Index

Project Description

This project aims to demonstrate short range wireless power transfer using beam steering to select the direction of power. A phase array of patch antennas will be used to achieve this goal, and a SP4T switch will be used to control which receiver will be selected. If the project is done successfully an LED at each location should be able to be powered from a distance of around a meter.

1 Global Considerations

1.1 Environmental (Josh Kusbel)

From an Environmental standpoint, this specific project has little impact. However, on a larger scale, there begins to be more concern. The possibilities that wireless power transfer provides from a commercial standpoint are numerous, however, with these given possibilities there are risks involved as well. Companies such as Epirus are seeking to militarize technology such as this, which poses certain environmental threats. When dealing with wireless power transfer and highly directional beams, a great amount of power is required to generate such goals. As well as the amount of power required to generate such beams, wireless power transfer can cause radiation over large distances. Therefore, it is paramount to think about the impact that large scale versions of this device could have. If chemical treatment of RF boards is to be implemented in a large scale production then it will also be necessary to adhere to waste regulations in the manufacturing process.

1.2 Health and Safety (Nick Loeffelholz)

Health and Safety is always a paramount concern when talking about anything to do with electricity. In our case, we dealt with the wireless transfer of power over a small distance. It is imperative that the group was acquainted with the risks involved in the wireless transfer of power. Therefore, safe lab practices have been strictly enforced when implementation, testing, and demonstrations were occurring. To guarantee the safety of the team and of the general public, various standards around RF design exist including 47 CFR 1.1310 from the FCC and IEEE Std C95.7-2014 [1]. This also applies to any future mass manufacturing as the the manufacturing process requires the use of chemicals and/or lasers which require their own safety regulations.

1.3 Social and Cultural (Josh Kusbel)

There are very few social and cultural ramifications for this specific project. However, the future commercialization of a product similar to this could change the way that devices are powered and limit the number of wires that are currently used in our homes, work spaces, and even cars. Additionally it has been brought to our attention that the successful implementation of our technology is heavily sought after by military contractors seeking to implement UAV technology.

1.4 Ethical and Professional (Josh Kusbel)

From an Ethical and Professional standpoint, the possibilities of this type of technology being used for militarized purposes is something to consider. Ethically, the possibilities of any design being used for military purposes is something that all engineers have to take into account. As mentioned in the environmental considerations section, companies such as Epirus are already using the idea of wireless power transfer for military purposes. However, when designing a much smaller scale power transfer model such as ours, the uses are much different, and can be thought of in a much more commercialized context. Such applications could include things as small as sensors within a vehicle that can now be charged and relay data on internal components that could not previously be done. Other applications could be as simple as a transmitter that could be plugged into a wall outlet and subsequently power devices within your home such as a television.

2 Detailed Design

The design of this project can be broken down into five major components. The first part of the project is the switch, which feeds an RF signal at 2.4GHz, into a 4x4 Butler matrix. The Butler Matrix then outputs into RF Power Amplifiers to increase the output power and overall gain of the system. Once the signal is passed through the amplifiers it reaches the antennas which create a highly directional beam towards the desired receiver. The image in Figure 1 shows a more detailed schematic. The FieldFox VNA will be used to generate the 2.4GHz signal.

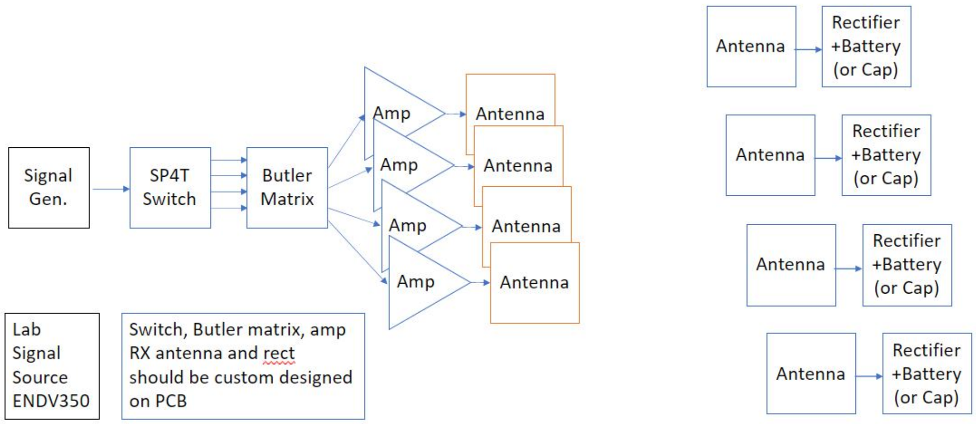


Figure 1: Block Diagram of Beam Steering Design

2.1 Switch (Josh Kusbel)

The switch that will be used is a single-pull, four-throw. This means that the switch receives a singular RF input, then has four possible output ports. The switch varies between each output port given some form of user input, which in this case, will be a button. depending on which button is pressed, the switch will go to that particular output port. When the switch is positioned to a specific port, the other three become matched to a 50Ω load. When the ports are matched to the 50Ω load, they are doing so to achieve reflection, and allow for the selected output port to fully transmit. Within each of the ports there is also an Electro-Static Discharge circuit which limits the risk of a port being compromised by external sources.

