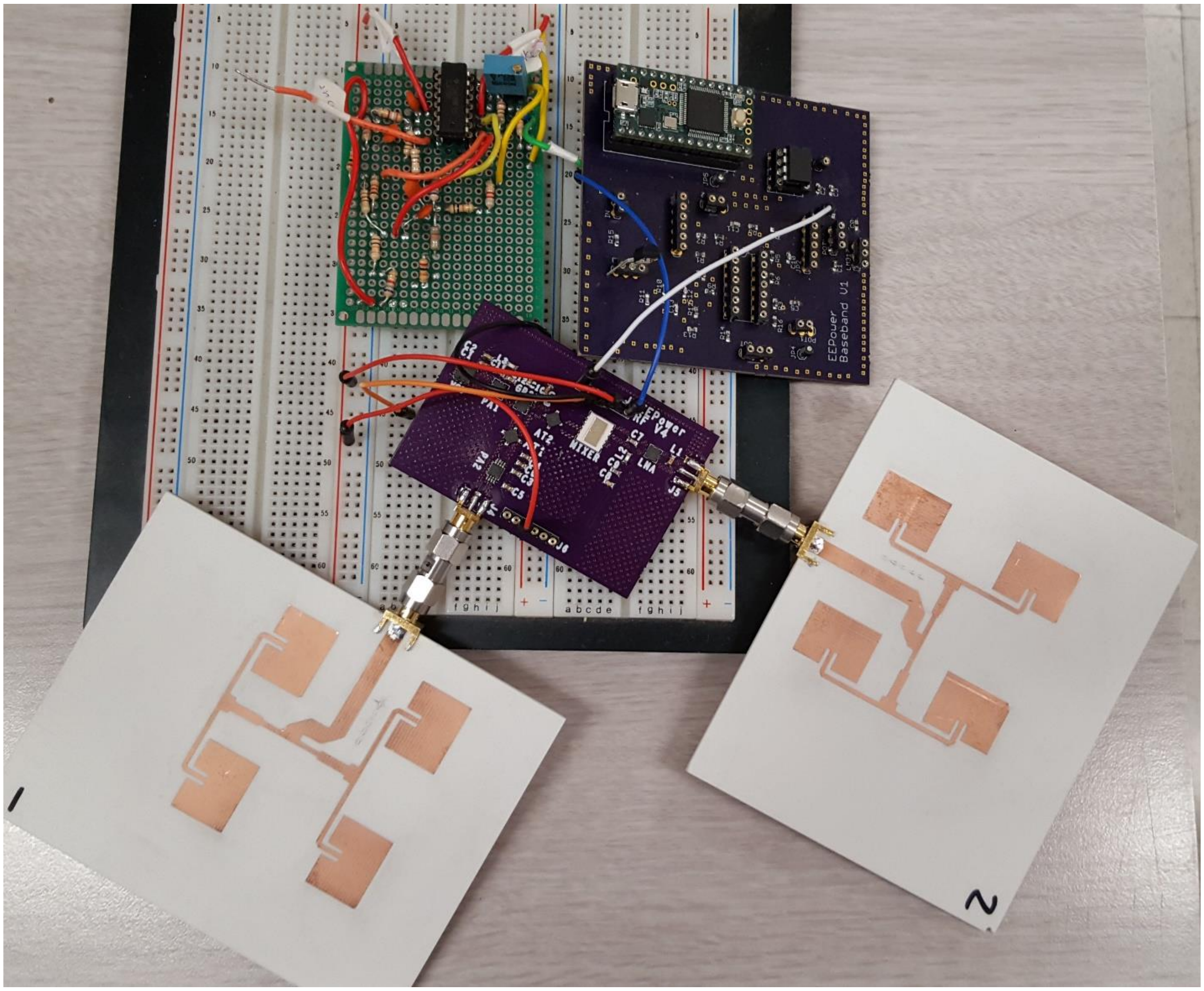
EEC 134 Group Final Report



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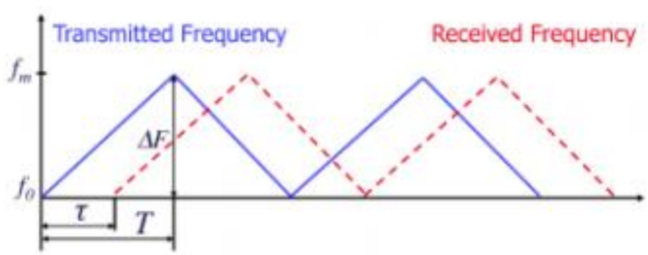
Introduction

The primary purpose of this report is to present the design and implementation of Frequency Modulated Continuous Waveform (FMCW) and Doppler radar. FMCW radar is an object-detection system that uses radio waves to determine the presence, range, and angle of objects whereas Doppler radar can detect the velocity of the objects. This radar system has many applications as it can be used to detect and locate aircraft, ships, spacecraft, guided missiles, motor vehicles, weather formations, terrain, etc. Our project can detect a distance up to ~50 meters. Our radar system consists of 3 main blocks: baseband board, RF board, and antennas. The RF system has some components that generate high frequency signals, amplify signals, attenuate signals, and change the frequency of the signals. The received signal in the RF board is mixed with a lower frequency signal so that we could perform signal processing with the baseband, where baseband filter can amplify signals at certain frequencies and filter out other-frequency signals.

The operating frequency of our radar system is 5.8 GHz. The modulation pattern is triangular (and step). After the radar signal leaves the transmitting antenna, its frequency will no longer change. Because the transmitter VCO keeps ramping up and down, when the reflected signal comes back to the radar receiver, it will see a different frequency coming out of the transmitter. The difference in frequency between the two signals can be extracted by a frequency mixer. This frequency difference is proportional to the round-trip delay of the radar signal to and from the target. By examining this frequency difference, the distance to the target can be calculated.

Figure 1 Plot Illustrating the Time Delay and Frequency Shifts

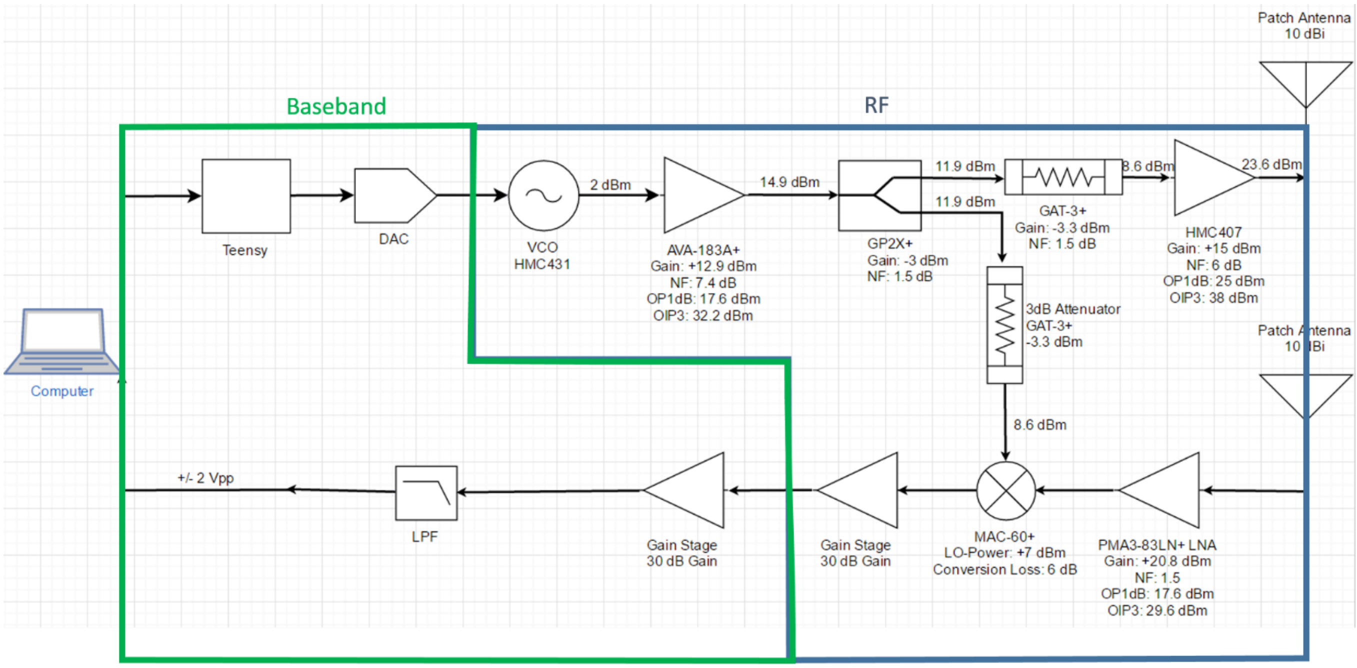


This report will analyze each of the listed above blocks in details. First, we will walk you through the system design specifications. Second, we will examine the design implementation of the RF board design, baseband design, and antenna design. Last, testing, troubleshooting and benchmarking of the overall system will be discussed in details.

Our goal was to create a radar system that is compact and more accurate than our radar system built during Fall quarter. Our plan was to have the baseband on top of the RF board. Patch antennas would significantly reduce the overall size and weight of the system. Our second goal is to reduce the noise and improve our designs.

System Design

Figure 2 Radar Block Diagram



The competition considers three parameters:

- Accuracy
- Weight
- Power consumption

The primary goals for the improved design were increasing range accuracy and reducing weight. Some of the RF components consumed a lot of power. Therefore, the overall system design traded off relatively high power consumption for increased accuracy and reduced weight.

The operating frequency of our improved design was 5.8 GHz. This frequency was chosen because it allowed for relatively small patch antennas, since the dimensions of each patch decreases as the center frequency increases. Also, there were not a lot of devices that use 5.8 GHz, therefore reduced the chance of interference.

Because the targets were placed between 5 and 50 meters, the radar system was designed to detect objects from 5 to 55 meters. Five meters were added to account for any loss. Applying the Friis transmission equation and the link budget gave an approximation for the minimum transmit and receive power for the improved system.

The link budget calculations are summarized below:

$f = 5.8$ GHz
$\lambda = 0.0517$ m
$\sigma = 4\pi w^2 h^2/\lambda^2 = 38.046 m^2$
$P_t = 23.6$ dBm
$G_r = G_t = 10$ dB
$$P_r = \frac{P_t G_t G_r \lambda^2 \sigma}{(4\pi)^3 R^4},$$
$R = 5$ m
$P_r = -20.858$ dBm
$R = 55$ m
$P_r = -68.114$ dBm
$$\text{Free Space Path Loss} = \frac{\lambda^2 \sigma}{(4\pi)^3 R^4} = -85.514 \text{ dBm}$$

RF Board

The components used in the RF board are summarized in the table below:

Transmitter Components		Receiver Components	
Name	Type	Name	Type
HMC431	VCO	PMA3-93LN+	LNA
HMC407	Power Amplifier	MAC-60+	Mixer
AVA-183A+	Power Amplifier		
GAT-3+	Attenuator		
GP2X+	Power Splitter		

While choosing the components, the following performance parameters were considered:

- Linearity (P1dB and IP3):
- Noise figure
- Power Consumption/ heat generation

Other aspects are considered, such as:

- Availability (purchase or sample)

Linearity

It is important to consider linearity when choosing amplifiers, specifically the 1-dB compression point and the third-order intercept. P1dB is defined as the point where the actual gain decreases 1 dB below the theoretical linear gain response. At this point, the output power does not increase with increased input power, and the gain levels off. Also, amplifiers operating in this region become nonlinear. In this nonlinear region, harmonics become amplified, especially the third-order harmonics. Third-order harmonics are troublesome because they are very close to the fundamental frequencies. IP3 is determined by finding the intersection of the extrapolated linear curves of the fundamental signal and the third-order signal.

