Demonstrating Principles of RF Communication Design with Multi-channel 13.56 MHz ISM Band AM Walkie-talkies

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***Abstract*—Our final project for EE133 demonstrated our working knowledge of RF communication principles and design techniques. In this project we designed and tested a walkie-talkie from analog components. Our paper will delineate the many design choices that were made in order to achieve a working prototype.**

I. Introduction

WALKIE talkies are almost a century old. They were initially developed by the military to keep soldiers in contact with their commanders. Their first patents were filed in 1935 with the first walkie talkies using vacuum tubes and more recent ones using transistors. In this project we attempt to build a walkie talkie with a mixer as the core RF component. We choose Amplitude Modulation (AM) as the modulation scheme as it can be more simply implemented with existing components. Additionally, we choose to broadcast at 13.56 MHz as it is within the ISM band.

II. Design Inspiration

To start the design and development of a mixer based walkie talkie, we began by investigating prexisting designs and schematics. This investigation was eyeopening as many of the circuits which claimed to work had fatal flaws in their designs. Many simple radios utilize a simple transistor based design that can be seen in Figure 1.

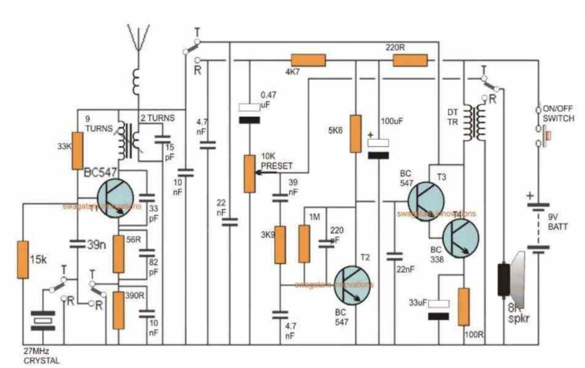

Fig. 1. Transistor Based Walkie Talkie Design [1]

We wanted to explore an alternate design which would force us to explore more core RF components from this class. This led us to a mixer based design. Our reference for a mixer based design is in Figure 2.

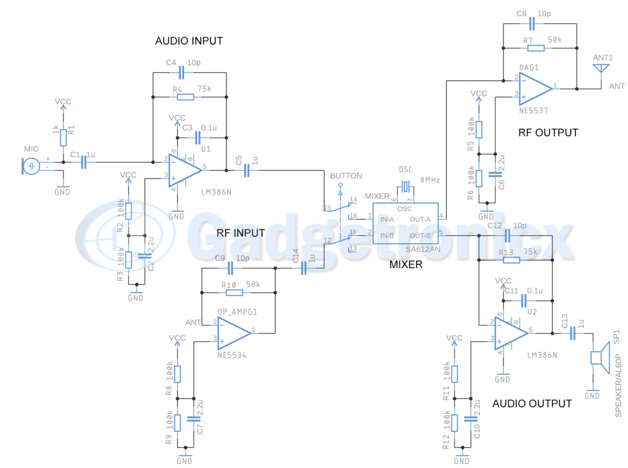

Fig. 2. Transistor Based Walkie Talkie Design [2]

This design is centered around the SA61A double balanced mixer and oscillator [3]. Upon further inspection of the mixer based design in Figure 2, it is evident that there are fatal flaws. The SA612A uses a Gilbert cell internally for mixing. The circuit in Figure 2 uses the differential drive of the gilbert cell to drive the transmit and receive portion of the walkie talkie separately. This is far from the intention of the differential drive in a Gilbert cell which can cause issues in the output of the walkie talkie. Additionally, the circuit only used one antenna for both the transmit and receive without any method of isolation, the RF amplifiers do not seem to have enough bandwidth, and the audio amplifier implementation can cause oscillations in the power supply. These flaws in the design made us skeptical of the circuits ability to function.

The initial goal of this project was to find and understand a mixer based walkie-talkie design that we could modify and enhance by channelizing the transmission and rececption frequency. Once it was evident that we were not able to find a schematic to reference, we decided to use figure 2 as inspiration and design and test a single channel walkie talkie.

III. Design

Through the design process, we went through many iterations of block diagrams. This allowed us to build and test blocks of the system one at a time before putting together the whole system. The final block diagram can be seen in Figure 3. In this figure, we can see the high level details of the system. In Figure 10, we can see more details regarding the specifics of the circuit and values of the passive components we use. We effectively use a DPDT switch to switch between a transmit and receive scheme and change the clock frequency accordingly.

