6.101 Final Project Report
AM Receiver with Visual AM Spectrum Display

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1. Introduction

Kayla Esquivel and Jason Yang

The invention and mass application of radio broadcast was triggered in the first decade of the nineteenth century by Lee De Forest with his Audion triode vacuum tube (Lewis 1993). By the first world war, radio transmission was in common use by many national entities, aided by the development of the superheterodyne receiver by Edwin Armstrong (Lewis 1993). This concept allowed engineers to filter, process, and work with signals at lower frequencies while still maintaining long distance transmission at higher carrier frequencies. While modern radio communication has predominantly moved away from amplitude modulation transmission in the lower frequency bands, the concept of the superheterodyne receiver has persisted in virtually every method of wireless communication since.

Because of our strong interest in radio transmission and the superheterodyne concept, our goal was to build a superheterodyne AM Radio Receiver circuit that had a bandwidth of the entire AM spectrum, and whose output was a speaker. In addition, we wanted to build what was essentially a spectrum analyzer for the AM band. We swept the full band and displayed the spectrum density using a galvanometer. These two circuits were calibrated, such that the currently tuned channel of the AM radio were a vertical line across the output spectrum plot. Figure 1 shows a full block diagram of our circuit, including all major circuit subsystems.

We were able to successfully construct the majority of this circuit. Our main unsolved challenge was to receive an AM signal from an attached antenna. While we were not able to do this, we demonstrated the full functionality of the project to the limits of our original scope and intention using an external signal source. Due to an unforeseen accident at the beginning of the project period, we were were unable to utilize the galvanometer. We did however decide to use an oscilloscope in X-Y mode to show the visual spectrum sweep.

2. System Diagram

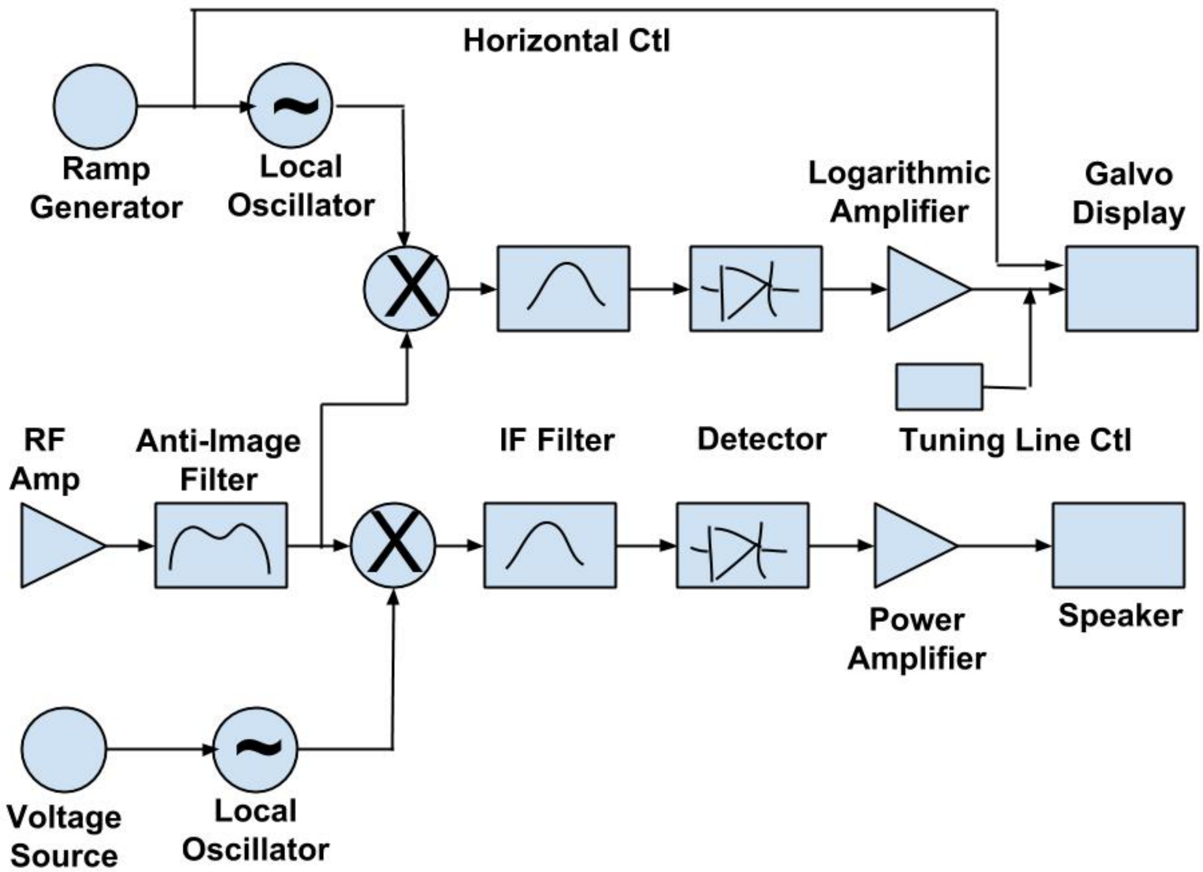

Figure 1. *High level system block diagram detailing major sub-blocks and interconnects between them.*

3. Sub-system Overview

3.1 Low Noise Amplifier (LNA) - Esquivel

The input module of the full system was an LNA high-bandwidth transistor amplifier that amplifies the signal before it is sent through the anti-imaging filter. This amp was a three-stage BJT amplifier comprised of an emitter follower, common emitter, and emitter follower. See Figure 2 for this topology. We expected an input voltage off of an antenna of between microvolt and hundreds of microvolt levels, so we had a gain of about 100. We chose the emitter follower for the input and output stage because of it's high input impedance and low output impedance.