The switch being used is the PE42441 with Evaluation Kit. This particular switch meets all of the requirements that are needed to function successfully in this project. The switch has low insertion loss, high linearity, and high isolation. As well as the switch meeting all requirements needed for this project, it also comes on an evaluation board, which is a fabricated PCB with the IC and SMA adaptors already mounted. With the PCB being fabricated professionally, it takes out a lot of the problems that can arise when dealing with RF components such as poor connection between the SMA adaptors. The evaluation kit also contains two extra SMA adaptors as the bottom of the board that allow the testing of the environmental conditions, and provide a better idea of how the board will function as as whole.

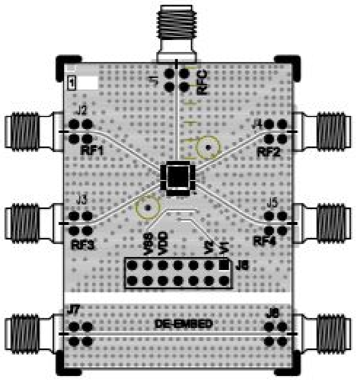


Figure 2: Top of SP4T switch evaluation kit

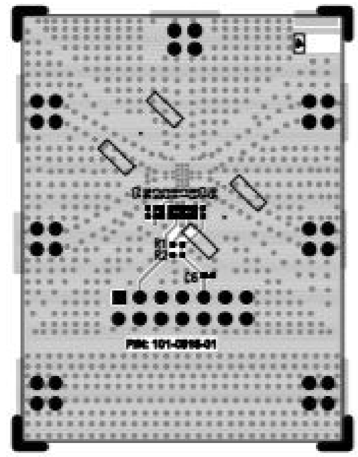


Figure 3: Bottom of SP4T switch evaluation kit

Figures 2 and 3 contain images of the evaluation kit that the switch is mounted on. Figure 2 shows the top of the evaluation kit with the control pins that take the input voltage and ground. Figure 3 shows the bottom view of the evaluation kit, and shows the solder points for the SMA adaptors and control pins.

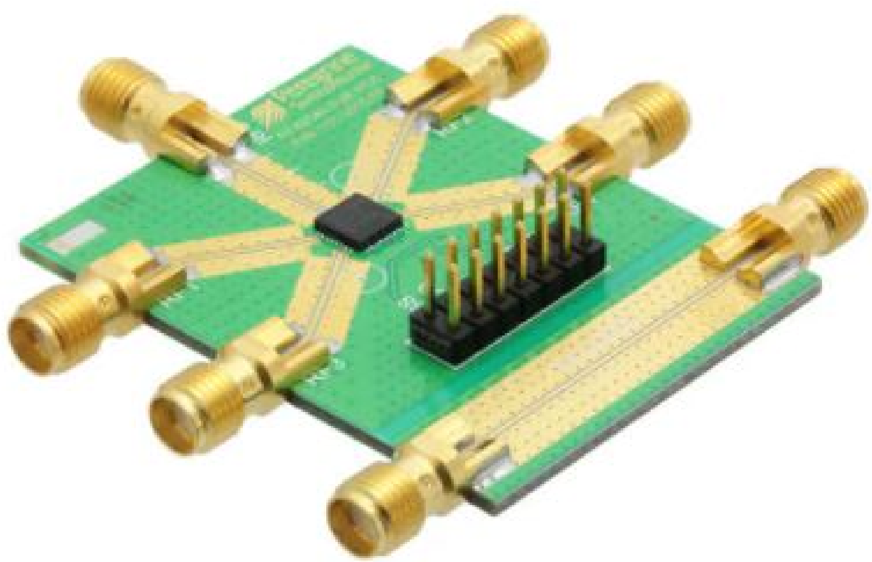


Figure 4: Three Dimensional rendering of SP4T Evaluation Kit

Finally, Figure 4 shows the actual evaluation kit that will be used in the actual device. The four output ports are shows on the left and right sides of the board. The top adaptor is the input port that will be connected to the signal generator via SMA cable. The four output ports will be connected to the butler matrix via SMA cable. A separate PCB will be connected to the control pins with buttons to select the output port.

To control the desired output port, 3.3V will be supplied to the VDD pin on the SP4T test kit evaluation board. Then, following the truth table provided in the data sheet, the desired output will be chosen by changing the voltage supplied to pins V1 and V2. This is referenced in Figure 5.

Table 5. Truth Table

State	V1	V2
RF1 on	0	0
RF2 on	1	0
RF3 on	0	1
RF4 on	1	1

Figure 5: Output port truth table for the PE42441 Evaluation Kit

2.2 Butler Matrix (Nick Loeffelholz)

The 4x4 Butler matrix serves to shift the phase of the signal delivered to the amplifiers and subsequently the antenna array. The antenna array requires this phase shifting to perform the necessary beam steering to target our individual receivers. The design of the matrix is such that we can form 1 of 4 different beams at a given time dependant upon which port of the matrix is being used as determined by the switch. For example, When the Butler Matrix is driven by port 1, we should see a phase shift of 135, 90, 45, and 0 degrees on outputs 5, 6, 7, and 8 respectively as can be seen in Figure 6. We evaluated two possible designs for our matrix: the traditional model [2], as seen implemented later in this document, and a novel design as suggested in various IEEE research papers but specifically the paper published by A. M. Zaidi, B. K. Kanaujia and M. T. Beg [3].

