inductors are even harder to build reliably).

The important and innovative aspect of the superheterodyne architecture is that tuning is that the final high-quality factor filter that selects the signal of interest is *not* tunable–it can be built and optimized for one "intermediate frequency" (IF). The radio is tuned by changing the variable frequency oscillator (VFO) frequency, which the mixer uses to produce an IF beat frequency with the incoming RF.

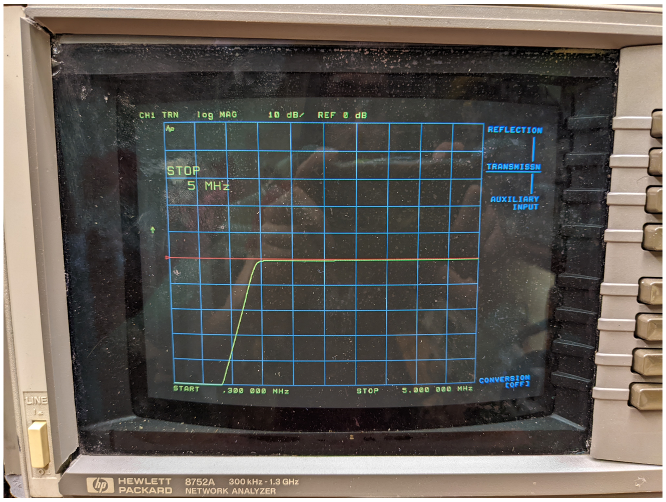

Fig. 2. Frequency sweep of external high-pass filter on HP VNA

Notably, the VFO will still require variable capacitances or inductances for tuning, but the voltages in a VFO circuit are multiple orders of magnitude higher than those in a receiver, so lossy components can be used with less issue.

The IF output of the mixer passes through a resonant fixed-frequency IF filter, then through an IF amplifier. According to [2], the bulk of the gain of a superheterodyne receiver signal chain generally resides in the IF amplifier stage. This is preferable to a high-gain RF amplifier because high-gain amplifiers are often less linear. Linearity is critical in the RF amplifier because that stage is extremely wideband–signals many megahertz apart are being amplified simultaneously, so any non-linearity in the RF amplifier would result in intermodulation and "ghost" signals being created in the receiver. Once the IF has been filtered, the IF filter can apply high gain without unintentionally mixing in undesired signals. In practice, the RF and IF amplifier circuits in our receiver are similar, but the IF amplifier should achieve higher gain because it is operating at a lower frequency.

The amplified IF is demodulated by a single-diode AM demodulator circuit. The audio frequency (AF) output signal of the demodulator is low-pass filtered to attenuate any IF that leaked through the demodulator, then fed to the audio amplifier. The audio amplifier is configured for a gain of 200 and drives the $8\,\Omega - 16\,\Omega$ speaker output.

B. RF Stages

1) High-Pass Filters: Using an Icom 7610 radio, we measured that some of the local AM broadcast signals were $60\,\mathrm{dB}$ over S9, equivalent to $-13\,\mathrm{dBm}$. Since these extremely powerful signals tended to couple into every circuit and overload the receiver (the audio amplifier chip even started demodulating them without any RF circuitry and producing an intelligible voice from its speaker), we put two off-the-shelf high-pass filters in between the antenna and the input to the radio. A Bode Plot of the frequency response of these

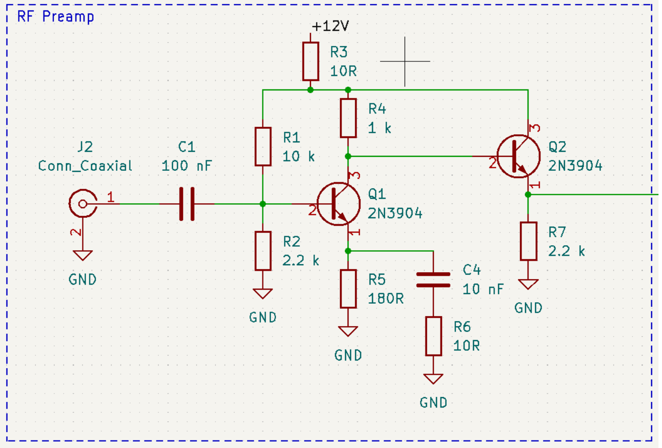

Fig. 3. RF preamp schematic

Marker	Trace	Type	X Axis	Amp
4D	1	Frequency	7.535800 MHz	-16.25 dBm

Fig. 4. RF preamp testing on Rigol spectrum analyzer

filters, which we characterized on an HP VNA, is shown in Fig. 2.

2) RF Preamp: According to [2], not all receivers actually need an RF preamp before their mixer. In many commercial HF radios, the RF preamp circuit can be enabled or disabled at the push of a button (and is generally only used for extremely weak signals). However, testing of earlier mixer designs indicated that we might need more RF power to drive it effectively, so we added the preamp in case. It adds about 30 dB of gain (based on the Rigol spectrum analyzer measuring the received RF from the antenna with and without the preamp).

The RF preamp circuit in Fig. 3 is based on the one from [5], but without the feedback and some of the later stages. It consists of an input decoupling capacitor feeding into a common-emitter amplifier with emitter degeneration, the output of which feeds into an emitter follower for buffering. Two-resistor biasing is used for increased bias stability. The amplification devices are BJTs, since low noise is extremely important for the microvolt-level signals at this stage.