However, even with this input stage, we were unable to successfully acquire an RF signal on either the loop or ferrite core antennas. We also attempted to use the long tailed pair input stage from the AM radio from Lab 1, with limited success. We suspect that our problems are related to the noisy environment of the 6.101 lab; we may have had more success if we'd tried to use our circuit in the glass hallway next to lab. For testing purposes, we used a modulated input from the RF signal generator while building the rest of the system.

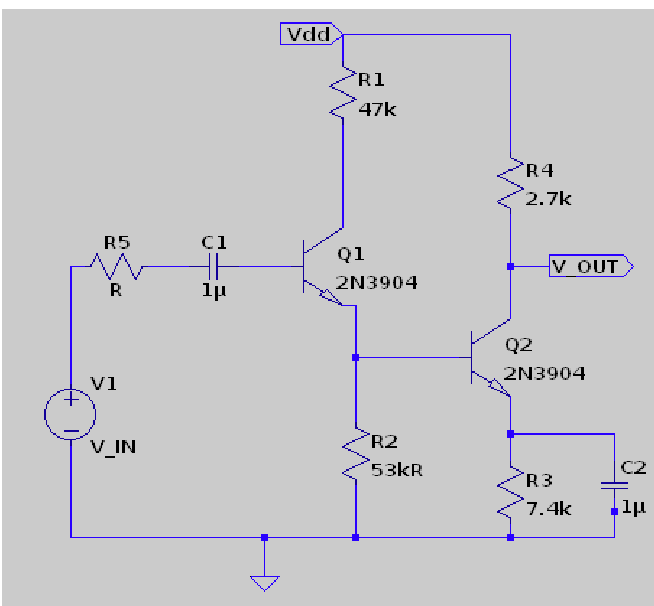

Figure 2. *Low Noise Amplifier Topology. Input is an attached antenna or signal source; output is the RF Filter. Source: Esquivel and Yang.*

3.2 Anti-Imaging Filter - Yang

Immediately following the RF amplifier was an LPF with a cutoff frequency of roughly 1.6MHz. This filter was necessary in order to remove high frequency noise that would be shifted into our passband after mixing with the local oscillator. Because this device was a fairly early stage in the signal chain, we designed the filter using only passive components in order to reduce the amount of noise injected into the system. The design consisted of two RC LPF filters cascaded with each other in order to create a 2nd order slope at the cutoff frequency.

Originally, we designed the filter to be a band pass filter by cascading a high pass filter after a low pass filter with an active buffer between the stages; however, due to the narrow passband that is the AM spectrum, this approach did not work. Because our approach called for the local oscillator to be at a higher frequency than the carrier (we were mixing the signal downward), it was deemed that we only needed a low pass filter to make this work.

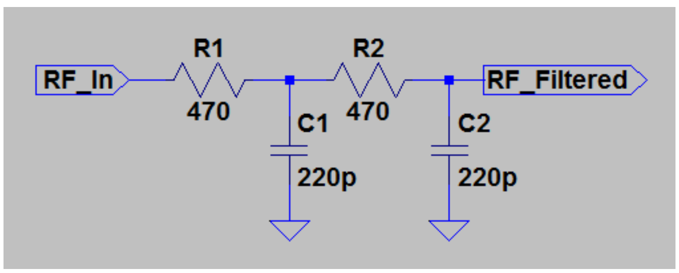

Figure 3. *Anti-Imaging Filter. Input signal is the output of the RF Amp, output is the Mixer/IF Filter. Source: Esquivel and Yang*

3.3 Mixer - Esquivel

The transition between RF and IF occurred in the mixer. The mixer was a block that multiplied the two input signals (the RF signal and the local oscillator), and whose output was two copies of the RF signal whose frequencies equal the addition and subtraction of the frequency of the two inputs. We followed this stage with a filter that isolates out the LO-RF signal, which reduced the signal to the standard 455kHz level of the AM range. This frequency reduction of the RF signal is what made this AM receiver in to what is known as a superheterodyne receiver.

At first, we attempted to build this block out of a simple reverse biased diode (pictured below). In isolation, the single-diode mixer appeared to work well, giving an expected output of addition and multiplication of the two input signals. However, it was soon apparent that this mixer would not meet the specs necessary for our radio because the addition component of the output was too large, and was saturating the output of the following cascode amplifier.

