Steerable Microwave Beam Phased Array

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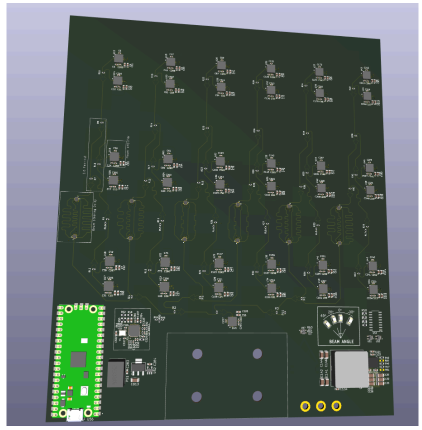
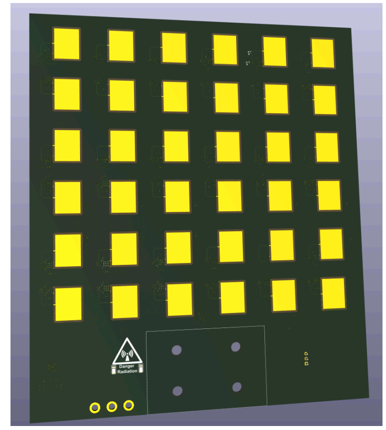
Status: In design





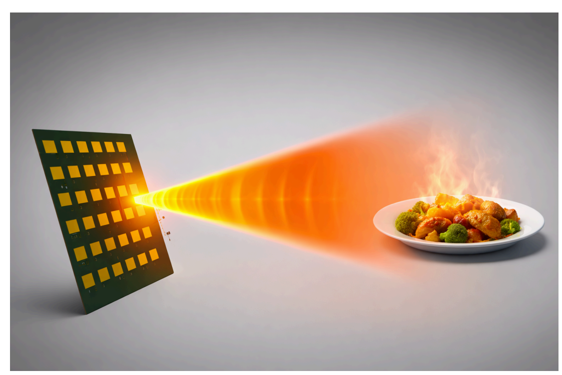
1. Project Overview

This project explores the design and construction of a steerable microwave phased array capable of delivering a tightly focused beam of microwave energy toward a target. This PCB was designed using Kicad and I intend to have it fabricated by PCBway once I secure funding or a sponsorship to bring it within a reasonable budget for a solo hobby project.

1.1. Purpose

The purpose of this project is to develop and improve my technical skills in areas that excite me, all while building a cool project that will show flashy, mind-bending results. The system serves as a science demonstration platform that reveals the power and elegance of microwave circuit design, phased arrays, and high-frequency PCB engineering. The core concept is to electronically steer RF energy without any moving mechanical parts, using phase control across an array of patch antennas.

1.2. Key Results



A successful project will have the following results:

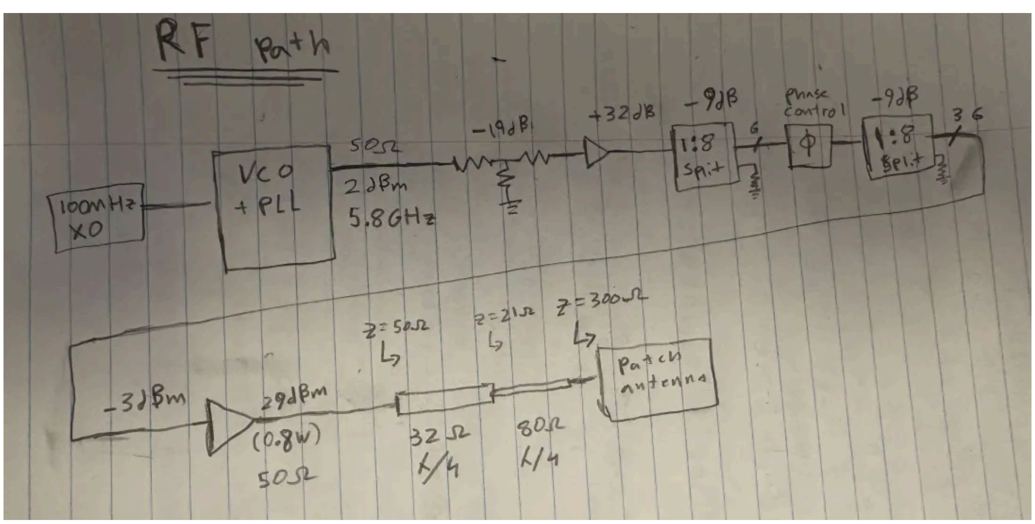
- Delivers focused microwave energy across a distance
  - heats up food, illuminates LEDs across a room
  - 50-150 Watts of radiated energy
- Focuses energy beam as tightly as possible
  - ~17° beam waist or 0.5m diameter at 2m
- Implementation of phased-array beamforming
  - Steers over a range of 75° in 1 axis
  - 4 programmable angles
- Extra things to show off (stretch goals)
  - Plasma generation inside noble gases
  - Recover radiated energy using a receiver antenna array (wireless drone charger?)