When it comes to choosing components, P1dB indicates the input and output power at which the amplifier will saturate and become nonlinear. In practice, the IP3 value will never be reached, but this value serves to indicate the linearity of the amplifier.

Noise Figure

Noise figure is defined to be the ratio of the SNR (signal-to-noise ratio) at the input to the SNR at the output in dB. The lower the noise figure, the better the system performs. When combining RF components, the noise factor cascades, with the first device contributing to the most noise, as shown in the equation below:

$$F_{CAS} = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \dots$$

Because the receiver will receive very low power signals and a lot of noise, a low noise amplifier is placed after the receiver antenna because it contributes little noise in the system and amplifies the low power signal. The chosen LNA had a noise figure of 1.5 dB. This was a low noise figure, compared to a noise figure of 5.4 dB for the power amplifier.

Power Consumption/ Heat Generation

The calculated transmit power of the system is 24.4 dBm, which equates to 0.2754 W. The Analog Devices HMC407 and Mini-circuits AVA-183A+ power amplifiers are chosen to amplify the VCO generated signal by 12.9 dB and 15 dB respectively. The cost of such high gain is high power consumption, which leads to heat generation.

A table of the power consumption of each active RF device is summarized below:

Device name	Device Type	Operating Voltage (V)	Datasheet Current (mA)
HMC407	PA	5	230
AVA-183+	PA	5	166
HMC431	VCO	3	27
PMA3-83LN+	LNA	5	60
		Total Current =	483
		Total Power Consumption =	2.361 W

Component Availability

All of the RF components but the HMC407 power amplifier and the HMC431 VCO, both from Analog Devices, were available for sampling. This greatly reduced the cost of the radar.

Design Considerations for RF Passive Components

Attenuator

The GAT-3+ attenuator was used to attenuate the power levels to prevent too much input power from entering the HMC407 power amplifier and saturating. Also, the same attenuator was placed before the LO port of the mixer to provide some impedance matching between the LO port and the splitter.

Splitter

The GP2X+ splitter is a passive device that delivers the same amount of power to two output ports. It also attenuates the output power by approximately 3 dB.

Mixer

When choosing mixers, it is important to know how much LO power is needed to operate and the conversion loss. The MAC-60+ mixer from Minicircuits was chosen because it had an operating frequency range that covered the operating frequency of the radar.

Baseband Board

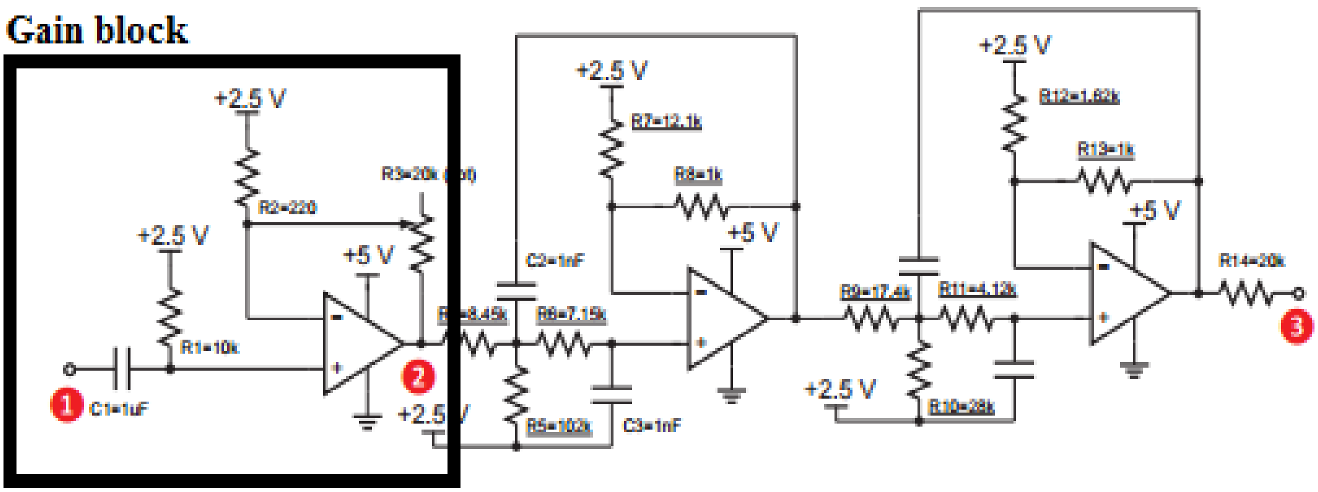
The baseband board primarily consists of 2-stage gain stages to amplify the signal coming from the RF board, a lowpass filter (LPF) stage to filter out unwanted signals, and voltage regulators. Then baseband was connected to the computer using an audio jack. The gain stage was tuned to have a gain of **35** dB as it gave the best results during testing. The baseband filter cutoff frequency is 15 kHz. The gain stage is then followed by a LPF. The low pass filter used after the amplification of the signal that come out of the mixer.

To select the component of the baseband board, we used the surface mount components that were used in lab 1. The op-amp used was TL974.

We used the following components for the baseband PCB:

• 1 × 8-DIP MCP4921 DAC IC
• 1 × LT1009 precision reference IC.
• 1 × 14-DIP TL974IN quad Op-Amp IC.
• misc resistors. Provided by the TA.
• misc capacitors. Provided by the TA.
• 1 × 2k potentiometer
• 1 × 20k potentiometer.
• 1 × small screwdriver.
• 1 × audio cable with 3.5 mm audio plug

Figure 3 Schematic of the gain stage and active LPF



Patch Antenna

In the link budget calculation, the gain of the transmit and receive antennas were assumed to be 10 dBi. This was reasonable because the typical antenna gain for a 2x2 patch array antenna was approximately 13 dBi. The 2x2 design was chosen because it combined the gain of each individual patch (typical gain of 5-7 dBi).

The first step in the patch antenna design was to choose the substrate. The Rogers RO4730JXR substrate was chosen. It had the following parameters:

- dielectric constant: 2.98
- substrate thickness: 1.541 mm
- copper cladding: 35 um

The following equations were solved to realize the dimensions of each patch antenna:

$$W = \frac{V_o}{2f_r}\sqrt{\frac{2}{\varepsilon_r + 1}}$$

$$\varepsilon_{reff} = \frac{(\varepsilon_r + 1)}{2} + \frac{(\varepsilon_r - 1)}{2}\left[1 + \frac{12h}{w}\right]^{-\frac{1}{2}}$$

$$\frac{\Delta L}{h} = \frac{0.412\left((\varepsilon_{reff} + 0.3)\left(\frac{W}{h} + 0.264\right)\right)}{(\varepsilon_{reff} - 0.258)\left(\frac{W}{h} + 0.8\right)}$$

$$L = \frac{v_o}{2f_r\sqrt{\varepsilon_{reff}}} - 2\Delta L$$

The equations resulted in the patch length and width to be:

- length: 14.28 mm
- width: 18.33 mm

The next step in the patch antenna design process was to design a 50 Ohm transmission line feed to the patch antennas. The inset-feed method was used because it was easy to obtain input matching than other methods, and the feedline can be placed on the same plane as the patch.

Once the dimensions of the antenna patches and the 50 Ohm feedlines were computed, they were implemented and the antenna was simulated in Ansys HFSS. The following parameters were analyzed:

- S11
- Gain
- Input Impedance
- VSWR
- Radiation pattern

Following the simulation, the antenna dimensions were tuned to correct any discrepancies.

Final Patch Antenna Dimensions (After Tuning)

Patch Length	13.65 mm
Patch Width	18 mm
Inset Width	1.07 mm
Inset Depth	4.4 mm
50 Ohm Feedline Width	4.075 mm

NOTE: The following plots are of the final tuned patch antenna.