With a bit of testing, we resolved this problem by feeding the filtered and amplified RF signal directly into the base of the first transistor of the IF filter stage. The signal was mixed by applying the local oscillator directly to the emitter resistor of this transistor. This acted like a diode, and applied this operation up through the collector (so that the output of the stage was addition and subtraction of the frequencies). This worked significantly better than the separate diode because it was not an amplitude-dependent on the inputs and did not include the other harmonics that were dominant in the single diode output.

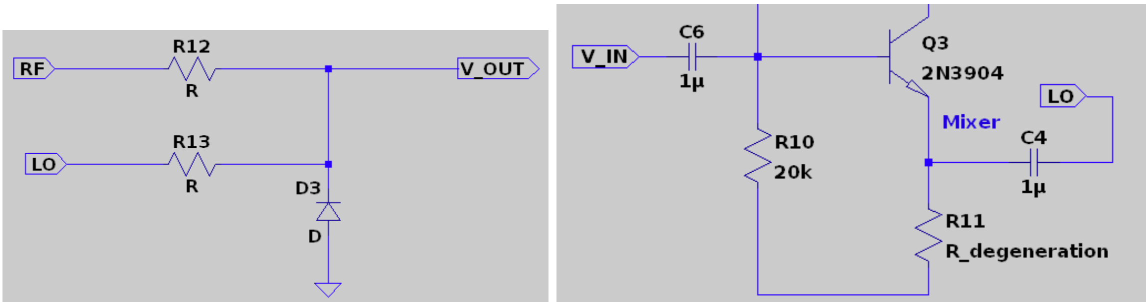

Figure 4. *Original diode mixer design (left) and redesigned BJT mixer/amplifier topology (right). Input to this system is the output of the RF Filter and the Local Oscillator, output is the IF Filter. Source: Esquivel and Yang*

3.4 Ramp Generator - Yang

The ramp generator was designed in order to create a linearly increasing voltage with a fast reset. This block was not only connected to the voltage controlled local oscillator in order to allow it to sweep the entire AM spectrum, but also provided the reference voltage to control the horizontal sweep on the oscillator to visualize the spectrum and tuning line. This was accomplished by using a BJT connected to an op amp to create a constant current source which was used to charge a capacitor connected to a 555 timer. When the capacitor reached a threshold value, the 555 would discharge the capacitor giving us the linear ramp and reset.

The key difficulty in this block was determining resistor values to be used with the BJT in order to achieve a slow enough ramp yet keep the current source stable. In order to remedy this, a potentiometer was incorporated such that we could tune the specific ramp rate we desired.

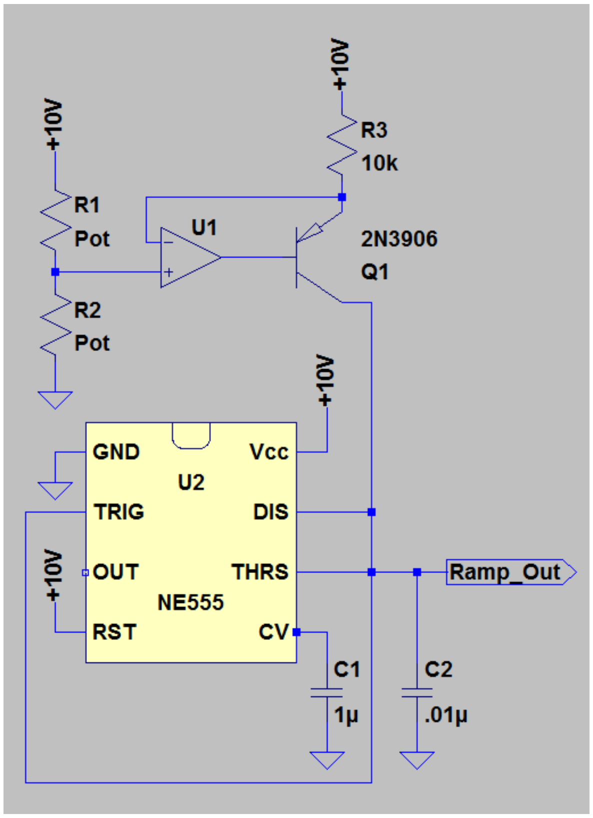

Figure 5. *Ramp Generator Topology. The top half of the schematic shows a constant current source driven by a BJT. The current charges a capacitor in a 555 timer which will discharge the capacitor after achieving a threshold. Source: Esquivel and Yang*

3.5 Voltage Controlled Local Oscillator (VCLO) - Yang

The voltage controlled local oscillators exist to provide a frequency dependant on a control voltage presented at a control terminal.This signal would be used with a mixer to move the AM signal into the IF frequency.The final oscillator was a variant of a colpitts oscillator with a varactor diode consisting of a resonant tank and a single BJT followed by a common collector amplifier to buffer the oscillator output and was capable of generating a frequency from 800 KHz to 2.5 MHz.