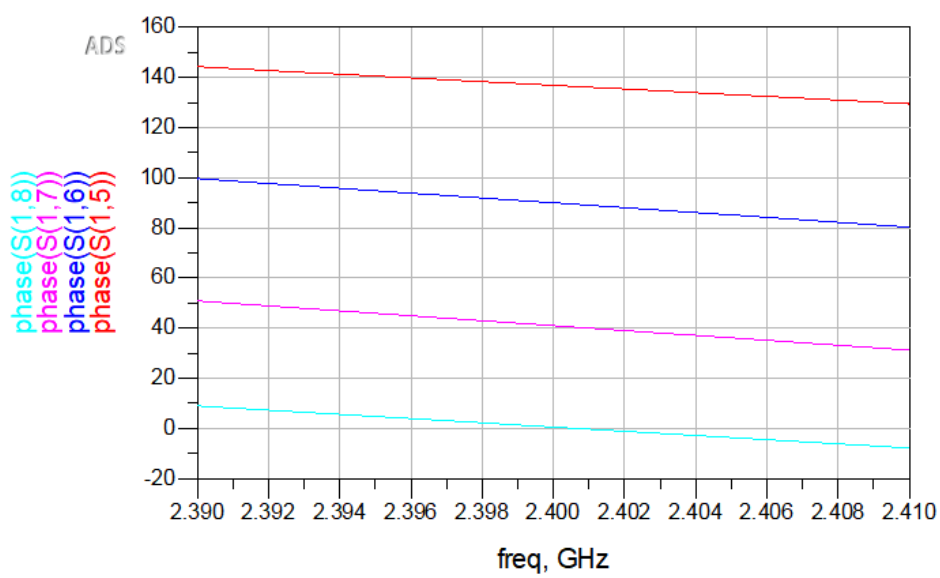
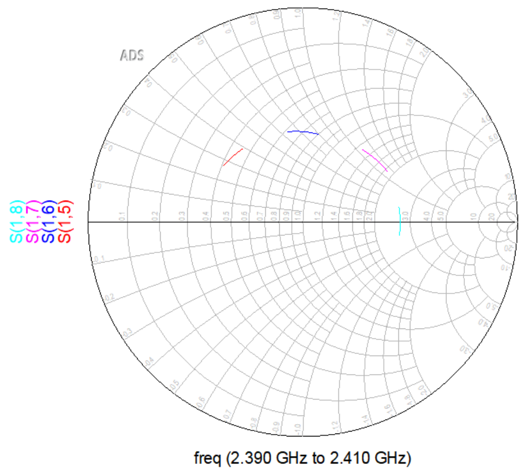
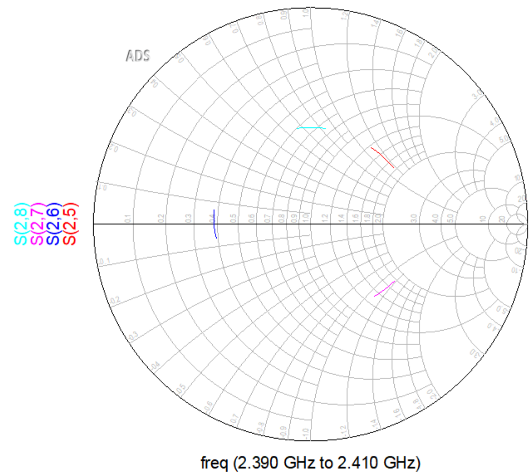


Figure 6: Graphical Representation of phase shift for Port 1 in ADS

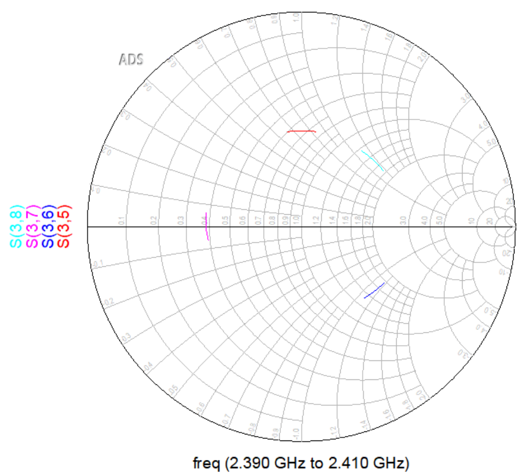
Further, the summary of the S parameters of our 8 port device can be summarized in the following Smith charts in Figure 7 as seen below. In ideal circumstances, the dB loss of the Matrix would be approximately -6dB. In our simulations in Keysight ADS the loss is much closer to -7 dB as can be