Figure 4 Patch Antenna Realization

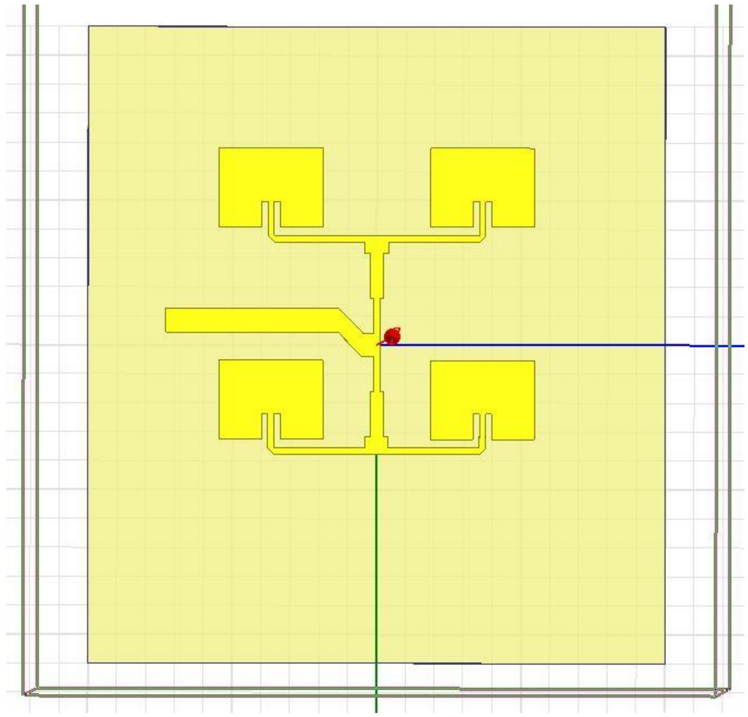


Figure 5 S11

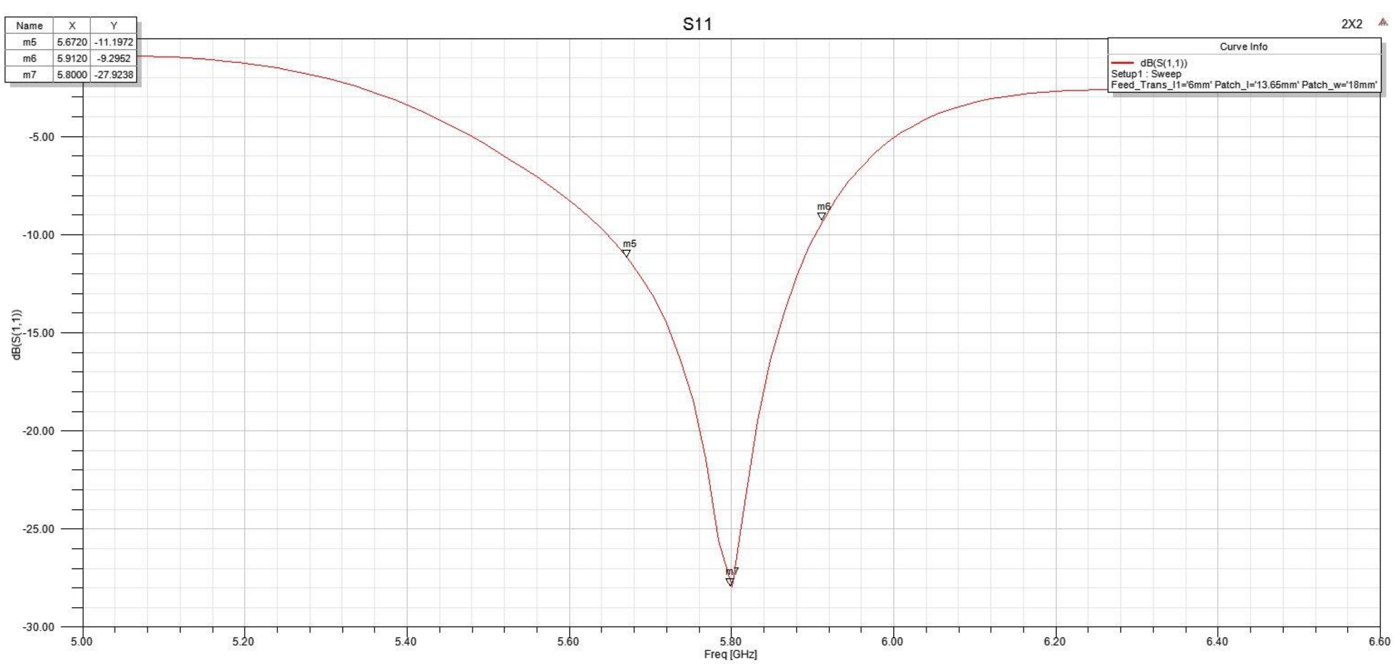


Figure 6 Gain

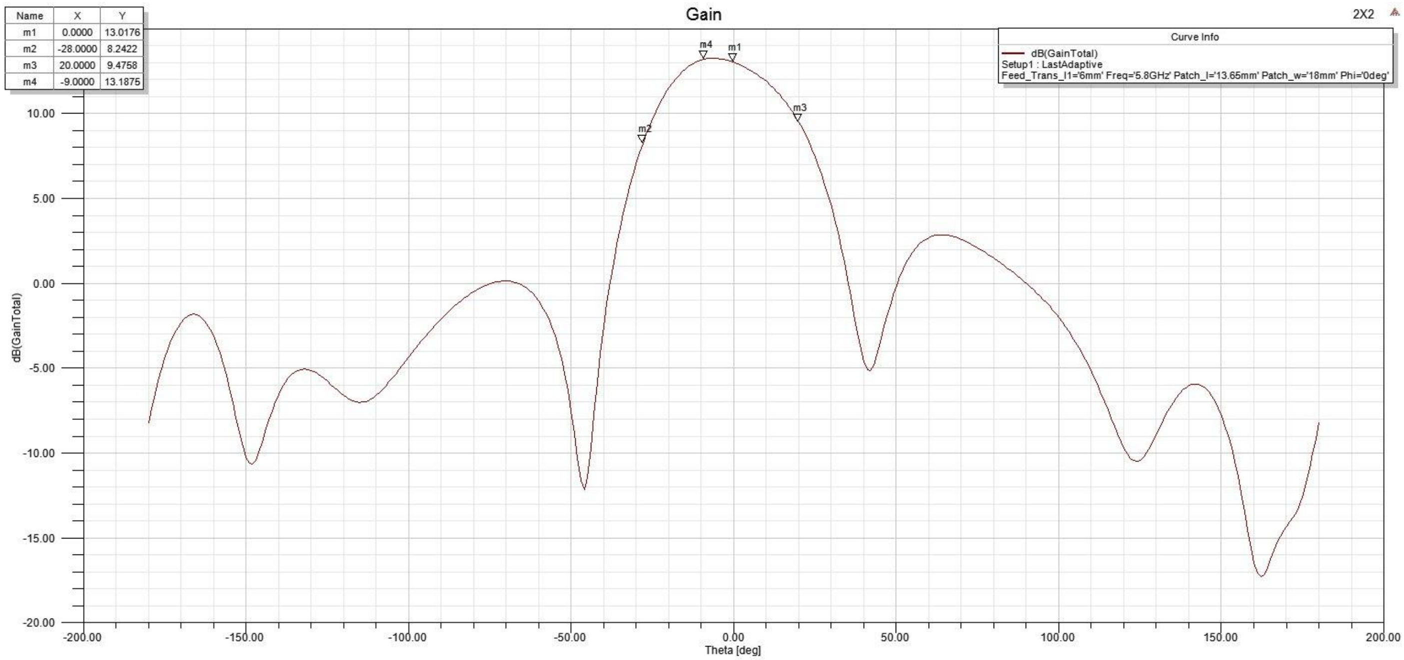


Figure 7 Input Impedance

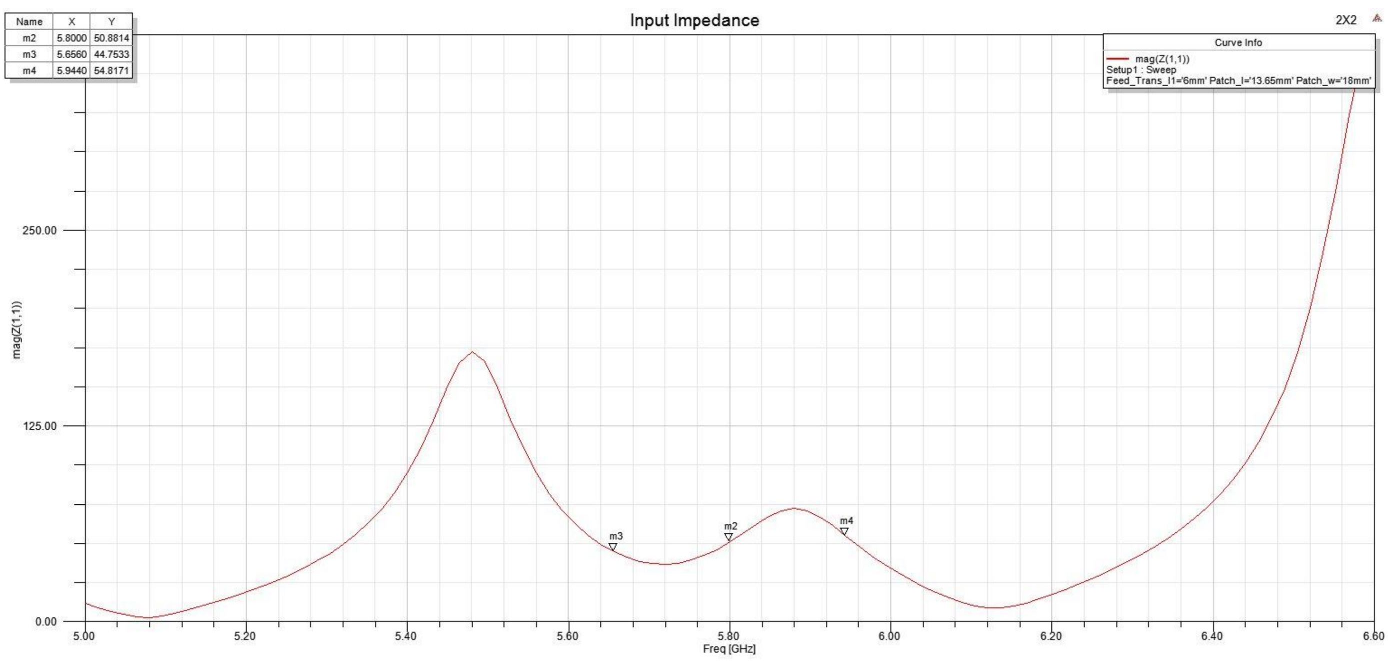


Figure 8 VSWR

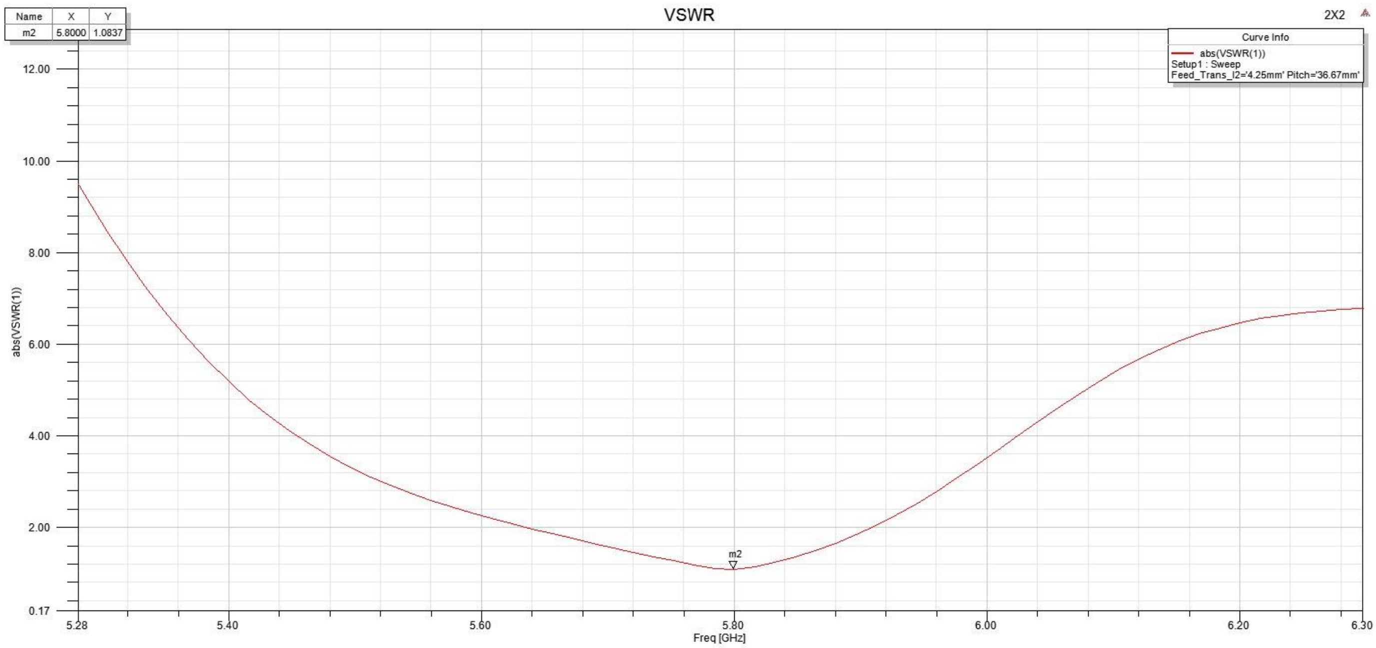
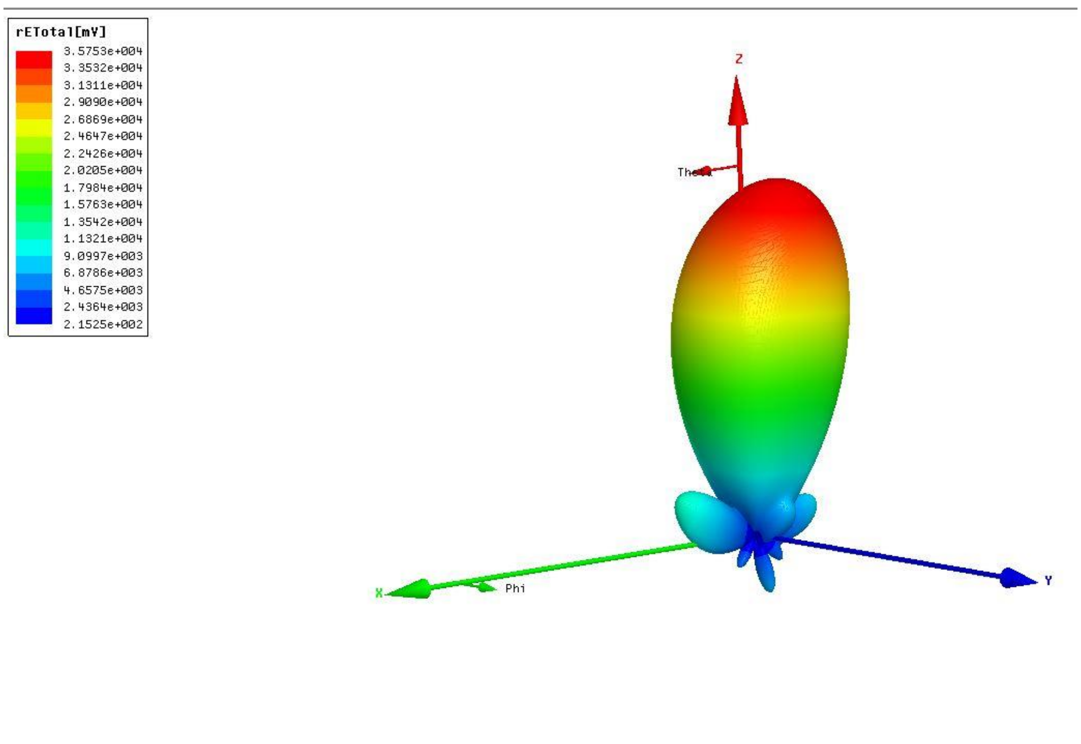