The principal behind the operation of the oscillator is to create a resonant tank and have a device introduce a 180 degree phase shift of the signal from the tank and gain to drive the resonant tank. At first the phase shift was achieved using a high speed inverting op amp, but due to noise and distortion, this was switched to a single BJT common emitter inverter where the bias voltages were determined empirically in order to reduce distortion at the output. For the resonant tank, the original implementation consisted of a single fixed capacitor with an inductor and varactor in parallel, but it was quickly discovered that the lack of symmetry of the tank caused variations in the output amplitude of the signal across frequencies. For this reason, we moved to a symmetrical two varactor design.

In addition to realizing reliable oscillator design, two identical oscillators had to be created - one for the sweeping radio and another for the tuned radio. Furthermore, the components of the oscillator must be well matched such that the voltage presented to both oscillators resulted in precisely the same output frequency. In order to achieve this, inductors were hand wound in order to precisely match them and trim capacitors were added to ensure the resonant tanks were reasonably matched.

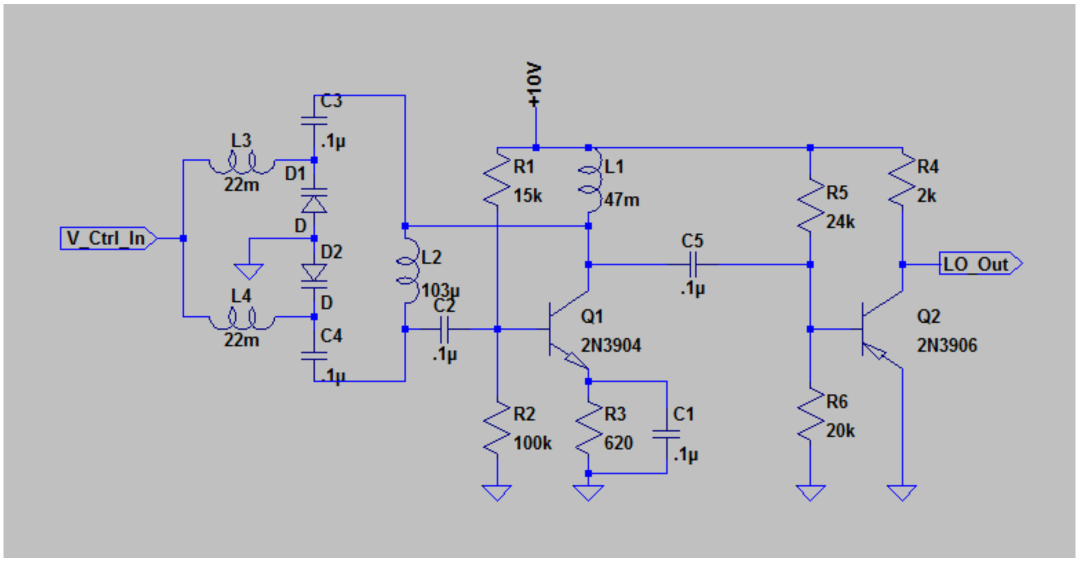

Figure 6. *Voltage-Controlled Local Oscillator. The left shows the two varactor diodes placed back to back biased by the control voltage to form a symmetrical resonant tank. This feeds into a common emitter amplifier (center) then to a common collector (right) for buffering. Source: Esquivel and Yang*

3.6 IF Filter - Esquivel

The IF filter existed to limit the frequency response to 455 kHz, with a bandwidth of about 10 kHz around that center point. This was necessary because the mixer component has an output of two frequencies, the sum and difference of the LO frequency and RF frequency. The IF filter was constructed of alternating high-Q filters and transistor amplifier stages. The high-Q filters were made using the tunable 455kHz transformers from 6.101 Laboratory 1. I used two of these filters for each of the arms of the system (radio and spectrum sweep), with all four being tightly tuned to the IF frequency of the system.

The transistor amplifier that buffered the input of each of these transformers was a simple 2-BJT cascode amplifier. These amplifiers were loaded by the input LC tank of the transformers. These provided very high gain because of the large impedance, but were un-ideal because the equivalent impedance of load varied largely with each transformer. It was necessary to tune the amplification of each by testing various combinations of attenuation methods, such as emitter resistor values and resistors in series with the transformer load. It was challenging to find a point where there was a good balance between limiting saturation and having a high enough gain to see a wide range of input signal magnitudes, but we were empirically able to find amplification stages that were effective for our purpose.