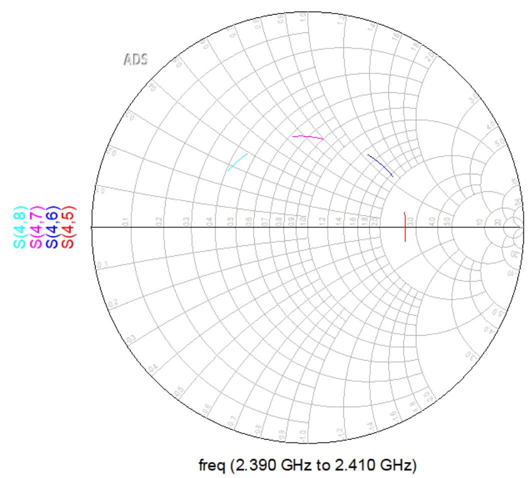
(a) S1x



(b) S2x



(c) S3x



(d) S4x

Figure 7: S Parameters

seen in Figure 8.

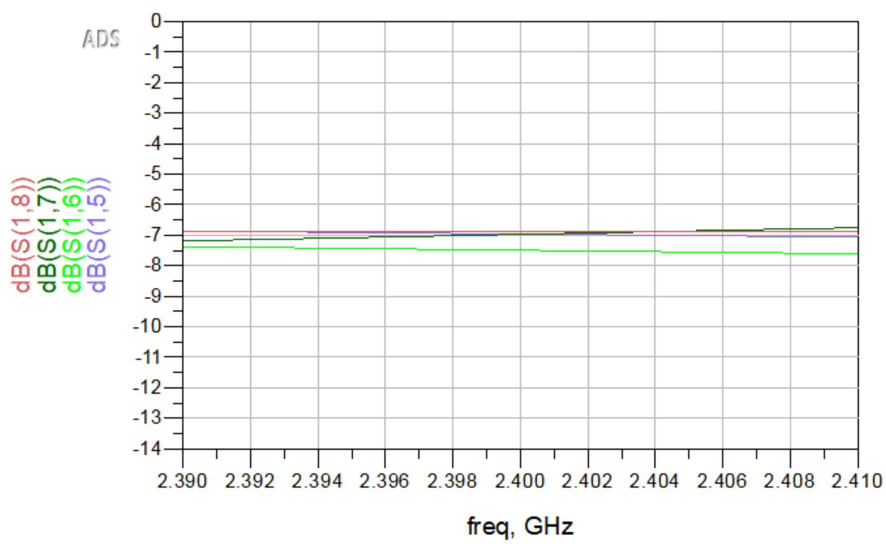
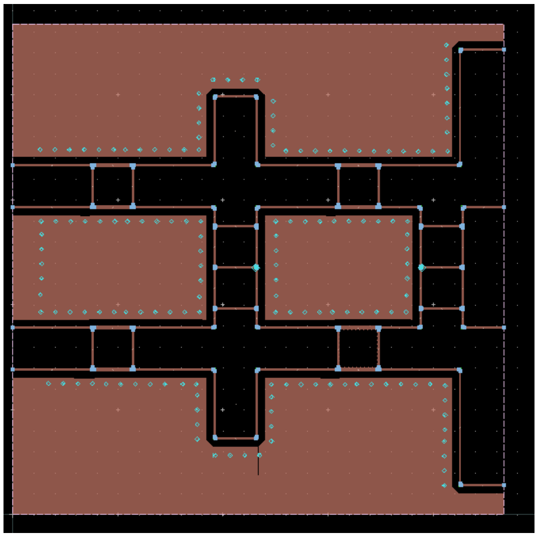
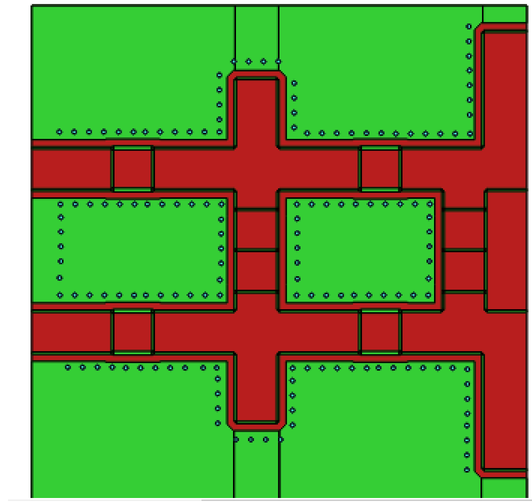


Figure 8: Loss of the Butler Matrix near the operating frequency

We then printed the Butler matrix in RO4350B using 1 oz copper by contracting with iPCB. For our outsourced board we have added the additional details of copper pouring with stitching vias to further improve our isolation and reduce unwanted noise from the environment in our signal as can be seen in Figure 9