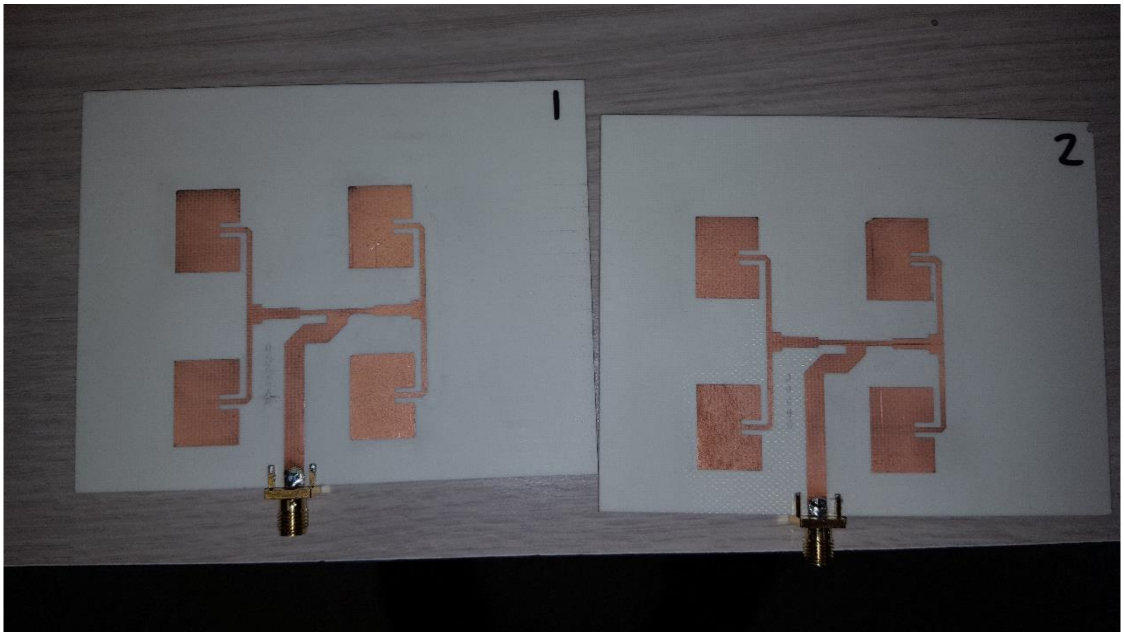


Figure 9 Radiation Pattern



The antennas were fabricated using the milling machine. Figure 10 shows the finished antennas.

Figure 10 Fabricated Antennas



PCB Schematics

Figure 11 Schematic of the main baseband PCB

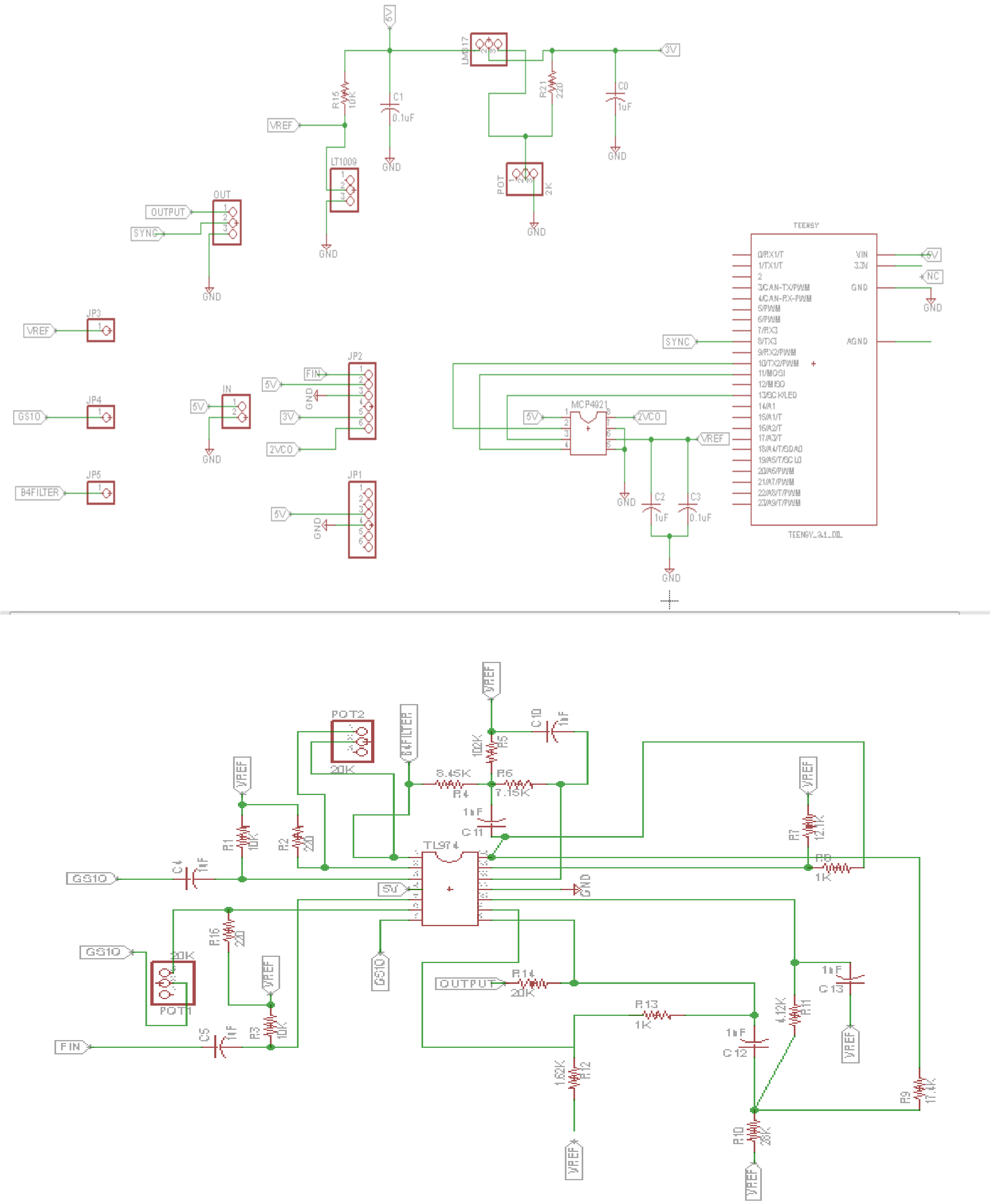
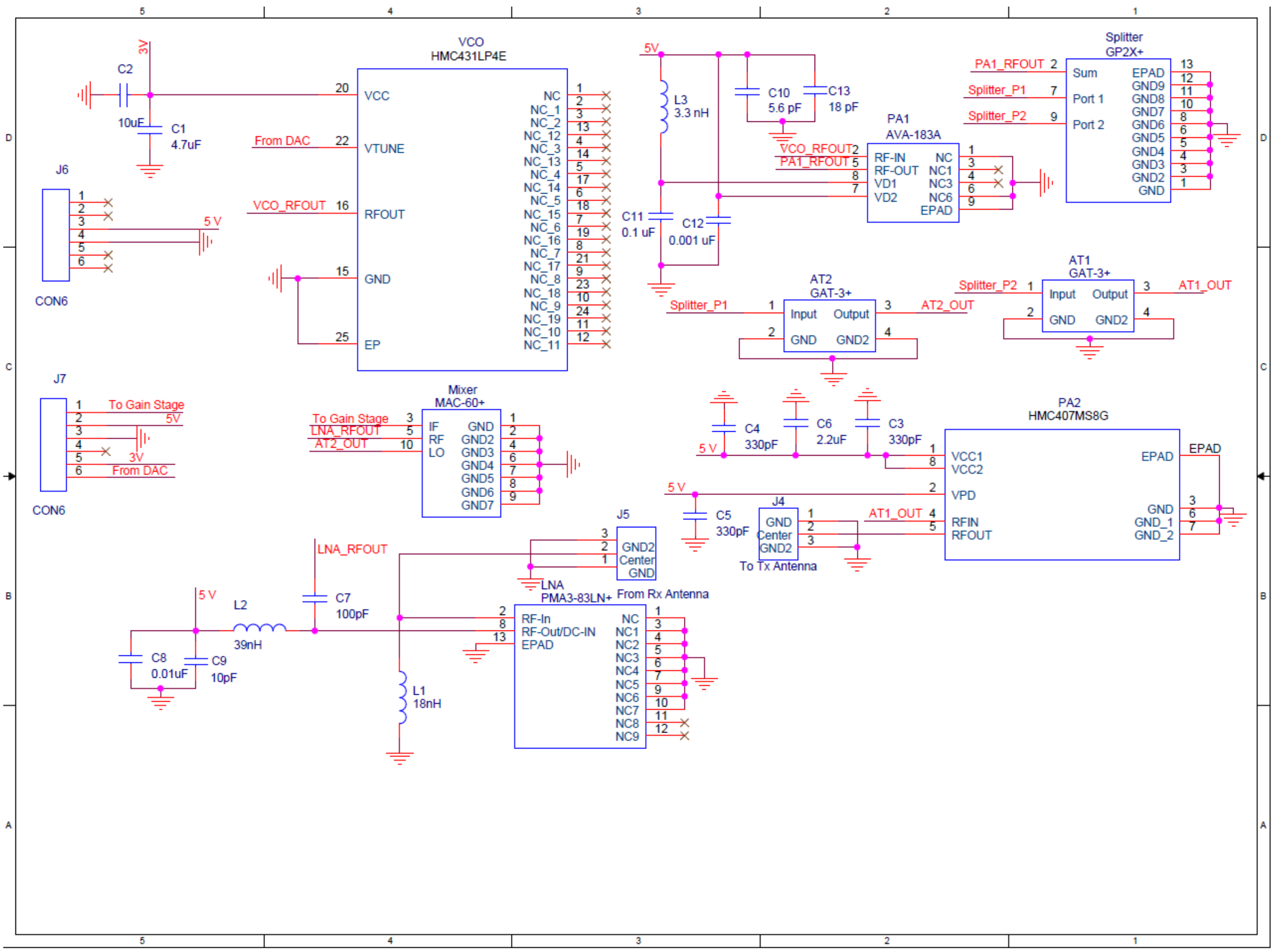