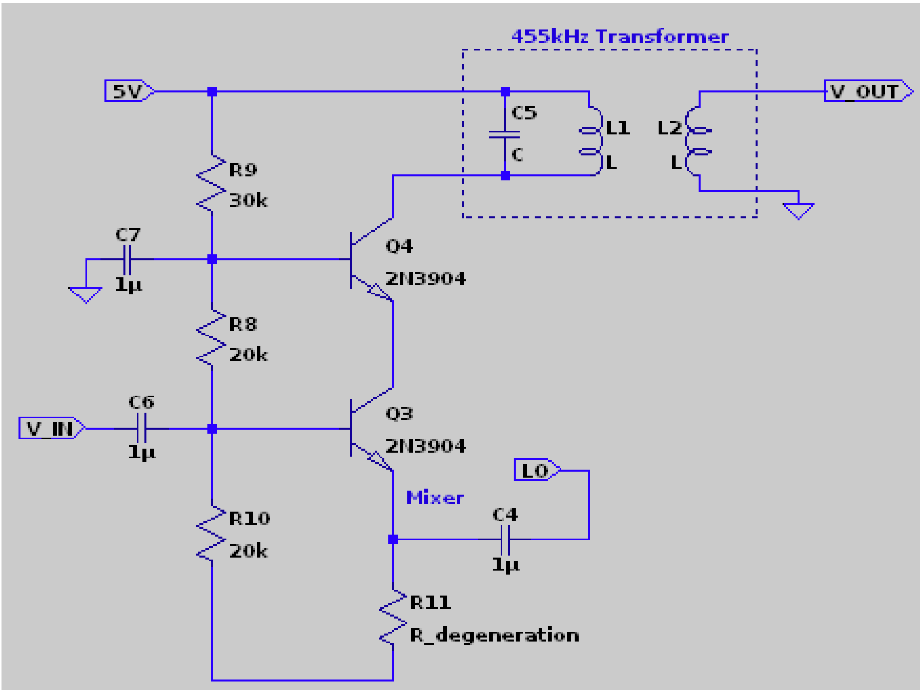

Figure 7. *Single Stage of IF Filter. Full Filter is composed of a second identical stage on the output of the system shown above. Inputs are the RF Filter and Local Oscillator, second stage output is the diode detector. Source: Esquivel and Yang.*

3.7 Detector - Esquivel

The detector of this system existed to rectify the signal of interest from the carrier frequency, like an envelope detector. This circuit was constructed from a half wave rectifier with a low pass filter on the output. This detector was very simple to construct and test, but was challenging to integrate into the system because of the minimum voltage necessary to overcome the P-N drop of the diode. We initially did not think that our detector worked at higher frequencies, but quickly realized it was because we needed a large gain from the previous stages for our input voltage to be of a larger magnitude than the P-N drop. This was a very quick and easy adjustment. We did not make any serious changes from our proposed detector design.

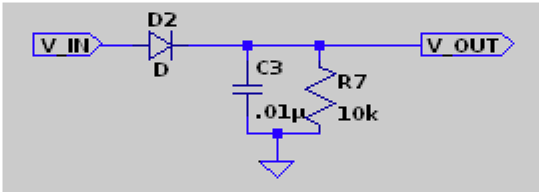

Figure 8. *Diode Detector for demodulating the input signal. Input is the output of the IF Filter, outputs are either the audio amplifier or spectrum sweep display. Source: Esquivel and Yang*

3.8 Logarithmic Amplifier - Esquivel

In our proposal, we said that we hoped to build a logarithmic amplifier that would boost the output of the detector to the appropriate voltage level required by the galvanometer. We thought this would be necessary because the detector output would vary by several decades, depending on power of a specific station. The galvanometer output, we said, would thus be much easier to read if the input signal was amplified logarithmically.

After constructing the system and viewing the output range on an oscilloscope, given three decades of range to the input, we determined that a logarithmic amplifier would not be necessary for our project. The amplification of the RF amp and IF stages were enough to show low amplitude input signals (on the order of magnitude of microvolts) and saturate the output for larger input signals (on the order of hundreds of microvolts). The output of the system, displayed on an oscilloscope screen, can be seen for a given input magnitude in Figure 10.

If we were able to connect our system to a functional antenna, we may have found this gain control necessary. However, because we only viewed a single input signal at a time, we did not see appreciable differences in magnitudes on the screen. If we were to build this system again we would likely include an automatic gain control feedback element that would also make the logarithmic amplifier unnecessary.

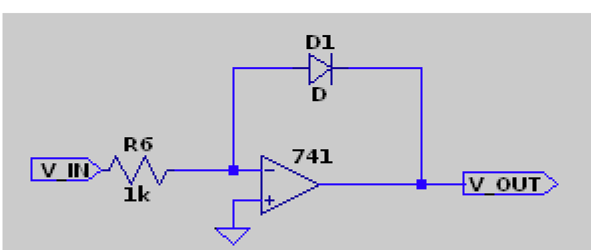

Figure 9. *Proposed design for Logarithmic Amplifier. Source: Esquivel and Yang*

3.9 Visual Spectrum Display - Yang

The display allows us a way of visualizing the AM spectrum such that we can identify where stations existed relative to each other. The visualizer also incorporated a pulse generator in order to create a virtual ‘tuning line’ to show where we were tuned to relative to the spectrum. Originally the display was to be generated via a galvanometer; however, unforeseen problems caused this to be impossible and the display was visualized on an oscilloscope in XY mode.

To synthesize the tuning line on the display, A comparator was used to generate a rising edge when the ramp voltage exceeded the voltage of the tuned VCO. This edge was passed into one end the D flip flop of the 555 and a delayed version of the edge (through inverters) was passed into the reset end thereby creating a temporary pulse at the output. This output was connected through a resistor network with the output of the logarithmic amplifier in order to sum the two signals together to be visualized on the spectrum display.