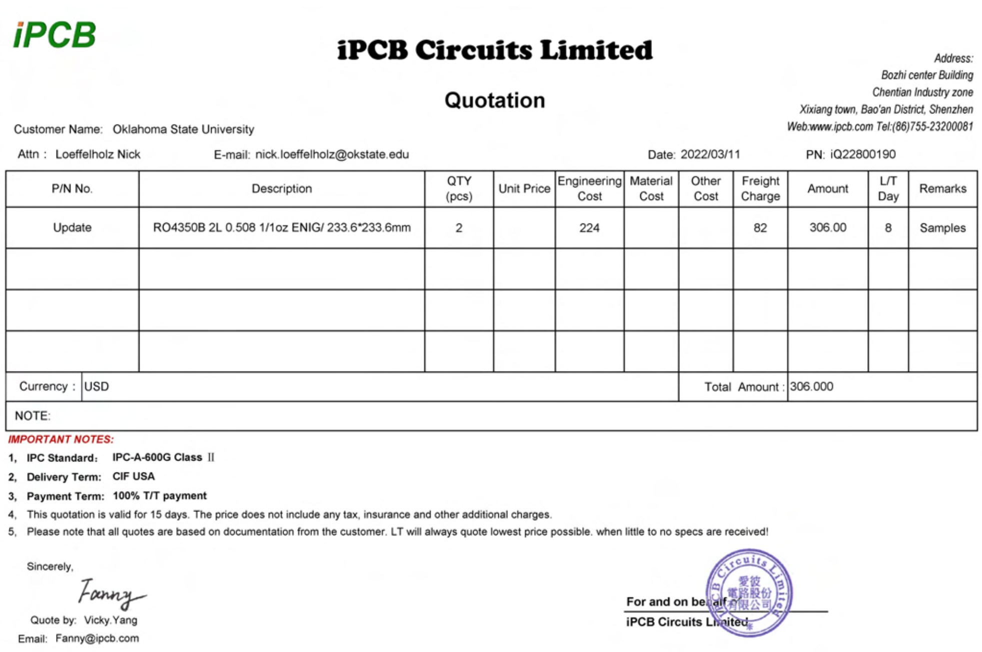
(a) Layout with Pour and vias



(b) visualization of Gerber files

Figure 9: Layout for Outsourcing

The quote from iPCB can be seen in Figure 10.



iPCB

iPCB Circuits Limited

Quotation

Address:
Bozhi center Building
Chentian Industry zone
Xixiang town, Bao'an District, Shenzhen
Web:www.ipcb.com Tel:(86)755-23200081

Customer Name: Oklahoma State University

Attn : Loeffelholz Nick E-mail: nick.loeffelholz@okstate.edu Date: 2022/03/11 PN: iQ22800190

P/N No.	Description	QTY (pcs)	Unit Price	Engineering Cost	Material Cost	Other Cost	Freight Charge	Amount	L/T Day	Remarks
Update	RO4350B 2L 0.508 1/1oz ENIG/ 233.6*233.6mm	2		224			82	306.00	8	Samples
Currency :	USD					Total Amount :	306.000			
NOTE:										

IMPORTANT NOTES:

1, **IPC Standard: IPC-A-600G Class II**

2, **Delivery Term: CIF USA**

3, **Payment Term: 100% T/T payment**

4, This quotation is valid for 15 days. The price does not include any tax, insurance and other additional charges.

5, Please note that all quotes are based on documentation from the customer. LT will always quote lowest price possible. when little to no specs are received!