A spectrum analyzer sweep of the initial breadboard prototype of the RF preamp circuit receiving signals from the actual antenna is shown in Fig. 4. Note that the amplitude of the peaks (representing signals at different frequencies being received by the antenna) is in the low-millivolt range, which is sufficient to drive the mixer. The marker selected with a power level of $-16.25\,\mathrm{dBm}$ at $7.536\,\mathrm{MHz}$ is a shortwave broadcast station close to the amateur band, which we used for receiver testing often.

C. RF Stage

1) Variable Frequency Oscillator:

For the variable frequency oscillator as shown in Fig. 5, a stable 6.5 MHz to 6.8 MHz frequency is required such that when mixed with the RF signal, an intermediate frequency of 455 kHz can be achieved for all frequencies within the 7.0 MHz to 7.3 MHz receiver tuning range.

For an oscillator, achieving good stability and a wide range for tuning limits potential designs as achieving one can mean sacrificing the other. For instance, an LC oscillator that is tuned by changing the capacitance or inductance will encounter stability issues in the form of frequency drift. Deviation from the desired frequency can cause unwanted interference from neighboring frequencies.

To resolve this issue, two 2N3568 NPN BJTs are used which act like varactor diodes. The BJTs are biased with connected collectors with one BJT having a grounded gate and the other connecting to the tank circuit. The collector of the BJTS are connected to a resistor and a variable resistor. The resistor network change bias at the collector which will tune the capacitance of BJT on the tank circuit, allowing the frequency to be tuned using a variable resistor instead of a more unstable variable capacitor. This allows for better stability, a wide range of tuning, and a more isolated frequency. The resulting oscillator produces 2 V peak-to-peak stable oscillations with a tunable range from 6.7 MHz to 7.0 MHz.

2) Mixer:

For the mixer, a double-balanced design would be ideal to isolate the mixer products from the mixer inputs. However, these designs can be complicated to build and often require both an inverting and non-inverting input, which may be difficult to achieve due to amplitude and phase differences (they require generating a precisely phase-inverted version of the LO signal, which ideally would involve a PLL circuit). Unbalanced mixer designs, though they may pass the input frequencies in addition to the mixing products, are simpler to construct and can still reliably down-convert to the desired IF. As such, an unbalanced design was chosen with the caveat that a more aggressive band-pass filter (or a greater separation between IF and RF frequencies) would be needed to isolate the desired 455 kHz frequency.

The BJT mixer as shown in Fig. 6. utilizes a single 2N3904 NPN BJT as the non-linear element to preform the frequency mixing. The RF input is fed into the base of the NPN while the VFO output is fed into the emitter of the NPN. This produces the sum of the mixer products and input frequencies at the collector of the NPN. This output is buffered using a simple BJT emitter-follower and will be fed into the IF band-pass filter.