In order to create the display, the X axis (Channel 1) was attached to the output of the ramp generator discussed above. The Y axis (Channel 2) was attached to the output of the sum of the logarithmic amplifier and pulse generator to display the AM amplitude as a function of voltage applied to the VCO.

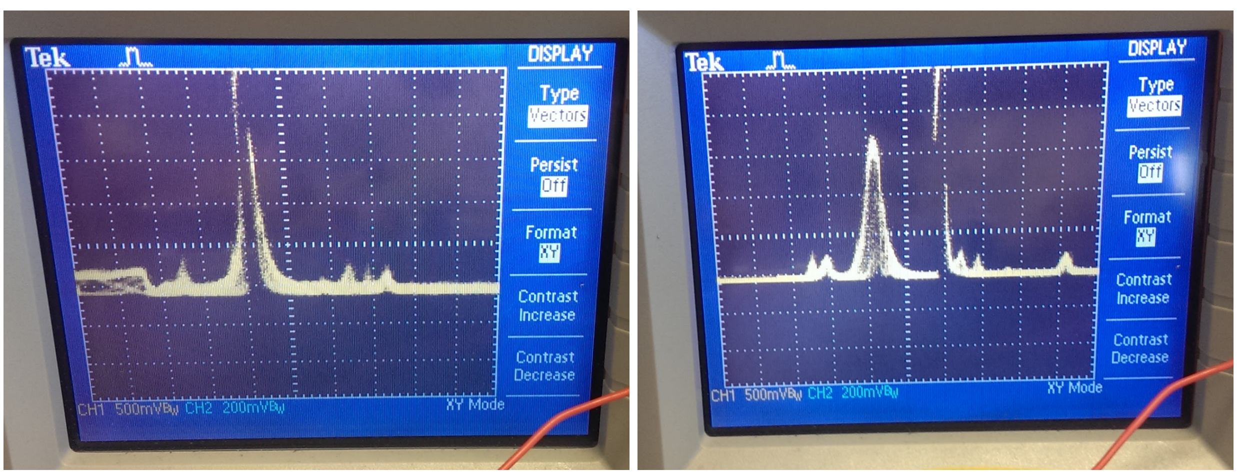

Figure 10. *Photograph of Spectrum Sweep Displayed on Oscilloscope in X-Y Mode. Left shows radio tuned to channel, right image shows radio station and offset tuner ine. Source: Esquivel and Yang.*

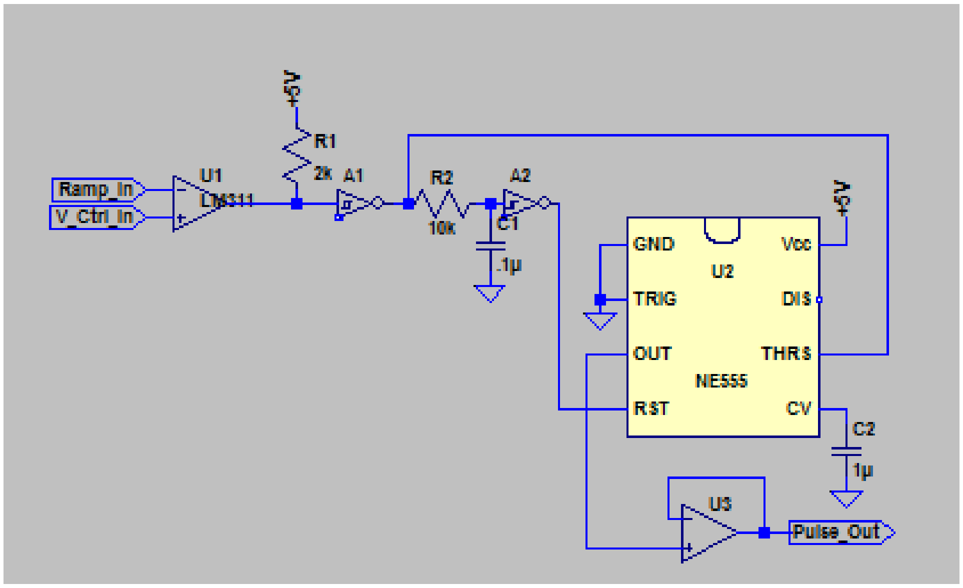

Figure 11. *Tuning Comparator Topology. The two signals are compared at the left and a pulse is generated by the 555. Source: Esquivel and Yang*

3.9 Audio Amplifier - Yang

Because the audio output of the detector is relatively small and unable to drive an 8 ohm audio load, an audio amplifier is needed to boost the signal as well as provide a low output resistance to drive a speaker. In order to achieve this, an op amp was used to amplify the signal followed by a push pull driver to be able to provide enough current into the load. This design is almost identical to the design used in lab 5 of 6.101.