Sincerely,

Fanny

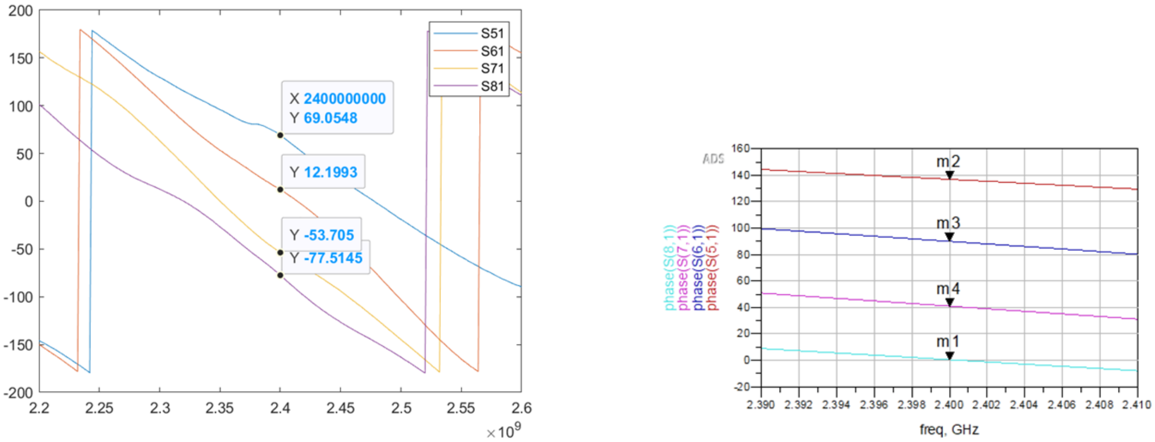
Quote by: Vicky.Yang

Email: Fanny@ipcb.com

For and on behalf of
iPCB Circuits Limited

Figure 10: Offer from iPCB

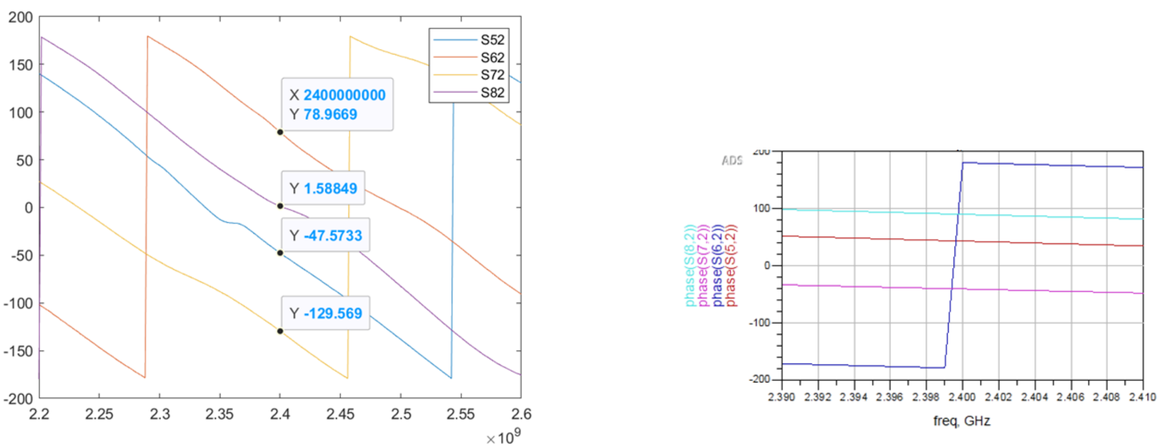
Our matrix took approximately 8 days to arrive via shipping with DHL and can be seen in Figure 15. We then tested it using the VNA to derive the phase shift across each port which we then compared with our simulated results. The comparison can be seen in Figures 11, 12, 13, and 14. Based on this data we can conclude that the phase array works within ¡ 10 degrees of the relative shift we are aiming for. With this data we could then assimilate the matrix into the rest of the project.