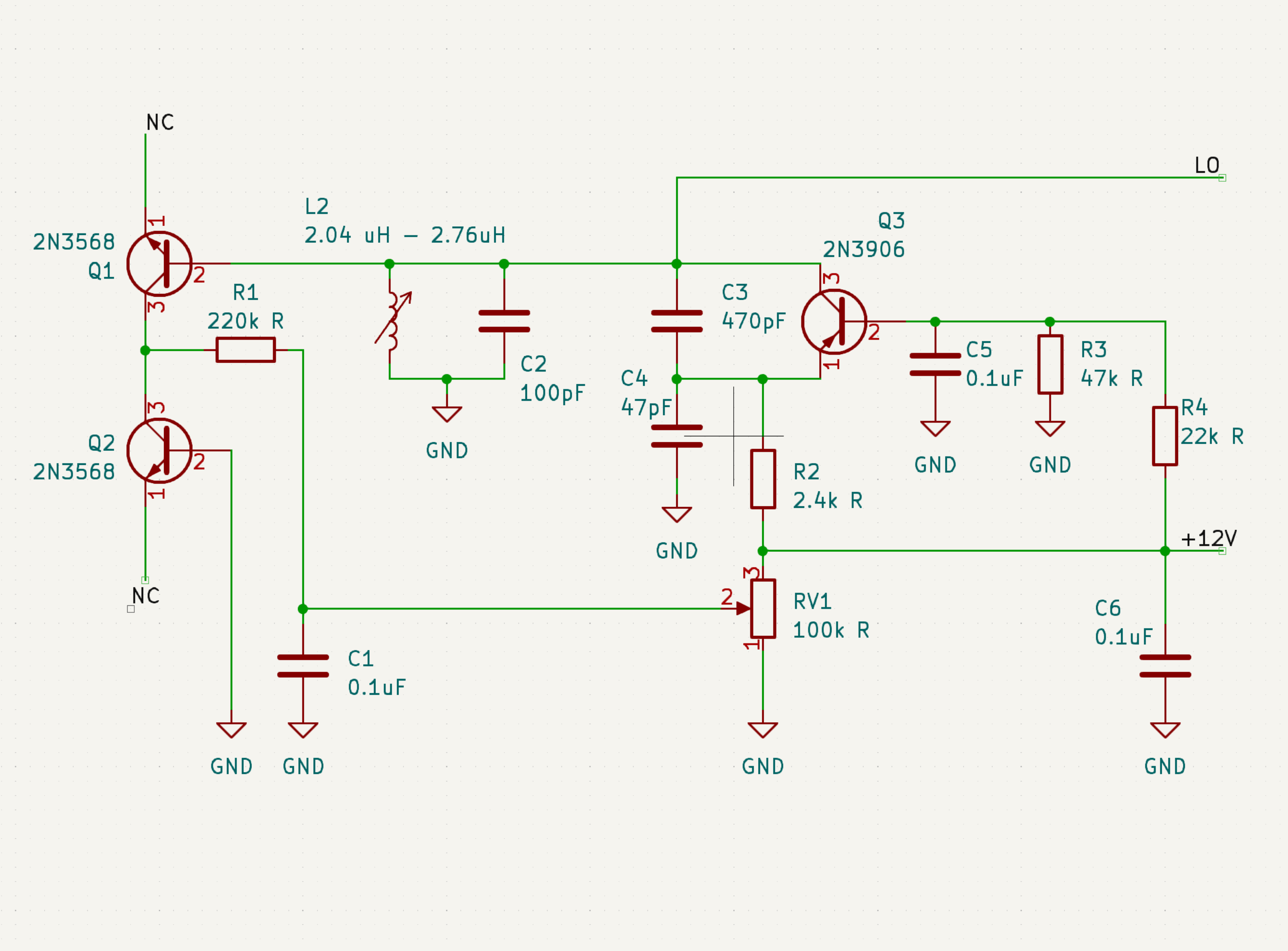

Fig. 5. VFO schematic

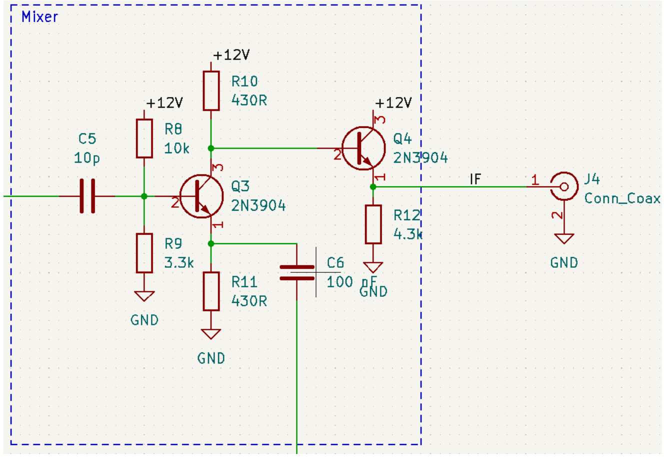

Fig. 6. Mixer schematic

See Fig. 7 for a plot showing the input and output frequencies for the mixer.

D. IF Stages

1) Filter and Amplifier: The filter is a bandpass filter with a resonant frequency at 455 kHz and a high quality factor utilizing the design from lab 1.

The IF amplifier is simple BJT common-emitter amplifier with degeneration using a 2N3904 NPN transistor for the amplifier and buffer. The amplifier stage aims to achieve high enough gain such that the signal can be detected in the AM demodulation stage.

2) AM Demodulator: The AM demodulator is a simple AM detector circuit with a diode, resistor, and capacitor. To be able to demodulate the AM signal, a glass germanium diode is used due to its low forward voltage and fast recovery time, allowing for less aggressive amplification in previous stages.

E. Audio Stage

The audio amplifier uses an LM386 low voltage audio power amplifier chip to amplify the signal to audible levels. The output of the amplifier is connected to an electromagnetic speaker. A potentiometer is used to adjust the volume of the speaker by adjusting the gain of the audio signal.

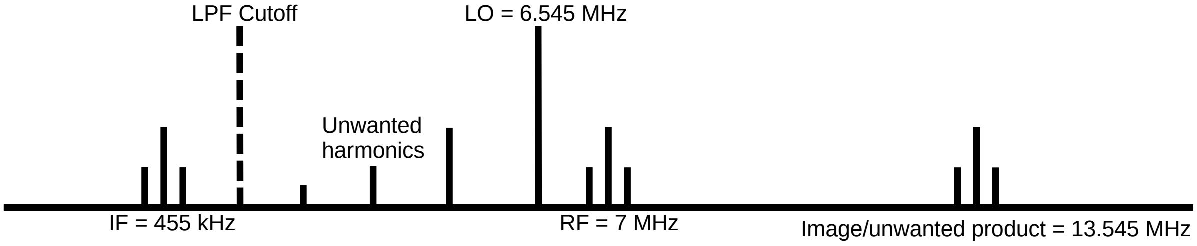

Fig. 7. Spectrum cartoon showing what the inputs and outputs of the mixer look like – horizontal axis is frequency, each line represents a signal where height shows relative power – note how the AM signal has sidebands but the LO does not

III. CONSTRUCTION

The physical construction of analog radios has enormous impact on their performance and noise characteristics. See Fig. 8 for a photo of the final constructed radio's internals.

A. PCB Layout

The radio is split into three boards, two of which are PCBs and one of which is a perfboard. The first PCB contains the RF stages (see Fig. 9), and the second PCB contains the IF and audio stages (see Fig. 10). This separation was intended to decrease the amount of RF that could couple from the RF stages into the audio amplifier, which was very prone to picking up and unintentionally demodulating stray RF.

Since the PCBs had to be fabricated last-minute using Othermills, trace widths and clearances were made extremely generous to allow for milling with a 1/32" endmill. Since milled PCBs do not have plated through-holes, most of the components were placed on the "back" of the PCB with their through-hole leads connecting to traces on the front layer.

A solid, unbroken ground plane is extremely important for boards that handle RF (both for shielding and for stable power rails), so all traces were routed on the front layer and the back layer was made into a solid ground plane. Large bypass capacitors were used in multiple places to ensure stable power rails. Bypassing included both a large electrolytic capacitor and a small non-polarized capacitor to reduce both low- and high-frequency noise.

None of the components on either board draw much current, so power could be routed on a relatively thin trace on the front of the board (with sufficient bypassing).

Since no op-amps or tubes were used, the entire design uses a single supply voltage.

B. Mechanical Design

The two PCBs were mounted on conductive standoffs inside an enclosed, grounded metal case. Mounting hole drills were built into the PCB layouts. According to amateur radio literature such as [6], mounting boards on stable standoffs inside a box that keeps stray air currents off them is helpful for reducing thermal effects.