2. System Architecture

The beam is formed using a phased array of microstrip patch antennas. Each antenna element is driven with controlled phase offsets, allowing constructive interference in a desired direction and destructive interference elsewhere.

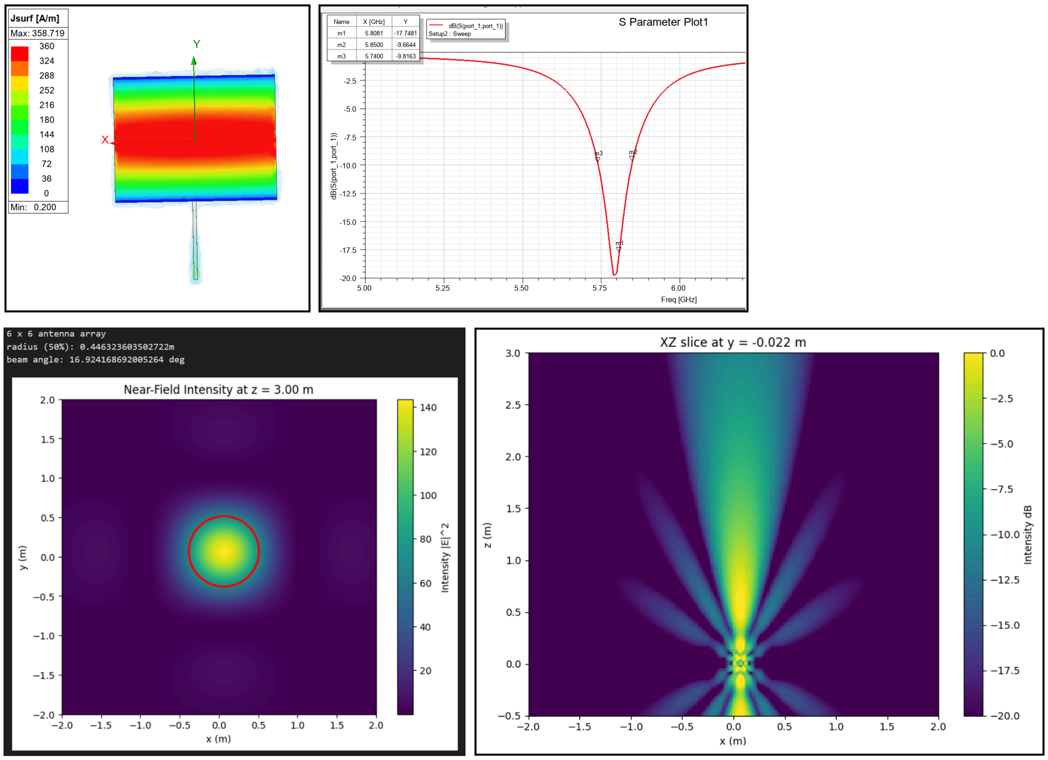
Core blocks include:

- RF signal generation
- Power amplification and attenuation
- RF splitting network
- Phase shifting network
- Impedance matching and length tuning
- Patch antenna design & array layout



3. Design Process

The design process involved lots of simulation. I used **Ansys HFSS** to optimize antenna shape, tuning, and impedance matching. I used python to simulate the array's beamforming characteristics and beam steering.