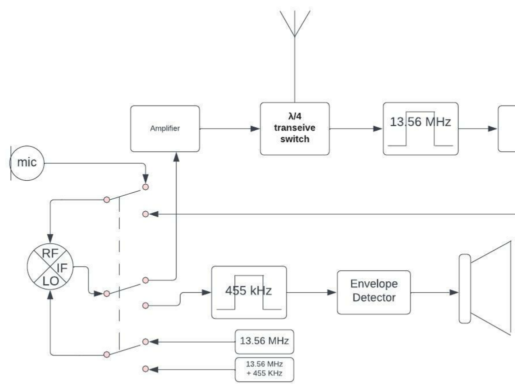

Fig. 3. A high level block diagram of our proposed mixer based walkie talkie.

A. Transmit Topology

To transmit, we first use a microphone biased to +Vdd and an AC coupling capacitor on the output to de-bias. The microphone signal is fed into a Class D amplifier. From there, the signal is fed into a mixer. The LO port of the mixer is set at 13.56 MHz and the signal is up-converted to that frequency range. The signal is outputted from the IF port of the mixer and is then ported to a low-noise rail-to-rail amplifier biased up to $\frac{+Vdd}{2}$ so that the signal is properly amplified. Finally, the signal goes through a $\frac{\lambda}{4}$ switch and is broadcasted through the antenna. The transmit topology was prototyped on a breadboard for testing purposes and can be seen in figure 4

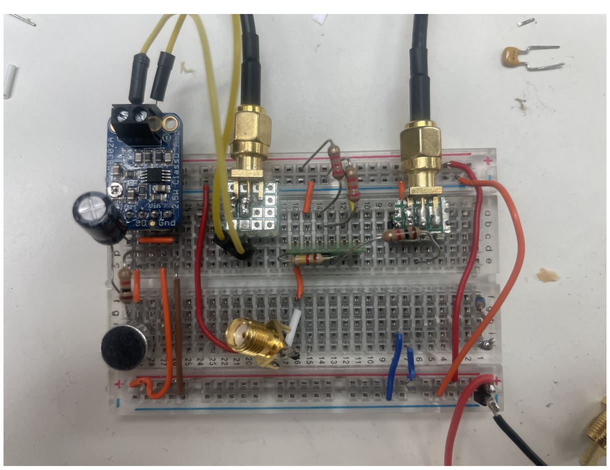

Fig. 4. Transmit portion of the walkie talkie on a breadboard.

B. Receive Topology

To receive, we must trigger the RF choke to allow signals from the antenna to flow through our pi network and into the receive portion of the circuit. The signal is received from the antenna and is fed into the mixer. The LO port of the mixer is set to 13.56 MHz + 455 kHz. This allows for us to down-convert the signal. We feed the signal from the IF port of the mixer into a low-noise rail-to-rail amplifier biased up to $\frac{+Vdd}{2}$ and then through a 455 kHz ceramic filter. The signal from the ceramic filter is amplified again through another low-noise rail-to-rail amplifier biased up to $\frac{+Vdd}{2}$ so the the signal is properly amplified. Next, it is fed into an envelope detector composed of a Schottky diode and a resistor and capacitor. Finally, the signal is fed into a class-D amplifier and outputted through a speaker. The receive topology was prototyped on a breadboard for testing purposes and can be seen in figure 5

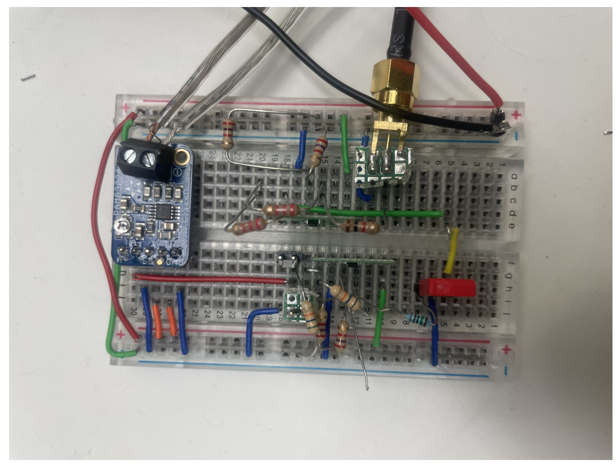

Fig. 5. Receive portion of the walkie talkie on a breadboard.