Since the coaxial cables for antennas are often quite heavy and inflexible, we replaced our initial design of a loose coaxial RF connector coming out of a hole on wires with one that was securely screwed into the case, so that the mechanical load of the cable is transferred to the case instead of the PCB's solder joints. This had the added benefit of improving the shielding, since there were no longer unshielded wires outside of the Faraday cage provided by the case.

C. Shielding

Both PCBs are mounted inside a metal case with multiple connections to ground. Especially because our circuits were unbalanced, any stray external RF signals during testing would couple into everything and cause interference. Only by shielding the entire radio were we able to sufficiently attenuate the local AM broadcast stations enough for them to stop being audible on the speaker.

The VFO is intentionally outside of the case so that stray RF from the oscillator cannot couple into the audio circuits, since it is a much more powerful "transmitter" than any other circuit in the radio.

IV. RESULTS, DESIGN CHALLENGES AND ITERATIONS

Older amateur radio literature such as [2] refers often to "the wobblies and the wanderies"–the historical terms for short-term and long-term instability. Generally, short-term instability in a radio makes it almost unusable, whereas long-term instability (or "drift") can be ignored but makes longer contacts difficult as manual retuning (or a crystal for re-calibration) is required to remain on-frequency. Short-term instability and phase noise tends to come from electrical effects like insufficient bypassing, unstable amplifiers, etc., whereas long-term instability comes from thermal or mechanical effects (like heating of transistors changing their properties or mechanical vibration of tunable components changing their values.

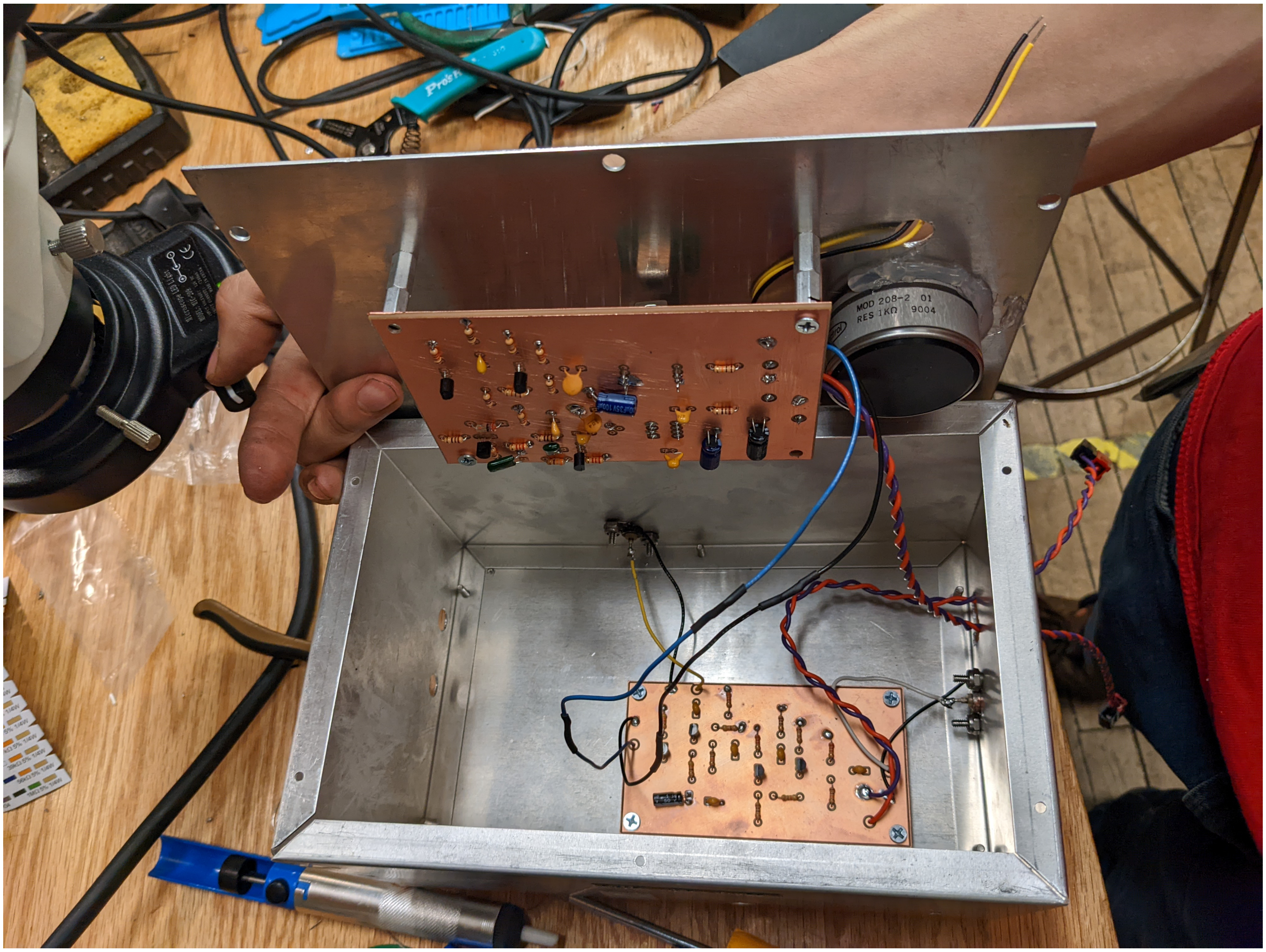

Fig. 8. Inside of the finished radio with both PCBs mounted on standoffs and the audio volume potentiometer glued to the case. Traces are not visible in this photo because components are mounted on the back of the boards.