Figure 12 RF Board Schematics



PCB Layout

Figure 13 PCB Layout

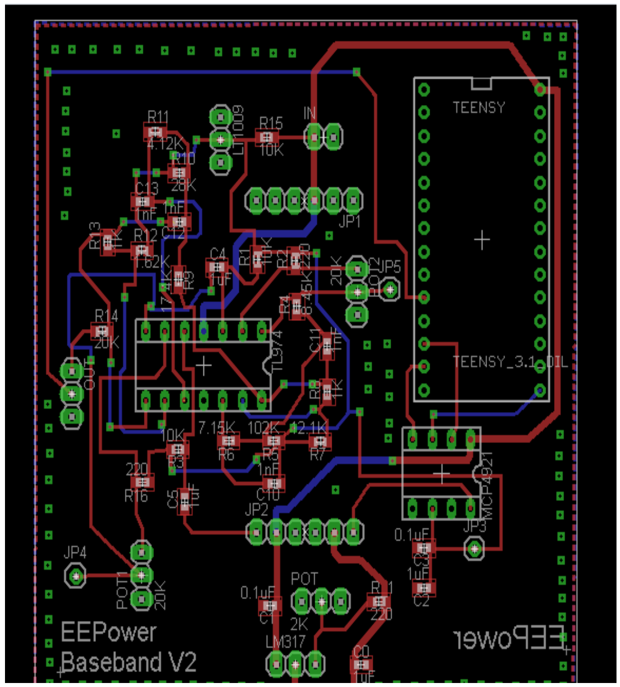


Figure 14 Soldered Baseband PCB

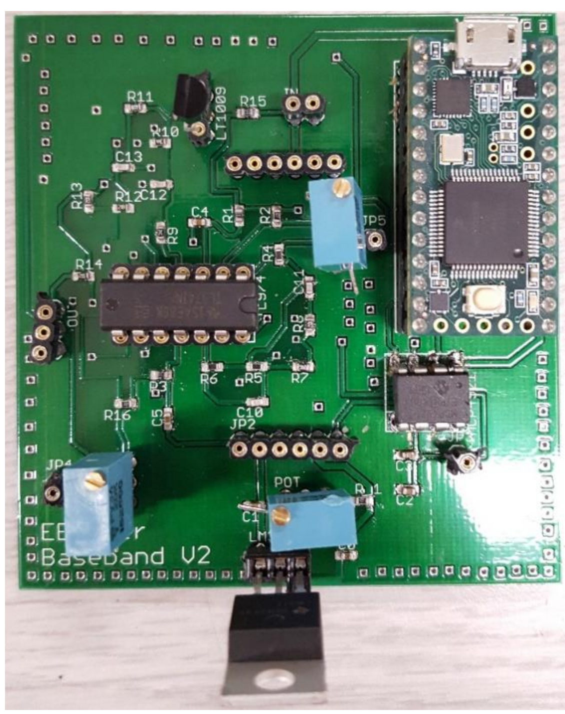


Figure 15 RF Board Layout

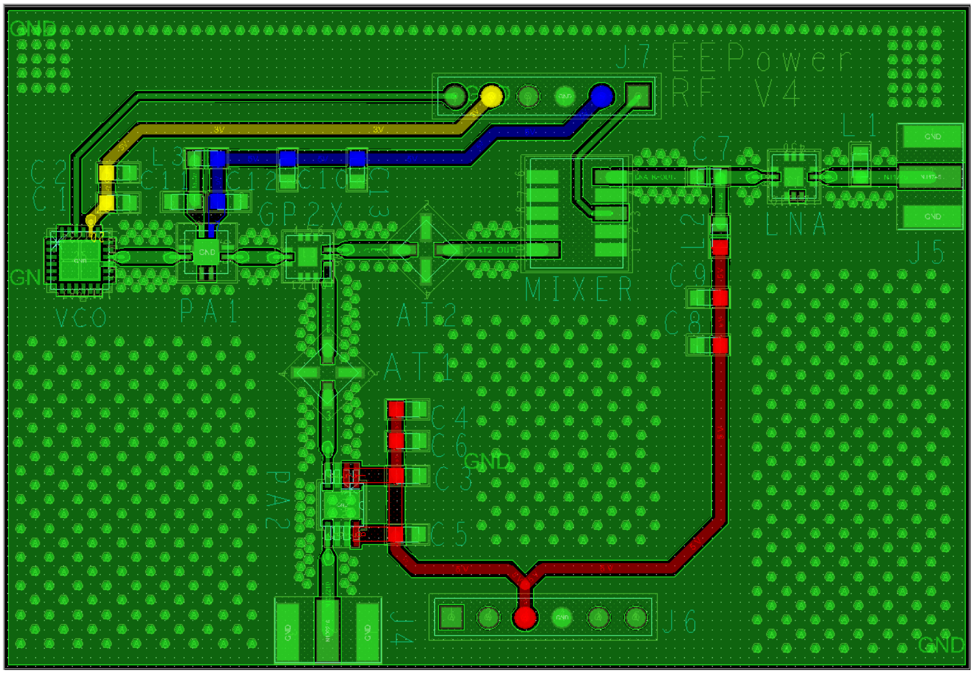
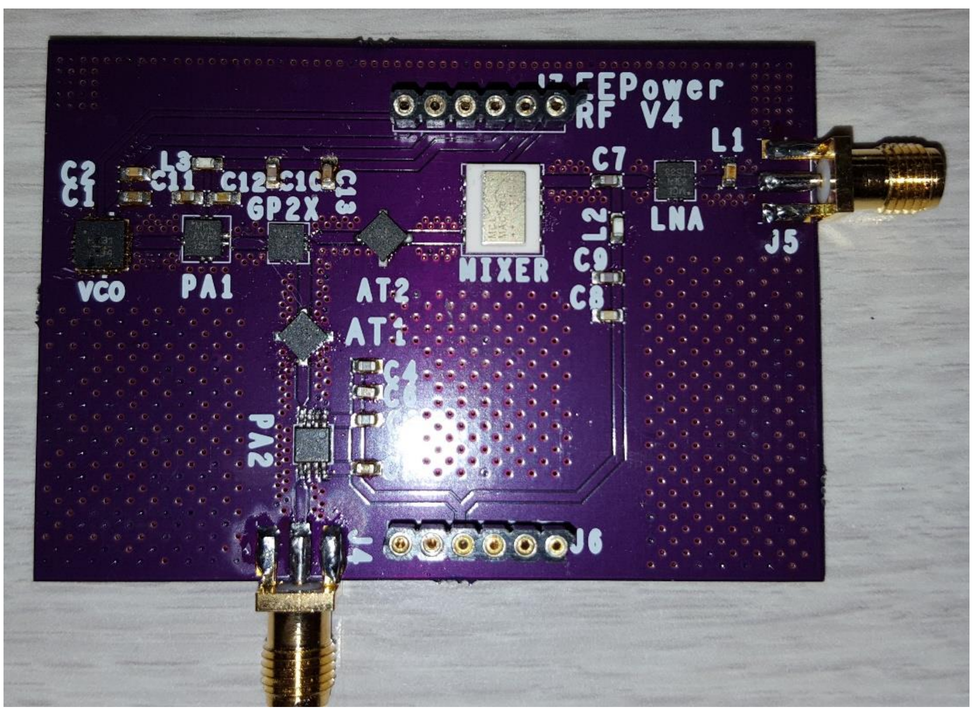
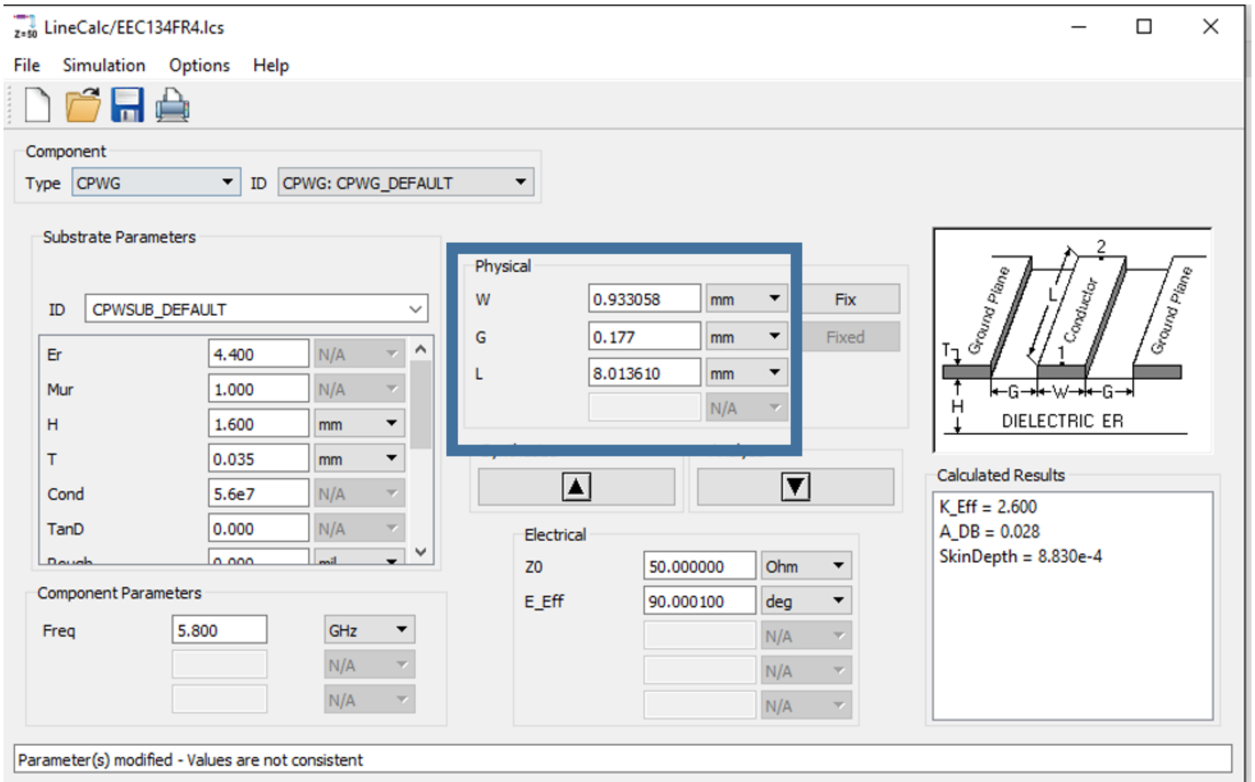


Figure 16 Soldered RF Board



The microstrip line widths connecting each of the RF components had to be matched to 50 Ohms, so ADS LineCalc was used to compute the necessary transmission line width, as shown in figure 17. The parameters for the substrate are summarized below.