C. Block Diagram Components

In this subsection, we will discuss the specifics of blocks within the block diagram.

1) Mixers: Our first design choice centered around which mixer to use. First, we wanted a configuration that would allow for both up and down conversion (for transmitting and receiving). This would initially point us toward a FET-ring configuration because its IF and RF ports are symmetrical. However, this configuration would not be acceptable for our second requirement: the mixer needed to facilitate AM modulation. There is no way to bias the input of the IF to avoid double side-band suppressed carrier output of the mixer. This leaves us with two options: we could use a diode ring mixer as a passive option or a Gilbert cell as an active option [4]. Our third requirement was that we needed to operate our mixer close to DC, since we need to mix audio (20 Hz - 20kHz). The diode ring mixer requires a differential output, and because a microphone will provide a single-ended output, we would need a balun transformer for each of the diode ring's IF, RF, LO ports. However, we did not have viable transformers that can operate at low enough frequencies. This leaves us with the Gilbert cell mixer configuration. Our last requirement was a mixer whose rails could be operated at around 5V, the same as our amplifiers of choice. We found that HFA3101 [5] fit all these requirements.

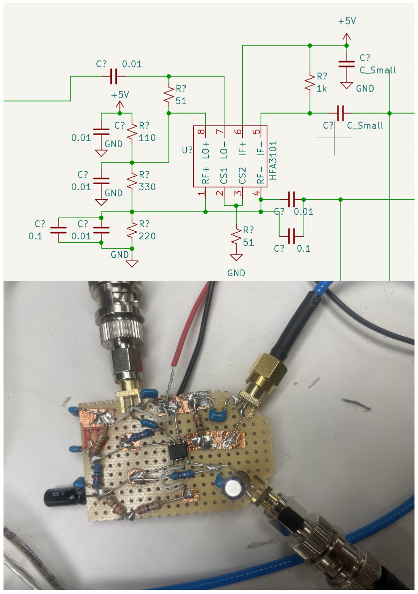

Fig. 6. Schematic for component and and test board laid out on copper tape

As seen in the above figure 6, we added additional .01 μF capacitors to the RF input and bias so that we can accommodate our low frequency audio input.

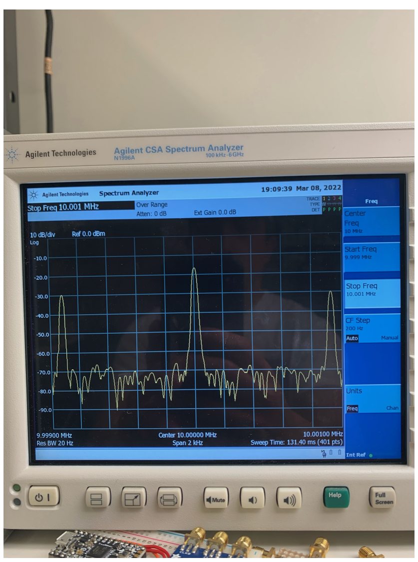

Fig. 7. Spectrum analyzer of Gilbert cell in the up-conversion configuration, with an LO of 10 MHz and an input of 1 KHz, demonstrating capability of low frequency modulation

We tested this configuration of the Gilbert cell and successfully saw up-conversion at near-DC values. As seen in figure 7, with a 1 KHz input signal we were able to see both the sum and difference signals appear on the output.

2) Filters: As we made the design decision to broadcast at 13.56MHz + 455kHz, we must filter out the 455kHz signal when receiving. We choose 455kHz, as this is convention and narrow bandwidth ceramic filters for 455kHz were readily available. We had a few different options in terms of the band width: 4kHz, 8kHz, and 12kHz. We needed characterize the filters, so we could choose the filter we wanted for our application. We hooked up an Analog Discovery 2 [6] to the input and output of the filter with a 1kΩ termination resistance and ran a frequency sweep from 430-480kHz. This effectively gave us a Bode plot89. We can see in figure 8 and 9 that the pass-band has an attenuation of about 10dB. Due to our uncertainty in the robustness of our walkie-talkie, we chose the largest pass-band available, 12kHz.