A. *Performance Metrics*

Testing using an HP 8656B RF signal generator showed that our receiver can cleanly demodulate signals down to $-50\ \mathrm{dBm}$. Due to the relatively low IF gain compared with today's radios, signals below that threshold are not strong enough to fully drive the AM detector diode into conduction, so non-linearity starts making the output audio for weak signals sound like a distorted buzz.

At that low power level, the receiver bandwidth was tested by tuning the VFO off-frequency until the audio output changed, which resulted in a bandwidth of $110\ \mathrm{kHz}$.

For comparison, the $3,249 state-of-the-art HF software-defined transceiver with direct sampling we used for comparison during testing, an Icom 7610 with the receive preamplifier enabled, could cleanly detect an AM signal down to $-70\ \mathrm{dBm}$ when we tested it with the same setup. The IC-7610 has DSP filtering and multiple analog prefilters that can be enabled or disabled, so comparing selectivity directly does not make sense, although Icom advertises an AM receive bandwidth down to $6\ \mathrm{kHz}$ and greater than $-60\ \mathrm{dB}$ attenuation at $15\ \mathrm{kHz}$ away from the carrier frequency. The Icom also does not suffer from the non-linear detector issue (its detector is in software), so signals smoothly fade to nothing as input power is decreased, instead of becoming heavily distorted.

Also note that the input of our receiver is not a matched $50\ \Omega$, so the sensitivity metrics taken from the power output settings of the HP signal generator are useful as a comparison but *not* an absolute value.

B. *Short-Term Stability*

Our initial VFO design (based on one from [7]) had a very narrow range of bias-points where it would oscillate at all (hence the potentiometer for manually adjusting the bias). Even in its oscillatory regions, it would produce spurious emissions (4-5 harmonic frequencies with significant power above the noise floor visible on the spectrum analyzer) instead of a clean sine wave. These issues were solved by moving to the varactor-tuned design described in section II-C1.

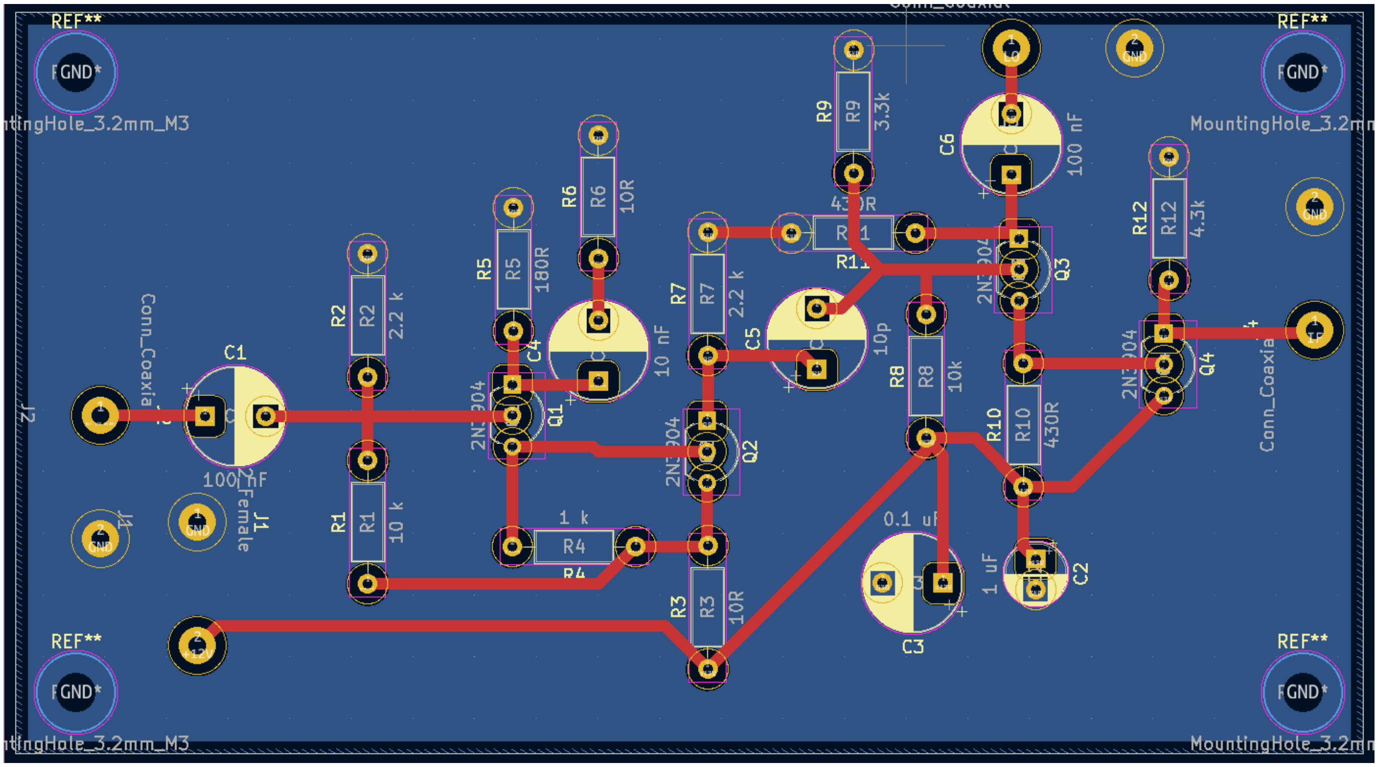

Fig. 9. Layout of the PCB for the RF stages

C. *Long-Term Stability*

Our initial VFO design also had significant drift–testing with an HP frequency counter indicated that its principal frequency drifted by about 3 kHz per second, which would have made it unusable for 10 kHz wide AM signals. Although the exact mechanism behind the drift was unclear, we note that producing a clean sine wave from that VFO design required biasing it such that the output voltage was 4 Vpp. [6] notes that very powerful LOs tend to drift a lot because the higher currents involved tend to produce more heat in the BJTs, which creates thermal effects.