(a) Real values

(b) Simulated results

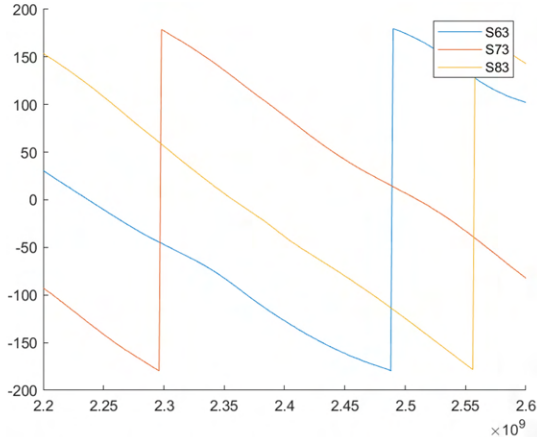
Figure 11: Phase of SX1



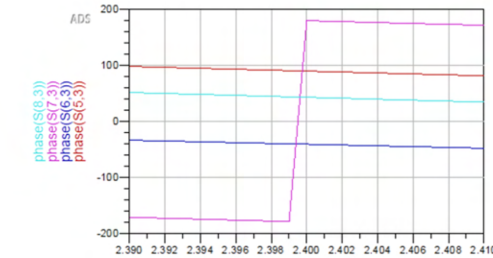
(a) Real values

(b) Simulated results

Figure 12: Phase of SX2

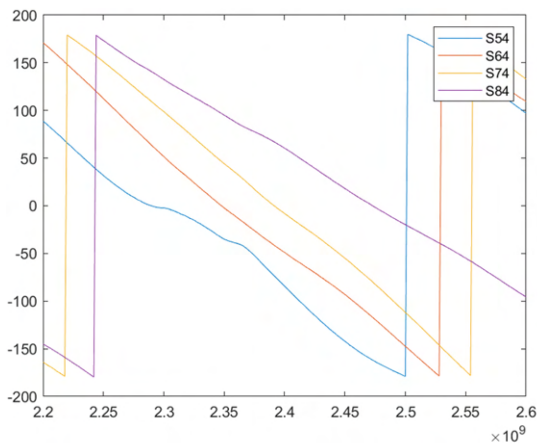


(a) Real values

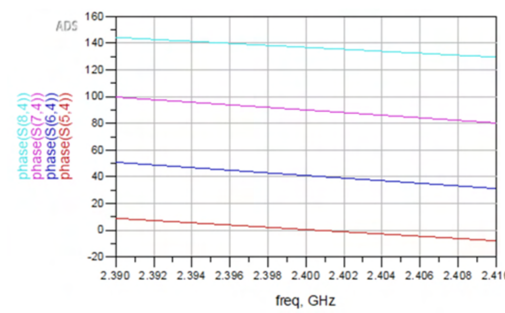


(b) Simulated results

Figure 13: Phase of SX3



(a) Real values



(b) Simulated results

Figure 14: Phase of SX4

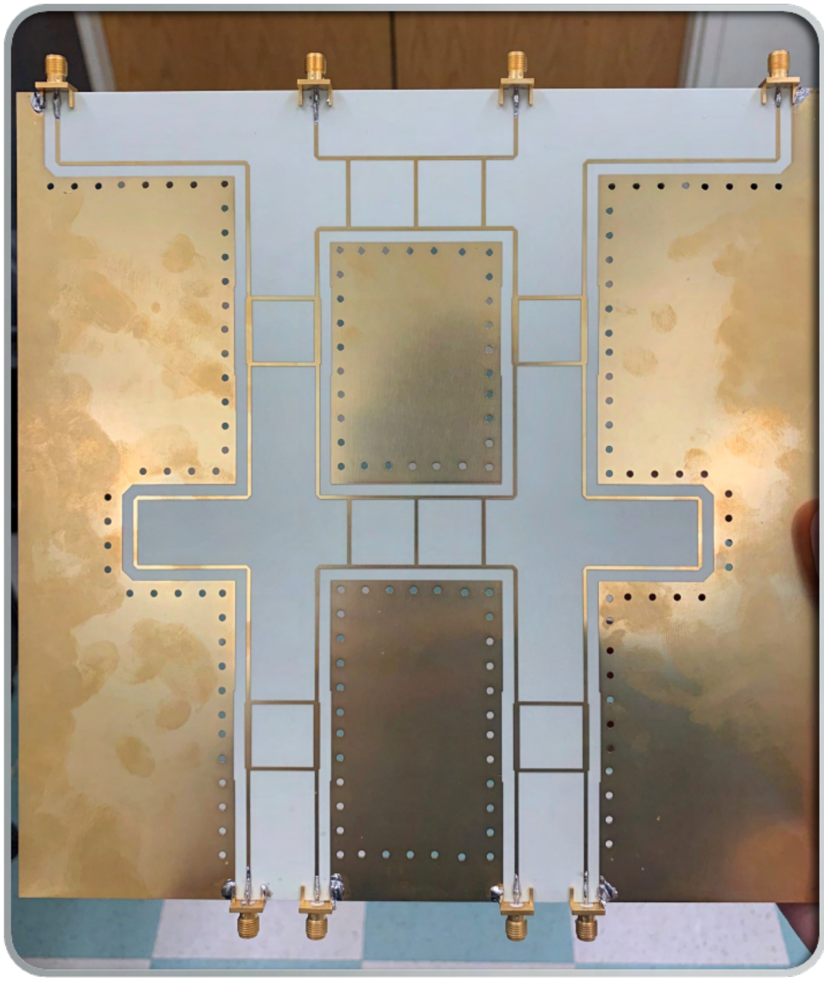


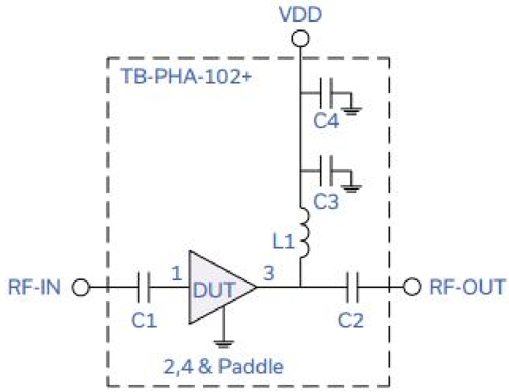
Figure 15: Fabricated Butler Matrix

2.3 Amplifier (Josh Kusbel)

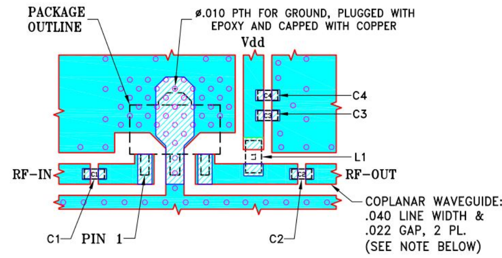
The RF signal amplification is integral to significant wireless power transfer. To achieve the desired level of power transfer, the amplifier is designed to generate around 15dBm output power, with around 20dB signal gain. To achieve these goals, several design iterations were kicked around. The first of these options was to design a Class F RF power amplifier from the ground up. The second option, and what was ultimately chosen, was to purchase an RF power amplifier IC and integrate it onto a custom made PCB.

As stated above, the initial idea for the amplifier design and integration was to design a Class F amplifier from the ground up. This option was appealing because it allowed for greater output power as well as possible integration onto the same board as the butler matrix. However, after attempting to design this amplifier, it was realized that the design and integration of such a circuit was not going to be feasible given limited knowledge in such amplifier design. Therefore, the second option of integrating an IC onto a test board was chosen.

Once the design process pivoted towards an IC integrated on a test board, the PHA-102+ RF amplifier was chosen. Then using some of the documentation provided by Mini-Circuits, the test board was designed to the specifications shown in Figure 16. These two images show the layout for the testing circuit and the integration onto a PCB.