3) Amplifiers: In order to amplify our signal in both the transmit and receive portions of the walkie talkie, we decided to use an op-amp. Another viable option could have been using a 2N3904 transistor. However, a properly selected opamp would have lower noise and higher precision, and gain-bandwidth. We evaluated a few different options such as the INA126 [7], however decided to use the LT6200 and LT6200-5 [8] since they were low-noise, rail-to-rail amplifiers which had significant gain in the MHz region in which we were broadcasting. These amps had a gain bandwidth product of 165 and 800 Mhz respectively. We utilized a total of 3 stages of amplification, one in the transmit and two in the receive and only used the lower gain bandwidth product after the 455kHz ceramic filter, as we knew the narrow band that we wanted to amplify in that region. These amps were in negative feedback with varying gains, but were all biased up to 2.5 Volts or $\frac{Vdd}{2}$ in order to allow for the signal to be fully seen while it was being amplified.

4) Clock Signal: The clock signal is generated from an Itsy-bitsy controlled clock generator (Si5351), previously discussed in this class [9]. We chose this configuration because of the availability of parts and the familiarity of the components. In addition, it allows us to use the same Itsy-bitsy micro-controller for other parts of the walkie-talkie. This configuration is one of the reasons why we will be broadcasting in 13.56 MHz range (rather than some higher frequency of ISM band), as the clock generator can only generate 160 MHz and its high frequency outputs tend to present a great deal of noise [9]. In practice, we used bench-top function generators to eliminate complexity when testing our design. However, in the final implementation, the input to the LO of the mixer will come from the Si5351 at 13.56 MHz (for up-conversion) and 14.015 MHz (for down-conversion).

5) Microphone: To take an audio input in the form of a voice, we used an electret microphone [10] which is an electrostatic capacitor-based microphone. The negative end of the microphone was connected to ground while the positive terminal was pulled up to 5 Volts via a 1kΩ resistor and the DC biased output was fed through an AC coupling capacitor to ensure only the vocal signal was outputted. This signal was fed through a class D amplifier.

The microphone proved to be a particularly difficult component to debug since it was difficult to send a constant vocal signal and read the output on an oscilloscope. To test our circuit, we produced a 500Hz tone on our phones and attempted to see the signal on an oscilloscope.

6) $\lambda/4$: In order to use the same antenna for transmitting as well as receiving (while protecting our circuitry) we decided

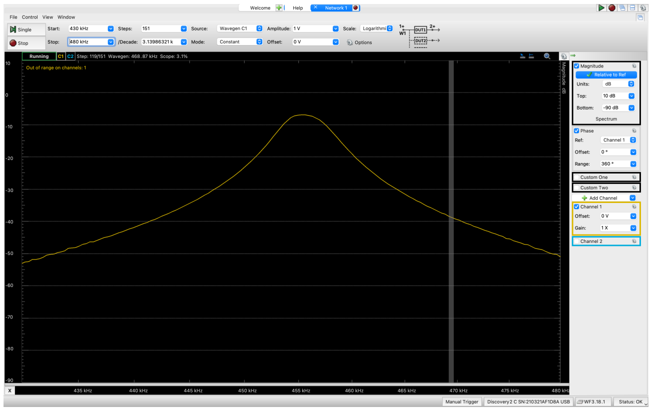

Fig. 8. 455kHz Ceramic Filter with 4kHz Passband

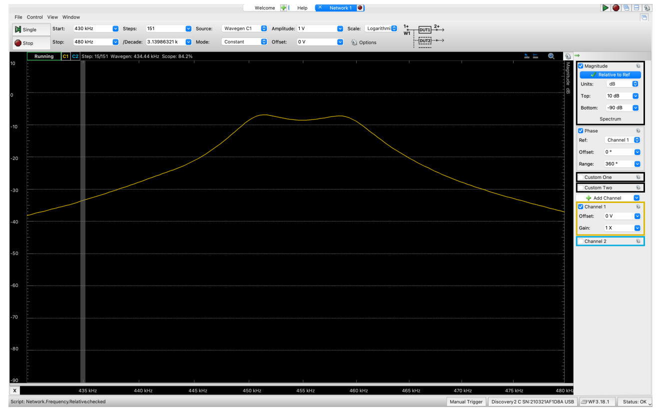

Fig. 9. 455kHz Ceramic Filter with 12kHz Passband

on a simple $\lambda/4$ pi network that utilizes simple electromagnetic wave properties to act as switch.