More stable VFO/LO designs use an oscillator with a low-power output that is then buffered and amplified separately.

D. *Noise*

Our initial mixer design, a “single-diode mixer” that was just two resistors summing the RF and LO into a Schottky diode (see Fig. 11), required an extremely powerful LO drive to work at all and added so much noise and attenuation to the RF signal that it was not usable in real-world conditions. This was fixed by moving to the BJT mixer described in section II-C2.

During testing, interference was a huge problem for every circuit, even the non-RF circuits. Shielding everything and moving to a PCB with a ground plane and 2 bypassing capacitors (one with a very high value of 100 uF) helped reduce noise.

E. *Oscillation*

The LM386-4-based audio amplifier had a strong tendency to become a very noisy 1 kHz square wave oscillator, which would produce a loud tone that drowned out any actual received radio signals. Research indicated that the LM386 chips are quite prone to oscillation because of their high current draw, especially in the high-gain configuration we used. Adding more and larger bypass capacitors to the second revision of the IF/AF board fixed the oscillation. The addition of the second LPF stage before the audio amplifier may have also contributed to stopping the oscillation by ensuring that RF could not leak through the demodulator and wreak havoc by demodulating itself inside the audio amplifier chip.

V. BUILD NOTES

The RF PCB worked first-try, but the IF/AF PCB required a second revision. We also had significant noise issues that were eventually traced back to the “Aukenien”-brand electrolytic capacitor value kit we were using being full of leaky and underfilled capacitors.

Also, based on a tip from Daniel Sheen, we replaced electrolytic capacitors in AC parts of the circuit with non-polarized ones. Electrolytic capacitors perform poorly (and decrease in lifetime) when their voltage goes below zero, so they have to be biased appropriately or not used at all for AC.

In general, component quality matters a huge amount for radios. Literature like [2] goes into detail about the exact types of capacitors (usually film and mica) that perform better in RF