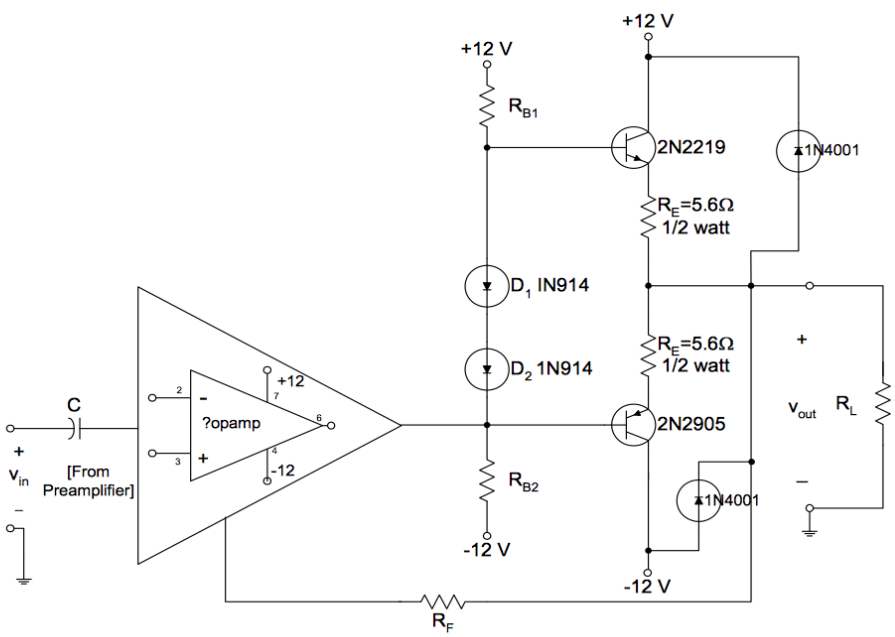

Figure 12. *6.101 Laboratory 5 Audio Amplifier. Source: 6.101.*

4. Discussion

Kayla Esquivel and Jason Yang

Noise

The broadest challenge that was encountered while physically constructing the AM circuit was noise. External noise, from the environment,equipment and power supplies, along with noise generated from our own circuits affected virtually every sub-system of our project. Many problems associated with debugging our circuit and integrating subsystems was a result of negative interactions between the respective systems. For example, in one integration step, the local oscillators were attempted to be moved on the same board as the rest of the radio; however, this proved to be impossible as the oscillators caused too much noise on the power lines as well as significant amounts of RF noise from the inductors. Given the construction of the inductors as well as the layout of our circuit, we had no choice but to move the oscillators as far apart from the other circuits in order to isolate as much noise as possible.

However, most of the noise originated from external sources rather than internal. Because our circuits were not only designed on a breadboard but also largely unshielded, most of the circuit acted as an antennae and amplifiers for stray RF noise. Given that the signal we were interested in was on the order of a few microvolts, any external disturbance caused a significant change in the output signal. This emphasized the importance of ensuring that all filter stages, IF and RF, were tuned tightly to their respective frequencies and had a high enough Q to reject all unwanted disturbances.

The challenge of noise rejection was most aggressive when we attempted to integrate our system with an external antenna. Despite many different combinations of antenna type and input stage impedance, we were unable to find a system that could effectively receive an AM signal through the noise floor. We suspect that the main explanation for our inability to even receive a signal we transmitted ourselves was because of the noisy environment of the 6.101 Laboratory. A combination of the equipment in the room, the many other projects being constructed and tested in the same area, and the heavy RF signals entering the room from nearby buildings' transmitters likely resulted in too much interference for our system. We suspect we might have had more success had we relocated our system into the main glass hallway in front of the 6.101 Lab, away from our equipment and peers, but we never tested this environment.