We configured our cell with pin diodes in parallel such that when a small DC current is introduced, we can pass RF signal from the mixer into the antenna and the path from the antenna to the receiver looks like a short.

We demonstrated in figure 12, when there is no DC current and the pin diodes are off, the pi network looks like a short at 13.56 MHz (as seen on the VNA) and the signal is split between the two 50 ohm resistors.

As seen in figure 13, our pi network, as seen from the input, looks like an open at 13.56 MHz.

7) Envelope Detector: The envelope detector (or peak detector) was a vital component of our project as it enables us to look only at the envelope of the amplitude modulated signal, hence demodulating our signal. We would feed in an amplitude modulated signal and output the envelope of the amplitude modulated signal at the output. The circuit to enable envelope detection can be seen on the bottom right of figure 10 before the Class D amplifier. It consists of a diode in series with a resistor and capacitor in parallel. The diode rectifies the signal while capacitor stores charge on the rising edge of the signal and dissipates it through the resistor on the falling edge enabling us to output the envelope [11]. An important design decision we made in the envelope detector was the diode being used. The initial design utilized a 2N3904 [12] in a diode configuration. After implementing this design however, we were not able to get any output from the circuit. Further testing and investigation led us to the conclusion that the band-pass filter before the envelope detector got rid of any DC offset which meant the signal was not able to overcome the 0.6-0.7V forward voltage required to turn the transistor on. As a result, we saw no output from the envelope detector. To rectify this problem, we utilized a Schottky diode as it has a very low forward voltage and has fast switching action. This enabled the peak dector to work with the signal from the 455kHz ceramic filter.

8) Speakers: The speakers were a relatively straightforward choice in our project. Since we were focusing mainly on the RF components, we started with a simple generic speaker component from Adafruit. The speaker was not 8 ohms and

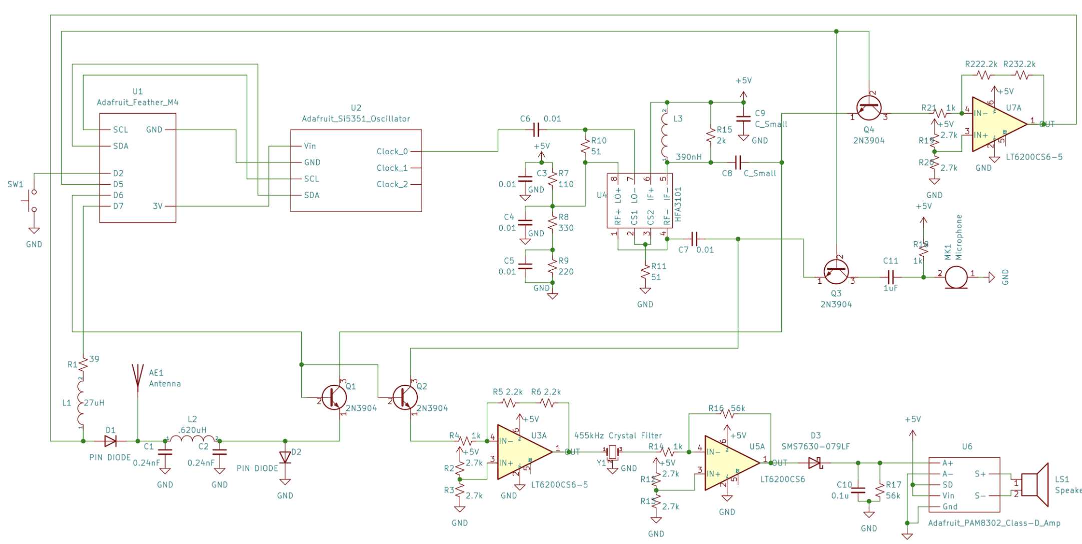

Fig. 10. Schematic for mixer based walkie talkie

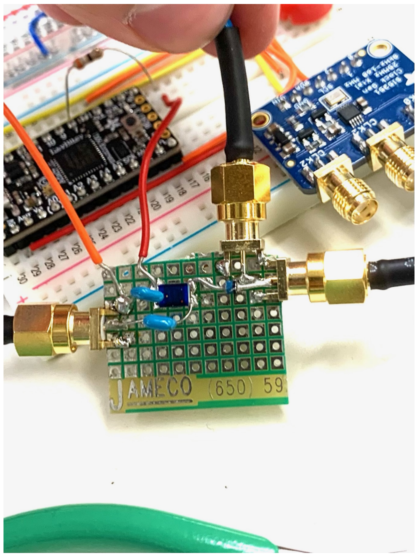

Fig. 11. Construction of $\lambda/4$ pi network according to simulation values with PIN diode in parallel