Figure 17 ADS Microstrip Width Calculation



Substrate Parameters

Er	4.4
Mur	1
H	1.6 mm
T	0.035 mm
Frequency	5.8 GHz
Z0	50 Ohm

System Tests

Baseband Test

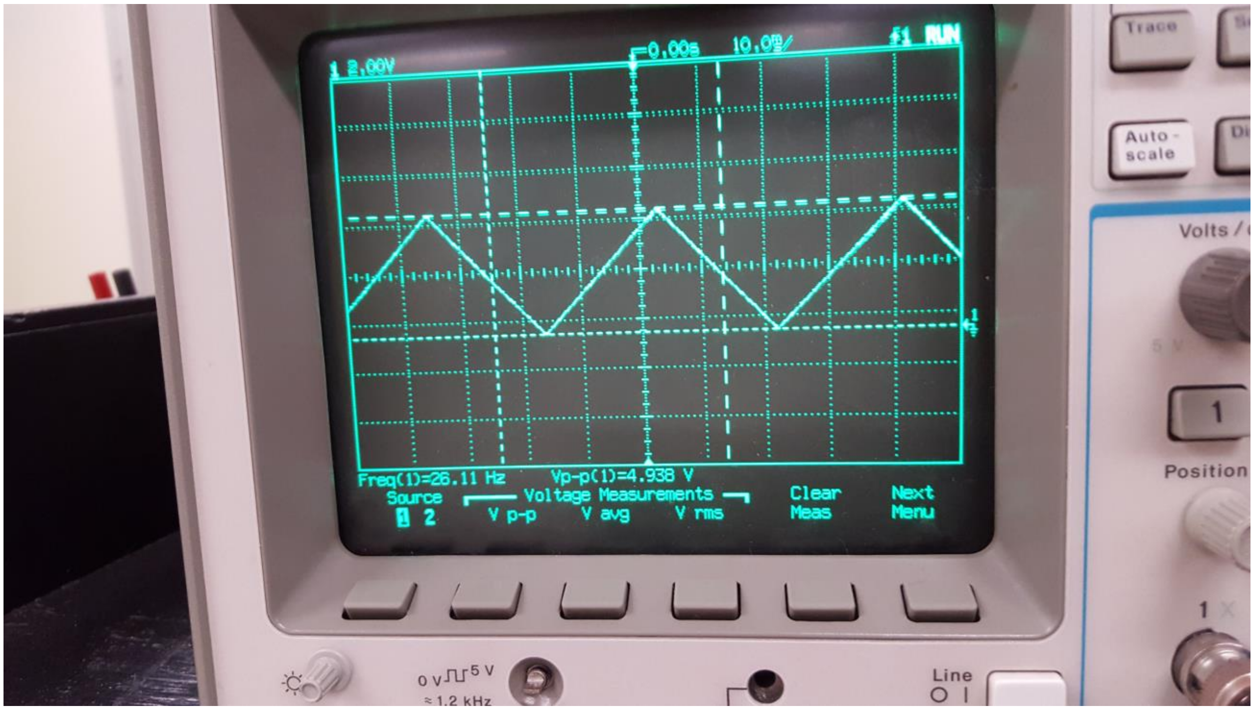
Two stages of the baseband PCB were tested:

- Teensy + DAC
- Gain + LPF

Teensy + DAC

The Teensy and DAC were testing by probing the output of the DAC. The expected output was a 25 Hz triangle wave with a voltage swing of 5V, from 0 to 5V. Figure 18 shows the measured output.

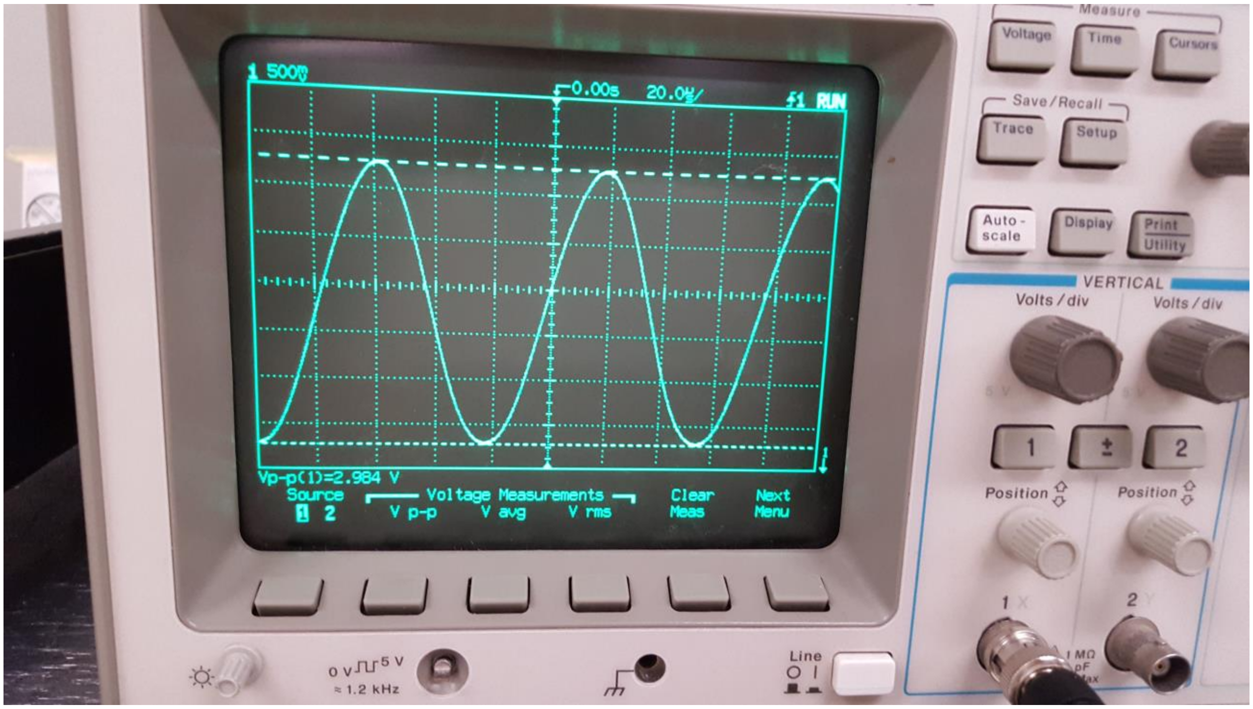
Figure 18 Teensy+DAC Output



Gain + LPF

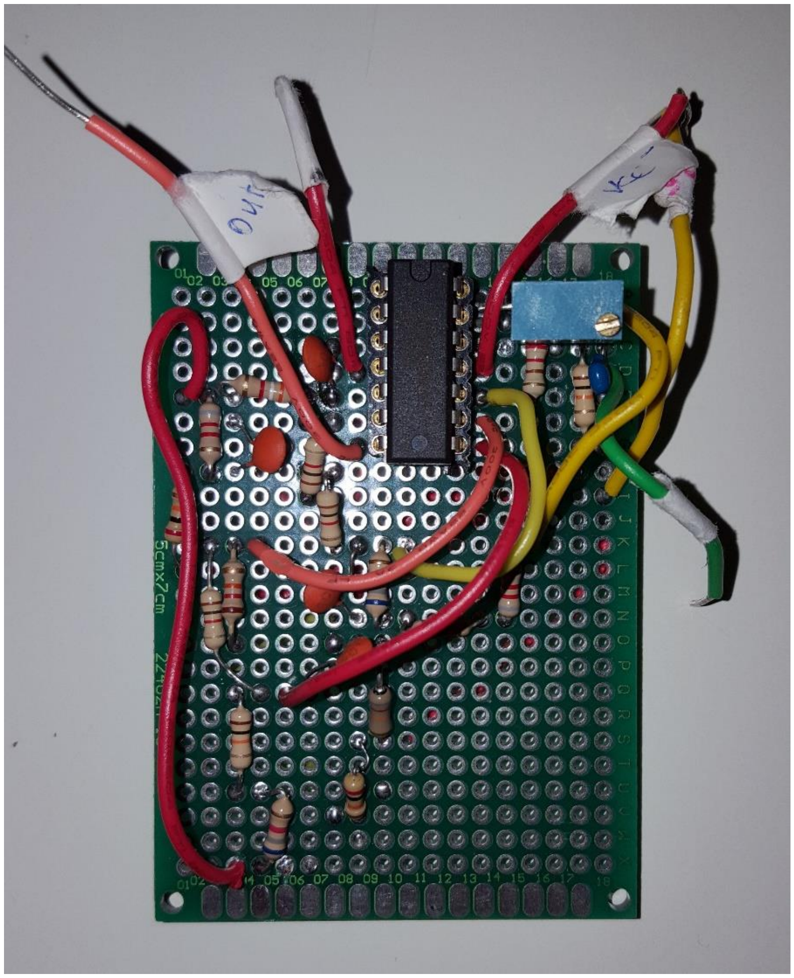
A 100 mV 13 kHz sine wave from the function generator was the input to the gain and LPF stages. While the output of the second gain stage was probed, the oscilloscope measured 2.984V, as shown in figure 19. This showed that the cascaded gain stages had a gain of 29.496 dB.

Figure 19 Gain+LPF Output



When the output of the LPF was probed, the oscilloscope did not see a signal, which meant that the LPF stage was not working. The possible cause of the malfunction is a loose solder connection between the header pins and the PCB. Without the LPF, undesired high frequency signals would distort the range measurement. To resolve this issue, a new baseband system was built on a protoboard, as shown in figure 20. The protoboard version of the baseband system had the same performance as the baseband PCB.