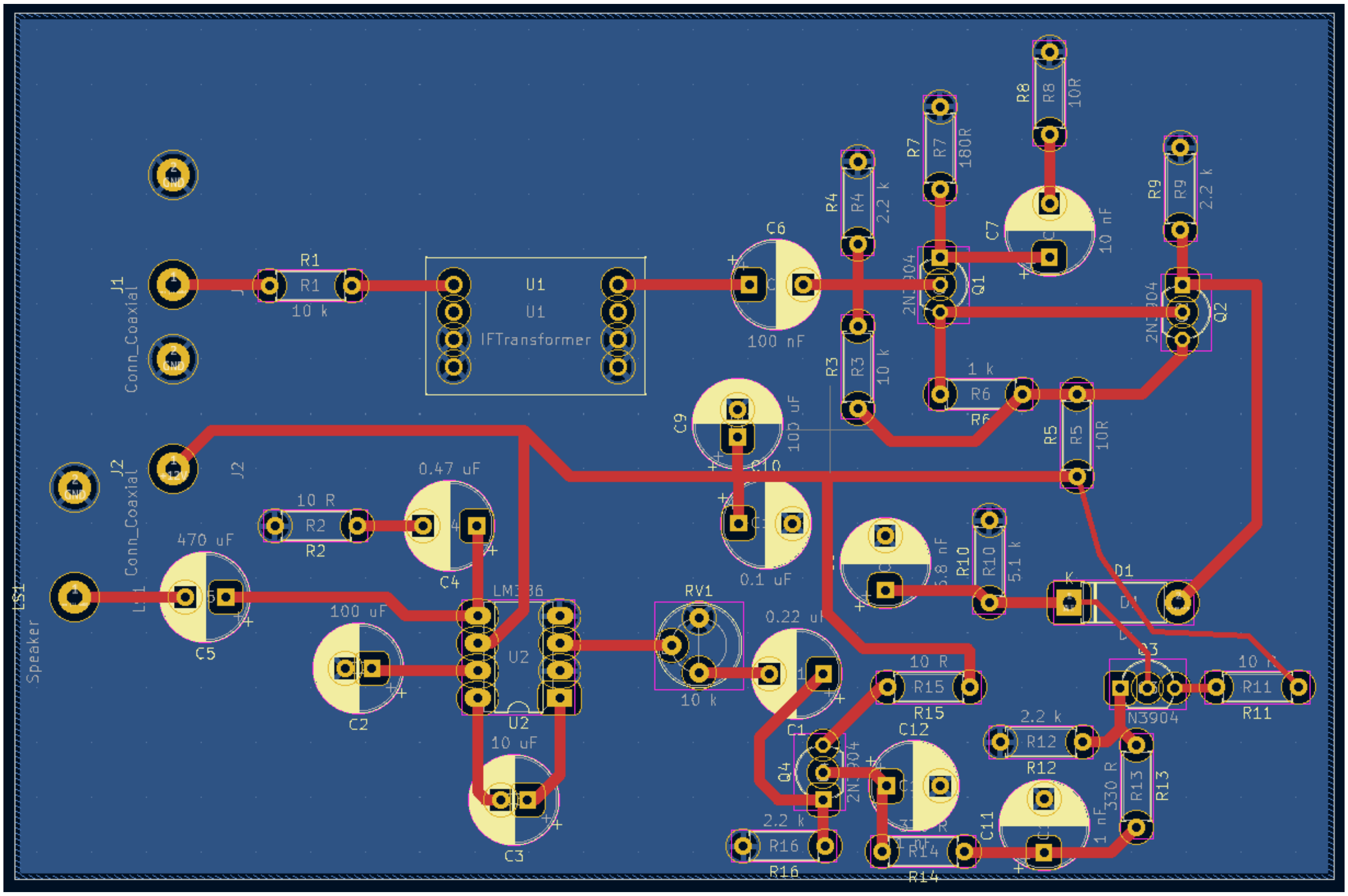

Fig. 10. Layout of the PCB for the IF and AF stages

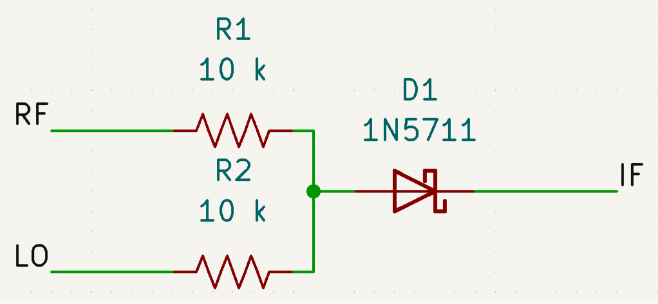

Fig. 11. Single-diode mixer using a Schottky diode – input signals on the left, output on the right

designs. We used special tunable RF inductors from Coilcraft that are designed with shielding and a high Q (low parasitic resistance). When building radios, it is possible to get away with using low-quality active components if the design works around them properly, but it is much harder to get around using low-quality passives, as cheaper passives tend to not be characterized/rated for RF.

VI. Advice for Future Projects

A. *Useful Resources*

In general, older DIY amateur radio literature like [6] and [2] was the most useful resource for sound, practical advice on building radios. Unlike most textbooks, amateur radio books are generally written to be understandable by a complete novice and with discrete, off-the-shelf construction in mind. Additionally, the accumulated wisdom of lots of amateur experimentation into the subtler characteristics of common off-the-shelf components (such as thermal drift or mechanical vibration) is irreplaceable.

B. *“If You Can’t Make it Good, Make It Tunable”*

This age-old adage of analog electrical engineering is especially applicable to the construction of discrete radios, where the values of breadboard and perfboard parasitics start to approach the values of the actual passives used in the design. Simulation may tell whether a design will amplify or resonate, but the exact gain or resonant frequency will depend so much on the exact construction of the device that building in adjustments during the testing phase is critical.

C. Bypass Everything

Numerous times during testing, we encountered circuits that exhibited all kinds of strange oscillations unless sufficiently bypassed. Bypassing should ideally include capacitors of different sizes in parallel to deal with wideband noise.

D. Use Good Test Equipment

We made heavy use of the Bode plot functionality of Radio Society's digital Keysight scope for analyzing filters and amplifiers. For testing the mixer and VFO, we used a combination of the FFT function of the oscilloscope and a Rigol spectrum analyzer. Using frequency-domain test equipment is critical to understanding why a radio design is or isn't working.

Having an analog oscilloscope (or a good "digital phosphor oscilloscope") on hand is also useful for viewing modulated signals.

Pay close attention to the limitations of your test equipment and whether your test setup is loading the circuit or introducing extra noise. We found the unconnected oscilloscope probes alone picked up local AM broadcast stations and produced visible peaks in the FFT, and it was important to realize that this was an inherent feature of the test setup (and not necessarily the circuit itself).

E. Make Sure It Works Before Why It Works

One working circuit on a breadboard is worth a hundred working simulations.

Analog electrical engineering is witchcraft and sometimes it's better to accept that something will work and not question the reasoning on why it works the way it does. Of course, don't go in without have a rough idea about how to build it, but don't expect that everything will go just like the simulations. When every inevitably stops working, sometimes it might be better to change designs just to get something that works instead of spending all your time figuring out why your circuit doesn't work.

F. Keep It Clean

If you can't even clean up your own circuits, who are you to give advice to the world.

KEEP THEM CLEAN. You do not want a box of random breadboarded circuits where you have no idea what any of them does because none of them are labeled and they all are random components. If you lose any important components on a breadboard somewhere, you will just waste time trying to find it. Keep labels on any important boards, keep components in designated boxes, and keep circuits that you aren't using away from the ones that you are.

VII. CONCLUSION

We set out to build a fully-analog superheterodyne AM receiver and succeeded in doing so using only off-the-shelf components found in Radio Society and the EECS labs. Additionally, we built a remarkably stable (only a tens of hertz of drift every few seconds) fully-analog variable frequency oscillator with varactor tuning that could be reused for a transmitter. Our receiver was capable of receiving signals down to $-50\ \mathrm{dBm}$, which is equivalent to "$20\ \mathrm{dB}$ over S9" in amateur parlance. In our general ham radio experience, for SSB, this is a signal strength generally achievable from full-power transmitters with highly directional antennas on the same continent and occasionally across the Atlantic if conditions are very good. For AM, which is less power efficient, this signal strength is generally achievable over a few states at maximum.

Creating this receiver taught us a lot about radio design and resulted in a simple, approachable design useful for explaining how superheterodyne architecture and AM modulation work.