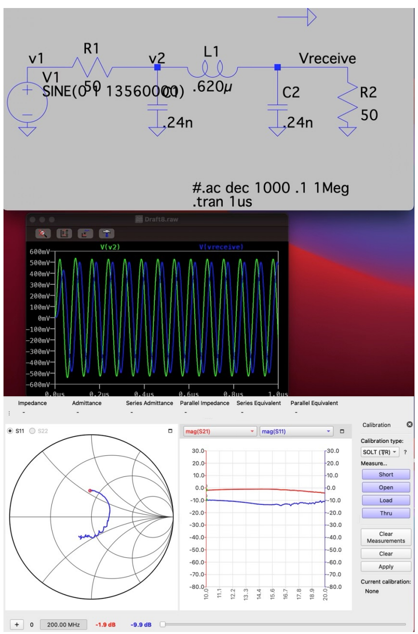

Fig. 12. Simulation of $lambda/4$ segment when no DC current is passing through PIN diodes and output on VNA

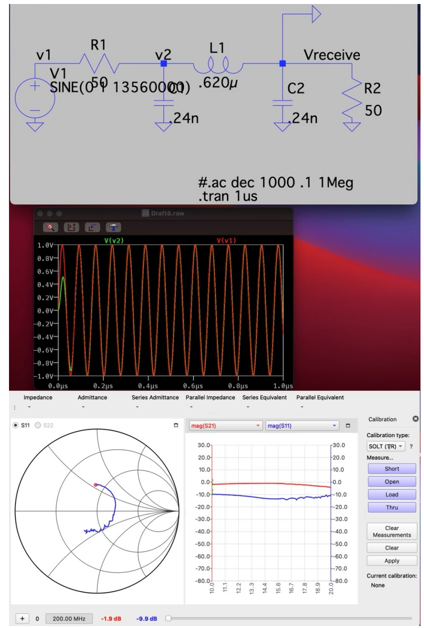

Fig. 13. Simulation and VNA output of $lambda/4$ segment when DC current is passing through PIN diodes, grounding the output of the inductor

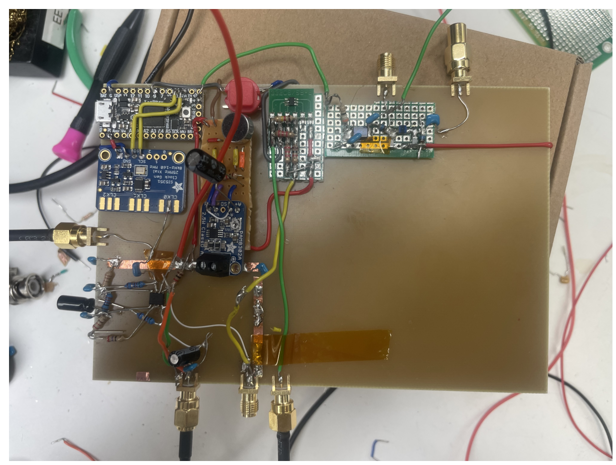

Fig. 14. Copperclad transmit circuit

since the Class D amplifier was rated to 8 Ohms, we switched the speaker for our final demonstration to a larger 8 ohm speaker.

IV. Design Iterations

Due to the complexity of the design, we began by iterating our circuit on a few breadboards. This enabled us to use power supplies as well as frequency generators for testing purposes. Figures 4 and 5 show these prototyped versions. The next iterations of design on copper clad is not fully complete, however figure 14 shows the completed transmit circuit on copper clad.

V. Discussion and Next Steps

Through designing our walkie-talkie, our group was able to utilize many of the tools and principles in RF communications design. We analyzed mixer components with a spectrum analyzer and our $\lambda/4$ segment with a VNA. We found limitations with our components, switched out and added components where needed, and troubleshooted almost every part of our circuit. While our project achieved many of the goals that we set for ourselves, there is still a great deal left wanting. Future steps may include the following: incorporating voltage-controlled switches and designing a PCB for a complete system; developing a more-robust multi-channel configuration; experimenting with different forms of signal modulation; and reconsidering our initial block diagram all together.

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