Figure 20 Protoboard Baseband



Antenna Test

The measurements conducted on the fabricated antennas are summarized in the table below:

Fabricated Antenna Measurements

	Measured BW (MHz)	Designed BW (MHz)	Measured Center Frequency (GHz)	Designed f_o (GHz)	Measured S11 at f_o (dB)	Designed S11 at f_o (dB)
Antenna 1	213.575	240	5.97	5.8	-21.003	-27.9238
Antenna 2	205.535	240	5.97	5.8	-19.431	-27.9238

As shown in the fabricated antenna measurements table above, the center frequency f_o of both patch antennas shifted by 1.97 GHz. Although the center frequency shifted, the fabricated antennas could still be used because the VCO generates frequencies up to 6 GHz. In addition, the S11s at 5.97 GHz were well below the recommended S11 of -15 dB. This meant that there was very little reflection at the input of the antennas at that frequency.

Figure 21 Antenna 1 S11

Figure 22 Antenna 1 Bandwidth

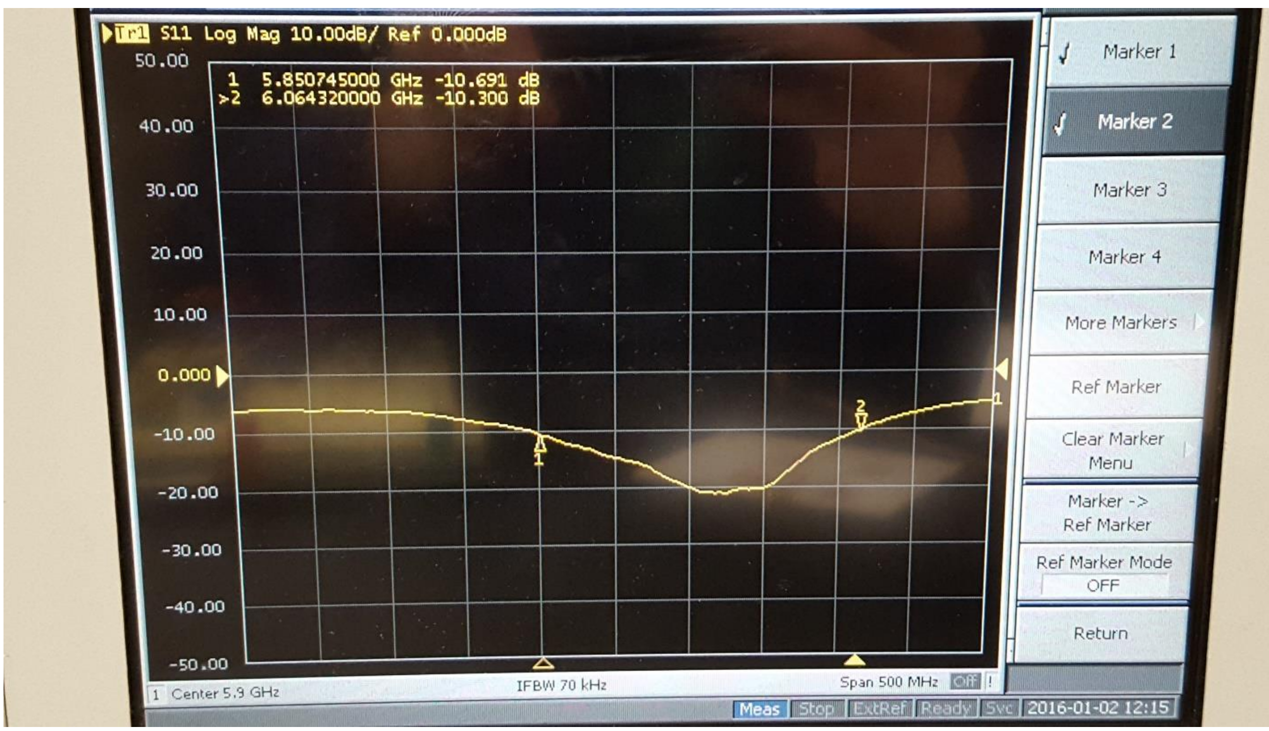


Figure 23 Antenna 2 S11

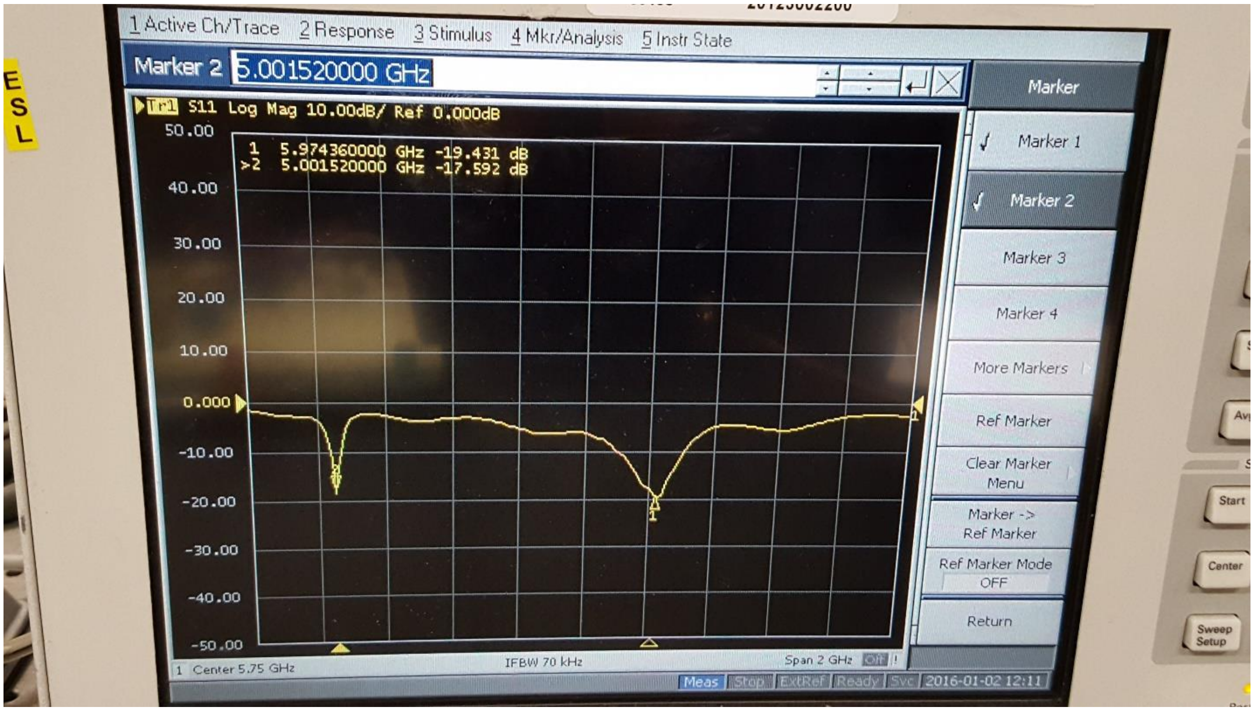
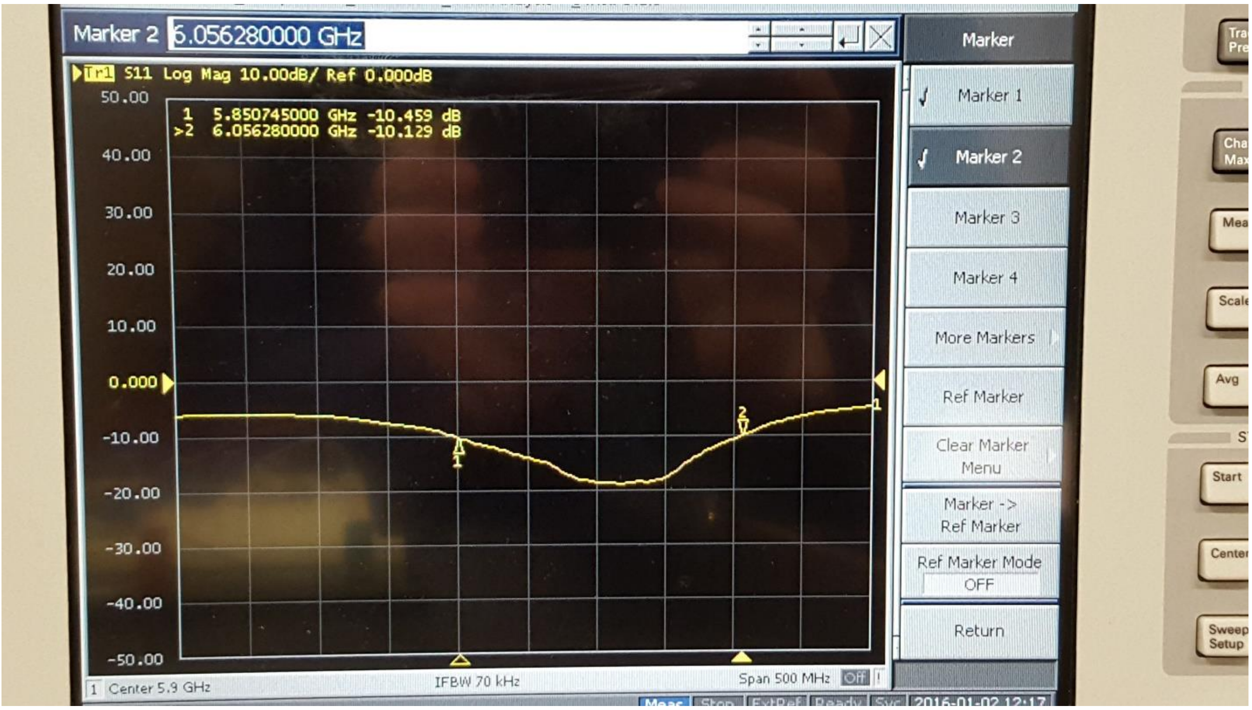


Figure 24 Antenna 2 Bandwidth



RF Board Test

The DC power consumption were measured after the RF components were soldered. The table below summarizes the current draw from each active device:

Datasheet Current Vs. Measured Current Values

Device name	Device Type	Operating Voltage (V)	Datasheet Current (mA)	Measured Current (mA)
HMC407	PA2	5	230	318
AVA-183+	PA1	5	166	143
HMC431	VCO	3	27	31
PMA3-83LN+	LNA	5	60	62
		Total Current =	483	554

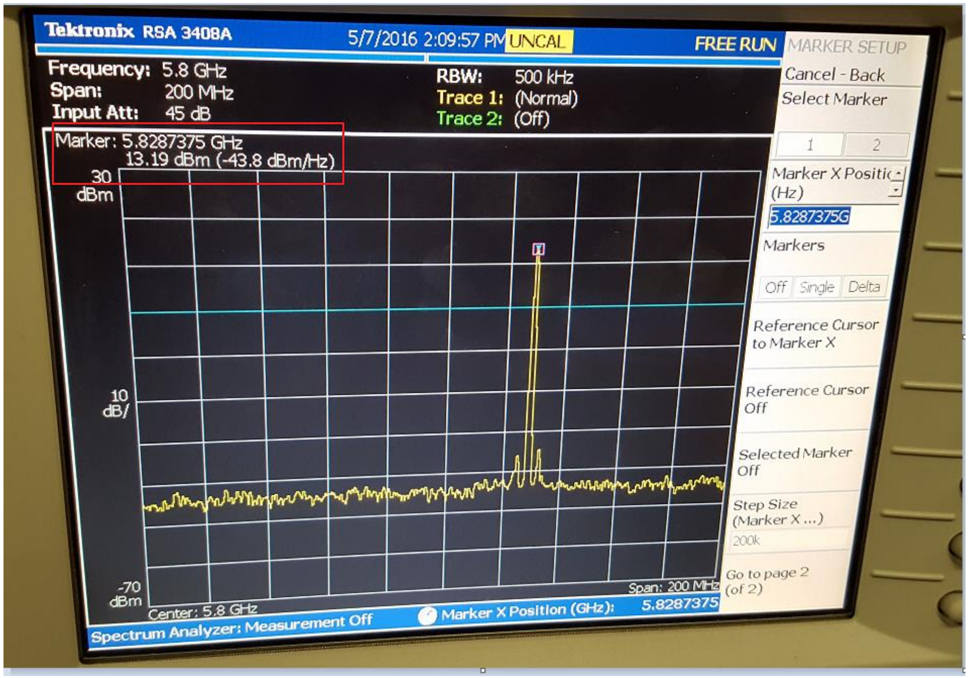
The table shows that the measured current was 71 mA greater than the sum of the currents listed on the datasheet. This error was most likely caused by the HMC407 power amplifier, which drew much more current than usual. Since the power amplifier already consumed 1.15 W of power, it got hot very quickly, resulting in more current draw.