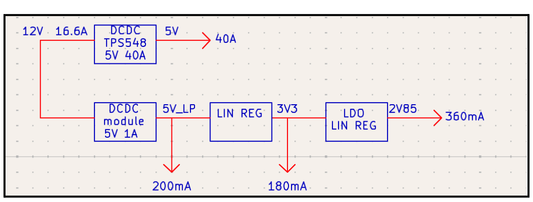
Simulating the beam from my array using python reveals a 3dB beam dispersion of 17 degrees.

3.1. Schematic design

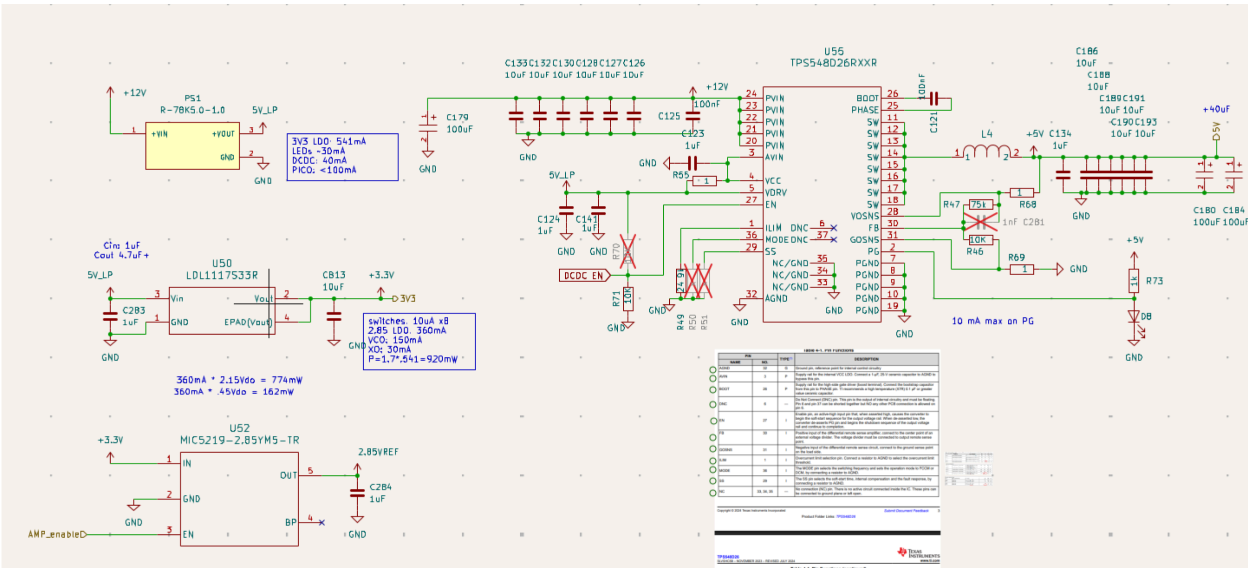
Below I show some of the core blocks in the schematic design.
The full schematic can be seen here

3.1.1 Power Distribution Network

To supply the power to the power hungry RF amplifiers, I'm using a DCDC switching regulator from TI. This chip can convert 12V to 5V at 40A. The onboard DCDC converter adds complexity as opposed to having an off board supply, however to ensure a clean 5V without losses from cables or connectors I decided this was the best option.