VIII. ACKNOWLEDGEMENTS

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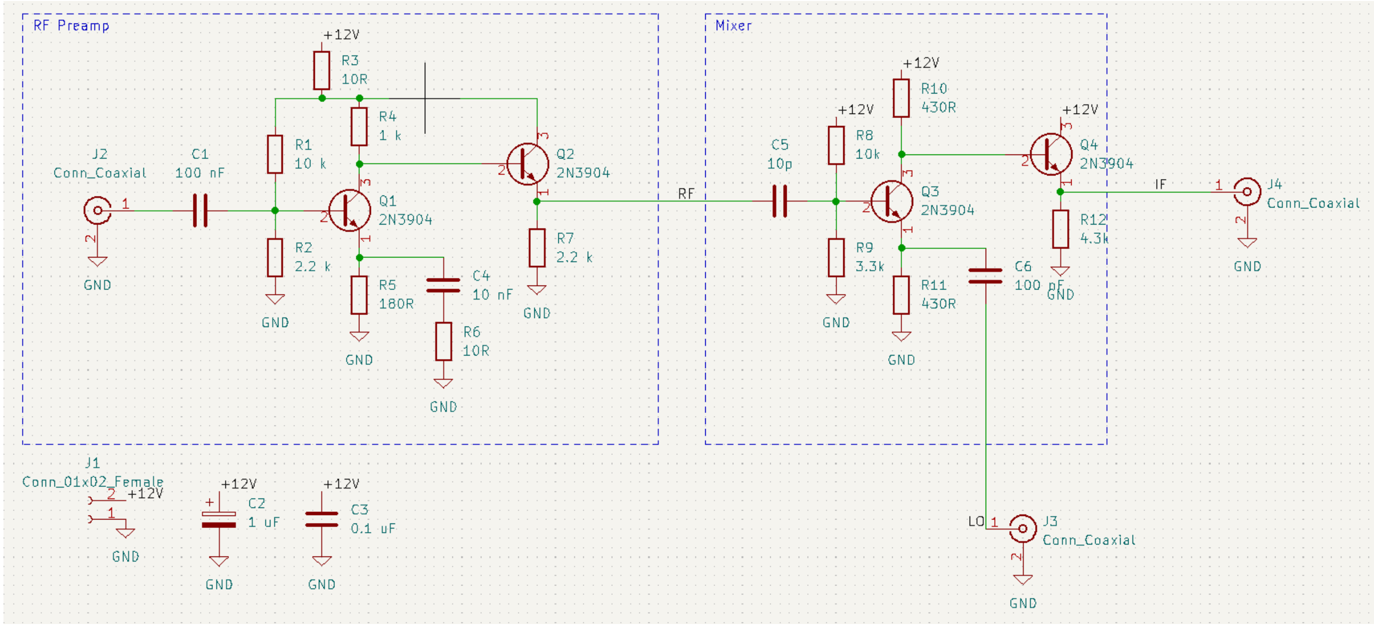

Fig. 12. Full schematic for RF PCB

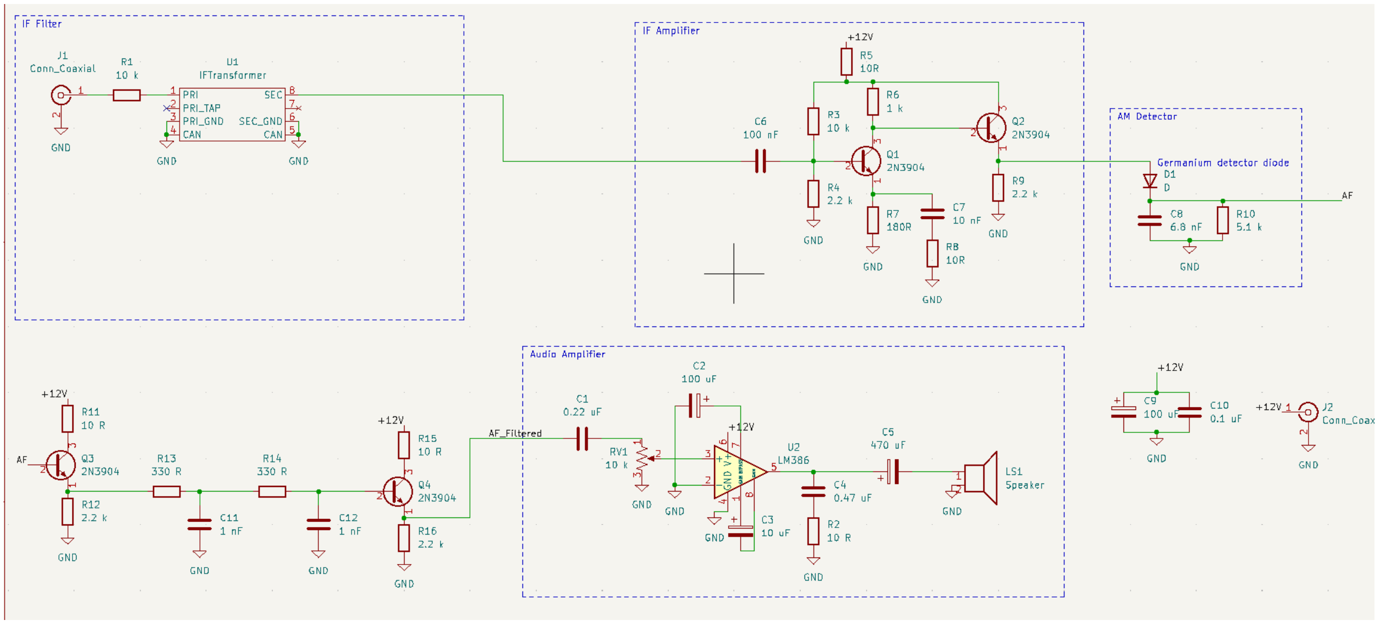

Fig. 13. Full schematic for IF and AF PCB