Despite the greater than usual current draw, the other three active devices did not experience a higher than usual current draw.

After the DC power was measured, the transmitter's output power was measured. With the VCO set to output a 5.8 GHz signal, the spectrum analyzer showed that the output power was 16.19 dBm, a 7.41 dB drop from the theoretical measurement. There were many sources of this power loss, including:

- More loss in the RF components than the datasheet listed
- Transmission lines were not completely matched to the input and output ports of the RF components, since they were all the same widths.

Figure 25 Spectrum Analyzer Measurement



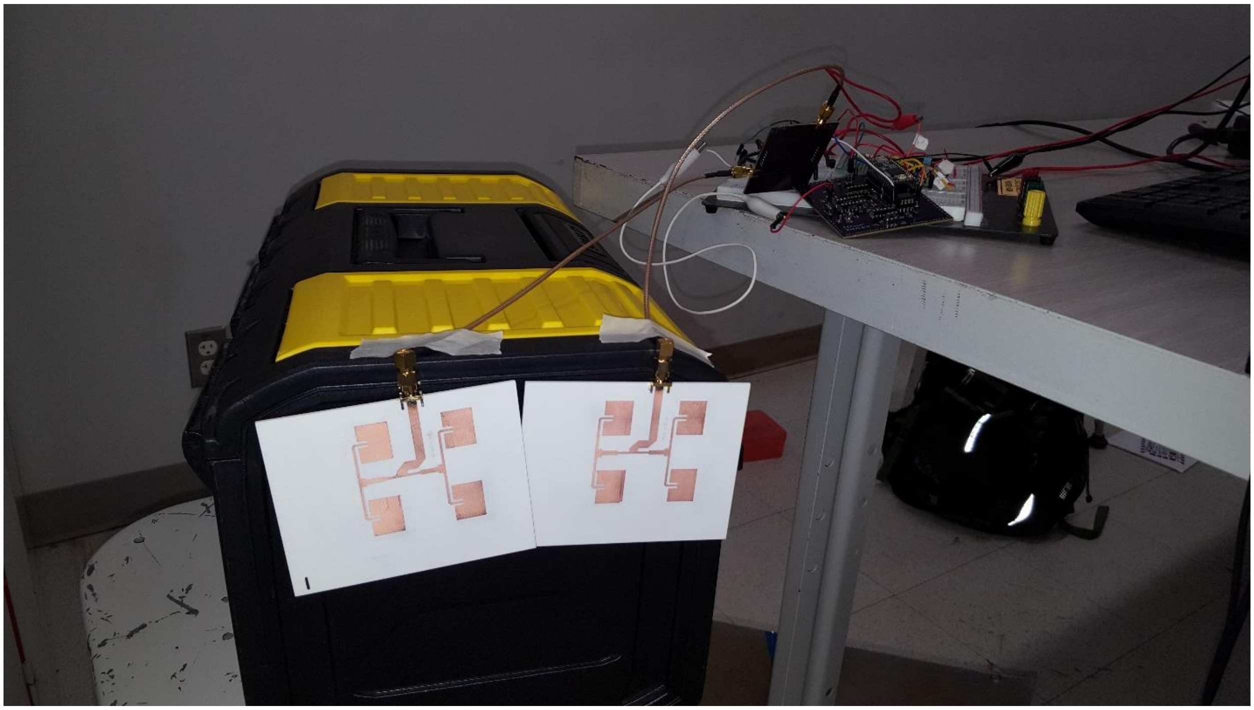
NOTE: a 3 dB attenuator was connected to the output port of the RF board to help prevent overloads.

Power measurements of each individual amplifier was not possible because they could not be probed. Although an RF probe could be used, it would not be accurate because the air attenuates the signal power. Even though there was a 10 dBm loss in power, it was an indication that the transmitter worked, and this was still enough output power to make range measurements.

Range Measurement

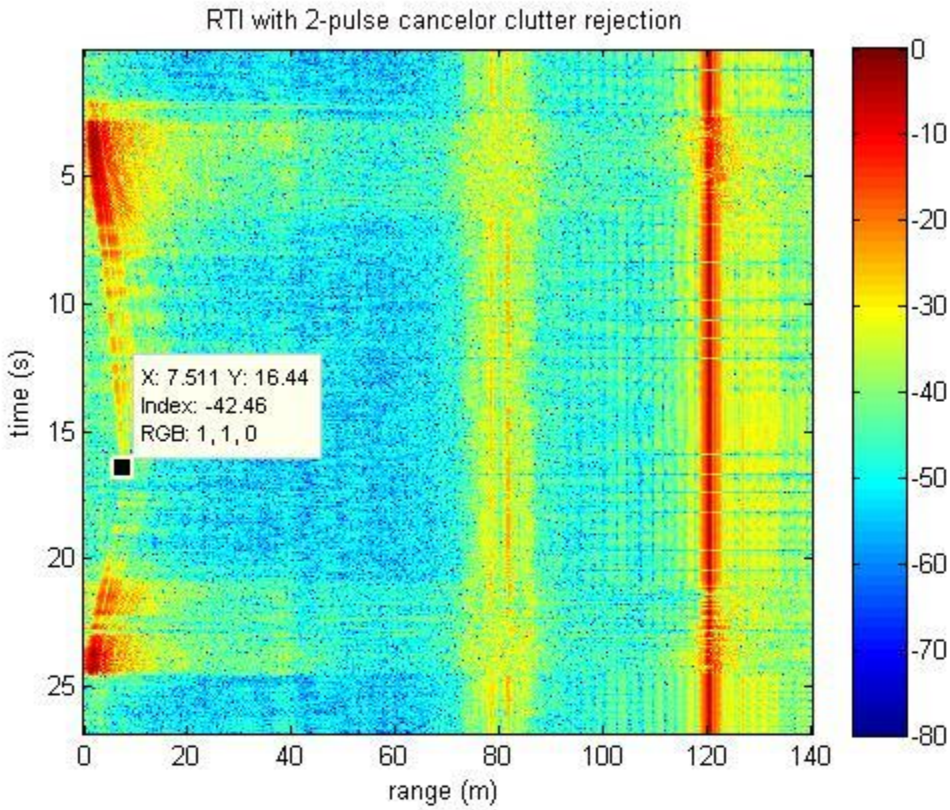
The measurements were taken at a maximum distance of 20 feet (6.096 meters), and the object was a square aluminum sheet approximately 15 square inches (571.5 cm^2).

Figure 26 Measurement Setup



The measurement began with the aluminum sheet less than 6 inches away from the antennas. When the data collection started, the sheet was moved slowly away from the antennas until it was approximately 20 feet away, and then walked slowly back toward the antennas.

The generated WAV file was processed using the MATLAB code, and the resulting plot was generated:



The plot shows that the radar detected the sheet moving away from the antennas and coming back, indicating that the radar can detect objects at least 7 meters away. The range intensity at the 80 meter and 120-meter range were the result of signals reflecting off the objects inside the room.

Conclusion

Our radar was successful but had some flaws. The patch antennas' center frequencies were shifted, resulting in a lot of reflection at 5.8 GHz. A combination of the trace's impedance mismatch and loss in each RF component resulted in the attenuation of the output power. The LPF on the baseband PCB did not work. Although there were flaws, our 5.8 GHz radar system was able to successfully detect an object moving away and toward it.

Recommendations for Improvement

The first thing to improve is to adjust the patch antenna dimensions to shift the center frequency to 5.8 GHz. This improvement will reduce the amount of signal reflection and maximize the power delivered to the antennas.

The baseband PCB could be improved by making the overall board area smaller and eliminating as many cross traces as possible. Rearranging the traces will eliminate the possibility of baseband components malfunctioning or performing in an unexpected manner. The redesign would also make it possible for the baseband PCB and RF PCB to stack on top of each other.

The code used to perform the signal processing could be modified to limit the range of the plots to 55 meters instead of 140 meters. Other signal processing techniques could be used to further reduce the undesirable signals and enhance the visibility of the desired signal.

Suggestions for Future EEC 134 Students

EEC 134 had a good setup which helped students to come up with their own designs using the materials provided. However, we have some suggestions that could improve the course:

- During the first quarter, the labs should be done faster, so the teams can start working on their radar system earlier.
- A rough guideline can be provided to the groups for quarter 2, so team members can work on their designs earlier and see whether they are falling behind or not.
- Some of the tutorials (including PCB design) can be provided earlier than quarter 1 (maybe in summer), so students can start earlier learning the software before fall quarter. Instead, in fall quarter, students can work on improving their skills while designing their system.
- Even though this is an RF systems senior design, students should also be provided with more guidelines/tutorials on the signal processing aspect of the project (for instance a detailed explanation of MIT sample program on Matlab can be provided to the students).
- The lectures during the first quarter should be longer, so more concepts can be taught to the students since this is a fairly new concept for some seniors. This will remind students that they need to present technical material in a clear format.
- During the senior design information session, a list of skills needed for the course can also be provided.

A few suggestions for future 134 students:

- We recommend future EEC 134 students to start early on their component selection and PCB designs, preferably before Winter quarter.
- Also, we suggest the students to get help from the professor or the TA as soon as possible if they are struggling with a part of their project or a concept that was taught in class.
- We recommend that the students keep a record of all their measurements and results.
- One thing that helps a lot is to start writing the app notes and the final report early (maybe the 7th or the 8th week).

- We recommend learning how to solder using the hot plate. It will make soldering small SMD components very quick and easy. Be careful about the temperature. Certain components have a certain maximum heat tolerance and can burn out if the hot plate is too hot.

Acknowledgements

We would like to acknowledge Professor Xiaoguang “Leo” Liu for providing a great learning opportunity and giving feedback on the improved design.

We would also like to acknowledge Hao Wang for answering all of our questions and assisting in the patch antenna design.