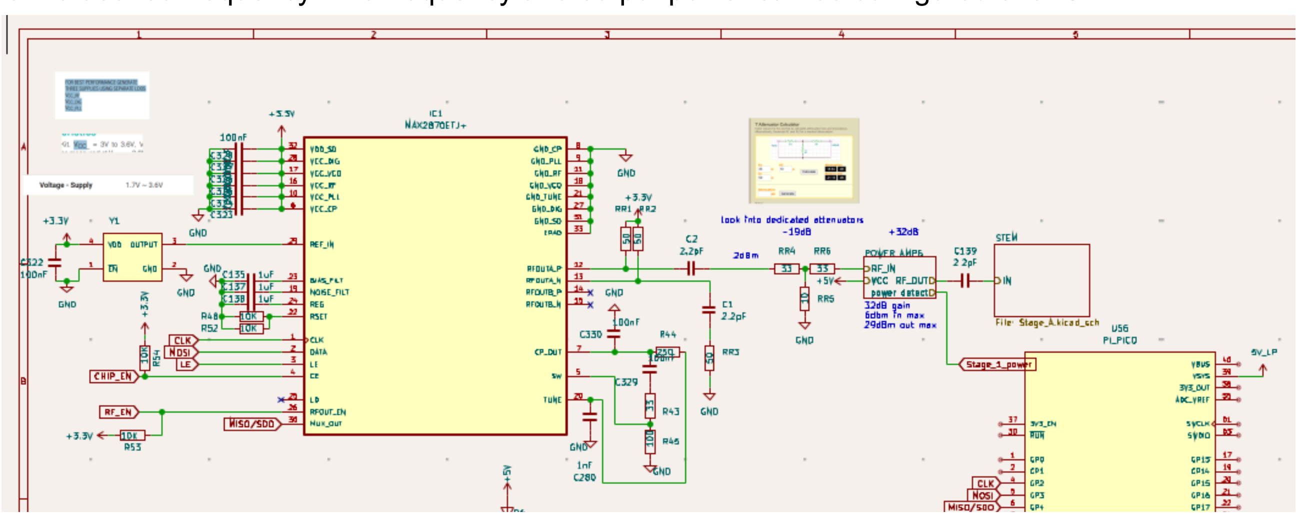


To power the rest of the circuit I used a separate 5V 1A DCDC power module. This allows the control circuits to not be affected by fluctuations caused by the power amplifiers, as well as adding a current limit so that short circuits in this rail don't violently explode.



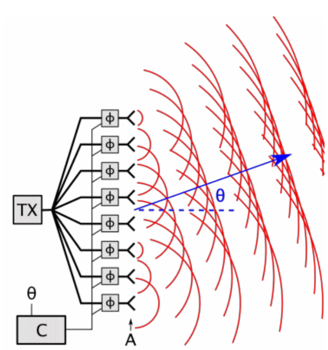
3.1.2 RF Generation

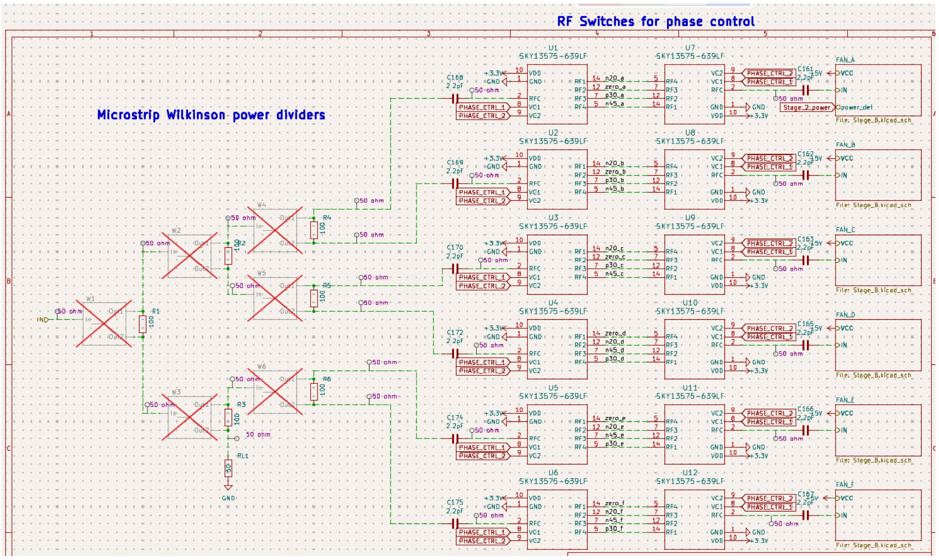
Creating a 5.8GHz signal is not trivial. I found a chip from Analog Devices: MAX2870ETJ+ that is a PLL + VCO frequency synthesizer. It is fed with a precision 100MHz signal and multiplies it to the desired frequency. The frequency and output power can be configured over SPI