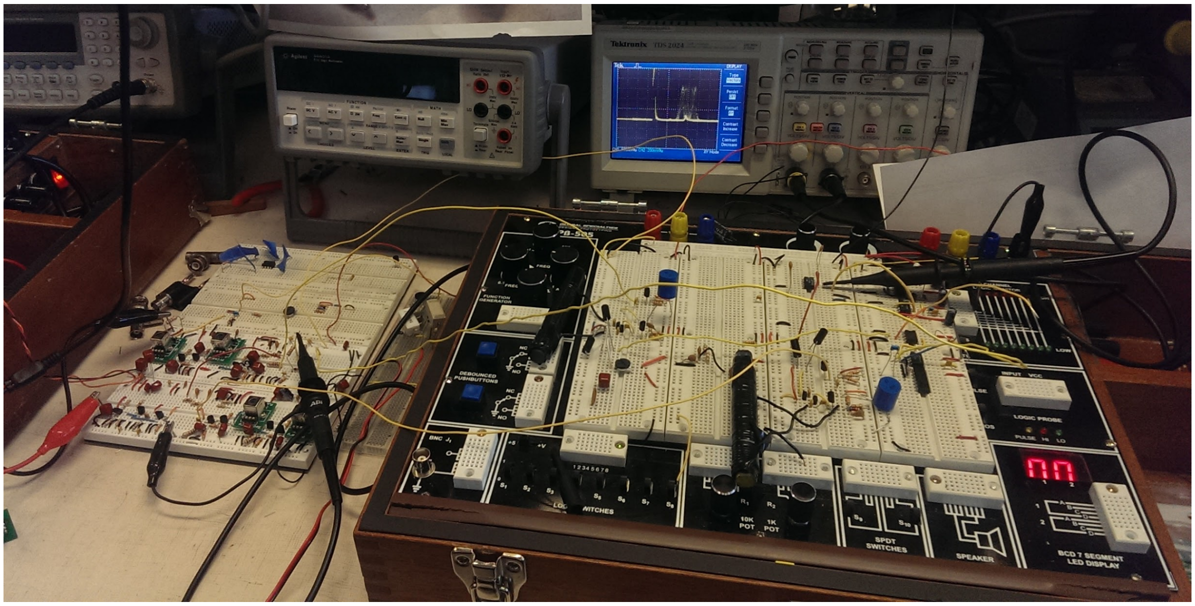

Figure 13. *Breadboard layout of radio and spectrum sweep. Breadboards and discrete components were a challenge for constructing an RF system. We attempted to reduce noise impacts by reducing wire lengths and clipping all components flat to the breadboard.*

Subsystem Integration

In addition to problems presented to us due to noise, the interconnects between subblocks of this endeavor also gated our progress at times. Because we approached different aspects of the design autonomously, when integrating our blocks together, we ran into problems with input and output impedances as well as voltage levels. For example, at one point, the output of the VCO ranged from 3-12 VPP across its entire frequency range. These levels overloaded the mixer and the block had to be redesigned to be compliant. In another case, we found that the loading from other blocks further down the signal chain degraded or even halted the operation of some blocks - the mixer distorted the output of the VCO and noise from the detector fed back and loaded the pulse generator. In order to remedy this, several buffers were created in order to decouple modules from each other and prevent loading effects. These came in the form of common collector current amplifiers or operational amplifiers connected in unity gain feedback.

Additionally, unexpected outputs of some subsystems resulted in the redesign of some components. For example, our original mixer design was faulty because it's output voltage amplitude was highly dependent on the amplitude of the LO. This was because the single diode mixer was not ideal, and output both the addition and multiplication elements of the two signal inputs. While this may have worked with another local oscillator, the voltage levels of the LO in our system were much too high for this design to be successful. The output of the mixer quickly saturated the cascode amplifiers of the IF chain, and rendered the IF filter useless. By moving to the BJT mixer design, we reduced the addition harmonics and increased the efficiency of the mixer/IF filter combination.

Suggested Technical Improvements for System

If we had more time to continue working on this project, there are many ways that we think we could improve the functionality of the existing system. To start, we would likely separate the two IF chains on to separate breadboards. The noise problems talked about above often had destructive interactions between the two chains, and we think we could have isolated this better by building the two chains on different breadboards. Alternatively, we might even do away with breadboards all together and attempt to layout our system on a PCB instead. We feel this would likely result in the most drastic improvements overall, because by doing away with discrete components and breadboards we would be getting rid of most of the parasitic interactions and components of the system.

In terms of improving our environment, we would have liked to try using a cleaner power supply for both the RF/IF and the Local Oscillator sections. The noise mentioned in the paragraphs above might have been reduced with an external power supply, rather than the one supplied with our kit.

If we had time to add on or expand the project, we would have liked to include an Automatic Gain Control (AGC) element. While there was a manual volume control switch, audio levels varied, to a degree, linearly with input amplitude. AGC would have helped significantly reduce the variance of the output signal with input levels and would help prevent the saturation of the amplification transistors if the input signal was too strong. Additionally, we would have liked to attempt to acquire a new galvanometer to test the laser display feature of the system instead of the X-Y oscilloscope screen.

5. Conclusion

Kayla Esquivel

This project presented a very interesting spin on a very old topic. Though AM radio has been around for decades, the superheterodyne concept is still widely used in commercial products today. Our implementation not only addressed the challenges in designing a proper AM superheterodyne receiver, but also presented a novel solution to being able to visualize the stations broadcasting on the spectrum of interest. Despite being unable to build a fully functional system, we were able to develop a prototype that demonstrated the intended functionality of the system given a single signal source. We were able to sweep a signal generator's input across the full AM band and effectively receive, demodulate, and hear/display the output for any signal in the mentioned band.

Our main technical challenges were in the form of the equipment and circuitry medium we used to build our project, and in the noise environment of the 6.101 laboratory. While our project covered most of the basic technical topics presented to us in 6.101, our biggest take-aways from the final project were the bread-boarding and layout skills that were required for a high bandwidth, discrete component system.

We believe that an interesting follow up to this project might be to design a similar visual spectrum sweep for a Frequency Modulated radio. This would require even more careful design and thought due to the higher frequency range, and would likely be a near impossible task using the breadboards and discrete components that we utilized in our own project. For a simpler follow-up, it would be interesting to layout this project on a PCB and see the improvements that a through-hole or surface mount system would have over the bread-boarded alternative.

6. Works Cited

Lewis, Tom. Empire of the Air: The Men Who Made Radio. New York: HarperPerennial, 1993. Print.

7. Acknowledgements

- Matthew D'Asaro; 6.101 LA and Team Mentor
- Gim Hom; 6.101 Instructor
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