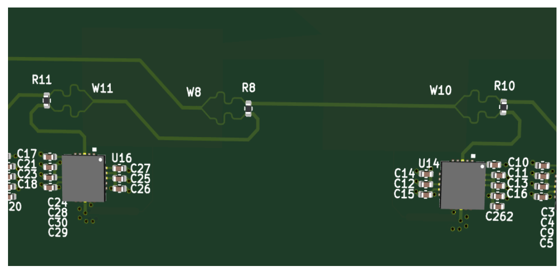
3.1.3 Signal splitting and phase adjustment

By adjusting the phase of the signal at the antennas, the focus of the antenna array can shift. For example, delaying the left antennas more than the right ones causes the wavefront to steer to the left.

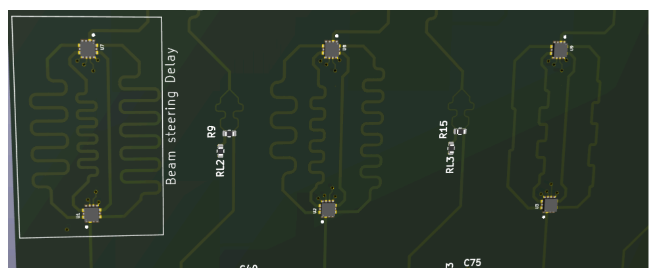




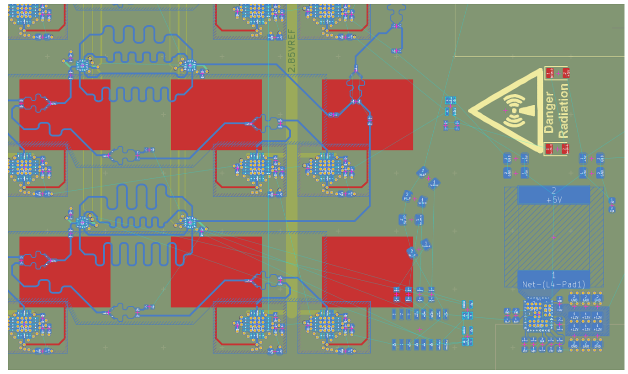
I use **Wilkinson power dividers** to split the RF signal into 6 for phase control, then 36 for final amplification. This type of signal splitter maintains matched impedance in the signal lines as well as providing isolation between the outputs.



Phase control is achieved using SP4T switches to select the appropriate delay path for the chosen beam steering angle. The chosen steering angles in degrees are: 45, 20, 0, -30. This provides 75 degrees of steerability, and 4 unique angles.



4. PCB design



- 6 layers. 170x200 cm
- Impedance controlled
- Component count: 398 (34 unique)
- PCB cost ~$370
- Parts cost: ~$400
- Assembly cost: ~$170

4.0 Cost Justification

Cost is an important factor for me in my hobby projects, but it is also important that I build a project that I can be proud of. There were many decisions that I made that increased the cost considerably including upgrading from a 4x4 antenna array to 6x6, increasing the layer count from 4 to 6, Making use of impedance control, and upgrading to HASL for predictable thickness on the antennas.

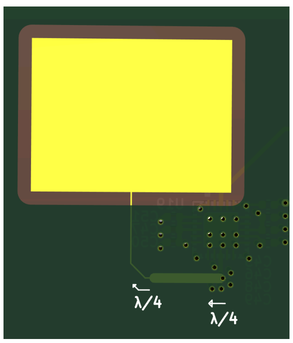
4.1 Stackup

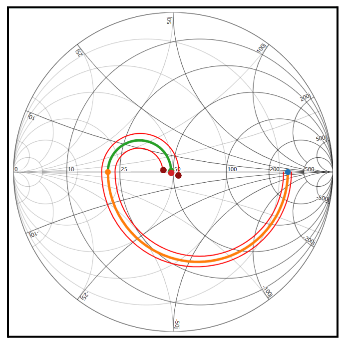
The following stackup was chosen using the 7628 dielectric material because of its affordability, low loss tangent, and its thickness - allowing for wider transmission lines, and less loss for high power signals. This also performed well in antenna simulations - giving the best bandwidth. This stackup was then used to calculate trace width for transmission lines, and propagation delay for the length tuning elements.

layer	Material	H (mm)	H (mil)	Er @6GHz	LossTg
F.Mask	Mask	0.010	0.39	3.3	0
F.Cu (antennas)	copper	0.035	1.38		
Dielectric 1	7628	0.210	8.27	4.38	0.0175
In1.Cu (GND)	copper	0.015	0.59		
Dielectric 2	core			~4	
In2.Cu (SIG)	copper	0.035	1.38		
Dielectric 3	7628	0.210	8.27		
In3.Cu (PWR)	copper	0.015	0.59		
Dielectric 4	core				
In4.Cu (GND)	copper	0.015	0.59		
Dielectric 5	7628	0.210	8.27		
B.Cu (RF SIG)	copper	0.035	1.38		
B.Mask	Mask	0.010	0.39		

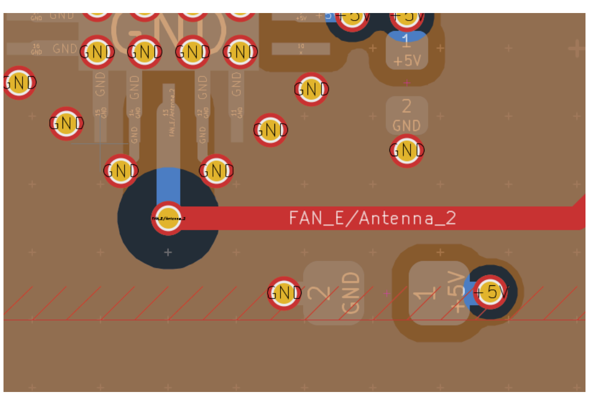
4.2 Microstrip Impedance Matching

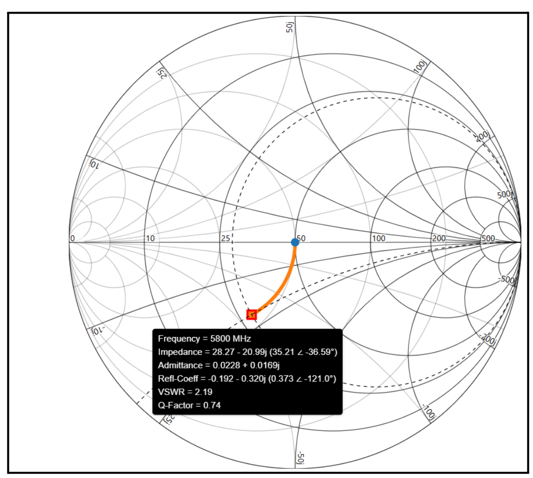
Quarter wavelength transformers are used to match the ~300 ohm patch antennas to the 50 ohm amplifiers. QWT was chosen over stub or lumped element matching due to its robustness: 20% inaccuracies in either the length or line impedance still lands with a manageable 10dB return loss. (this is now unnecessary with the new stackup allowing for antennas being 50 ohm)





Vias can cause impedance mismatch. The vias in my board are 1.6mm tall from the top to bottom layer. This is about 23 degrees of electrical length. Simulating my original via design (using Sierra via impedance calculator) revealed ~20 ohm vias resulting in a considerable impedance mismatch: increasing the VSWR above 2. Changing the via's parameters (increasing the antipad size). Allowed me to tune the via impedance to 50 ohm: mitigating the mismatch

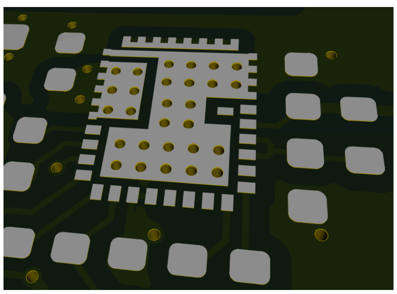




4.3. Thermal Considerations

The chosen microwave power amplifiers (SE5023L-R) are designed for telecommunication, and therefore have high linearity implying low efficiency. I estimate that using these amplifiers on a single tone at 1-4W output power, will result in efficiencies of ~25-35%. That means up to 7W of waste heat per amplifier: that's 36W/cm^2. The DCDC converter produces 200W at 96% efficiency. That means up to 8W of heat generated.

This heat is mitigated through generous via stitching in the thermal pads, and large ground and power planes to spread out the heat quickly. The device will not be able to operate at max power for extended periods of time, but I hope to achieve bursts of up to 30 seconds.

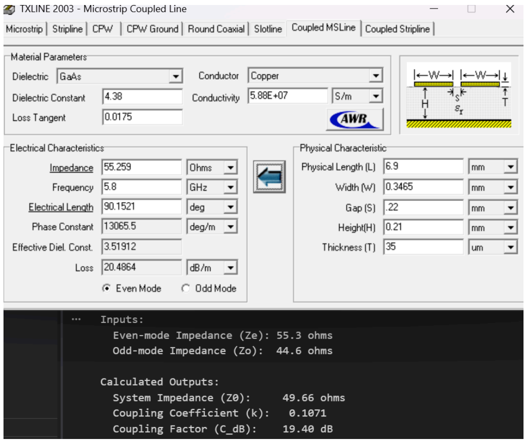


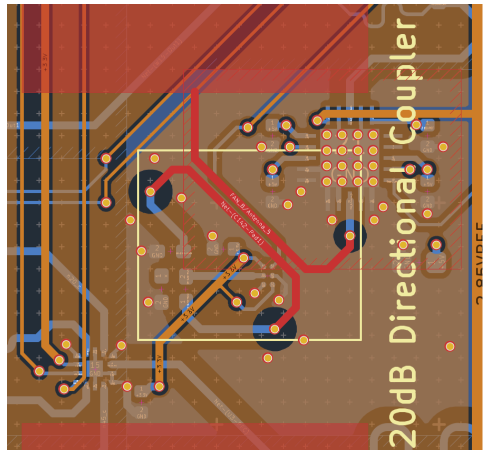
5. Testing

The biggest risk in this project is the antenna tuning. I need to trust the PCB manufacturer's material tolerance (dielectric constant, and loss tangent) as well as my accuracy in modeling them in Ansys. (also putting 36 antennas so close to each other likely affects tuning.) Unfortunately, I do not own a VNA rated for 6GHz, and the cheapest trustable VNA I could buy us upwards of $1100 CAD

5.1. directional coupler

My solution to verifying antenna tuning is to use a directional coupler between the final stage power amp and the antenna. This microwave circuit can sniff the transmitted and reflected power independently which allows me to calculate VSWR.





6. Technical Challenges

This project was full of technical challenges from start to finish. Many were predicted but many were unexpected.

- Sourcing RF components that operate reliably at the target microwave frequency (And which are within my budget)
- Managing PCB dielectric tolerances and losses affecting antenna tuning & electrical length
- PCB best Thermal considerations under higher power levels

Most resistors and capacitors do not provide documentation of performance at high frequencies - especially as high as 5.8GHz. Below shows impedance vs frequency charts for resistors chosen for the T attenuator, and capacitors chosen for DC blockers. Murata's "sim surf" website was very handy for choosing appropriate capacitors.