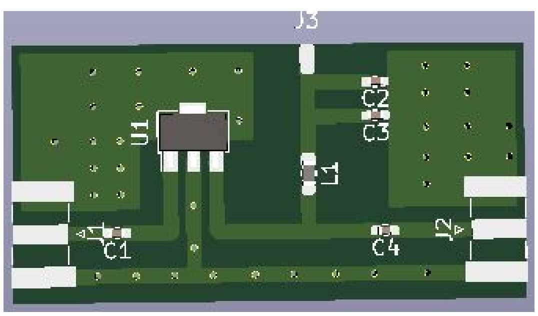
(a) Amplifier test board circuit schematic.



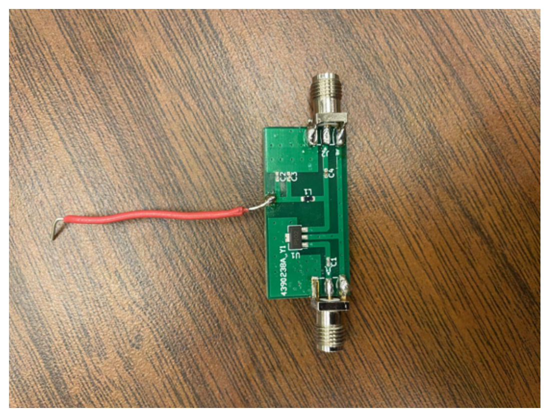
(b) Simulated results

Figure 16: Amplifier test board layout.

After acquiring the documentation represented above, the circuit could then be implemented into KiCad, and ultimately sent off to JLCPCB for fabrication. The board chosen was FR4, which while it does have drawbacks at high frequencies, 2.4GHz was still within the reasonable range of application. Figure 17.



(a) Three Dimensional rendering of custom PCB in KiCad.



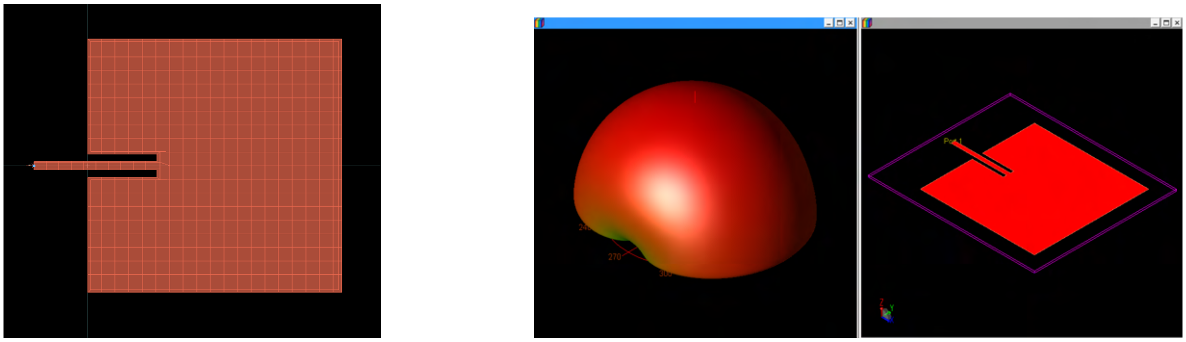
(b) Physical Amplifier Test Board with soldered components.

Figure 17: Amplifier 3D Rendering and Physical Board.

2.4 Antenna

The Antenna consists of two components, the transmitting antenna phase array and the receiving antennas. Both components consist of a base patch antenna design. The base patch design is a quarter-wavelength patch (in both length and width). Because a square patch of this dimension has an impedance of 438, an inset feedline was introduced to match the 50 impedance of the rest of the circuit.

The receiving antenna will consist of a single base patch antenna. The Antenna will have a side mounted SMA connector soldered onto the side so that it can connect to the receiver/rectifier pcb. Figure 18 shows the receiver antenna and ADS simulation at 2.4GHz.

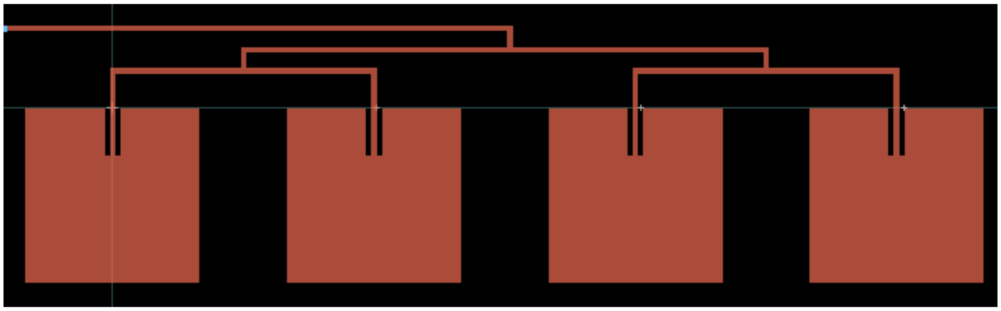


(a) Receiver Antenna Design

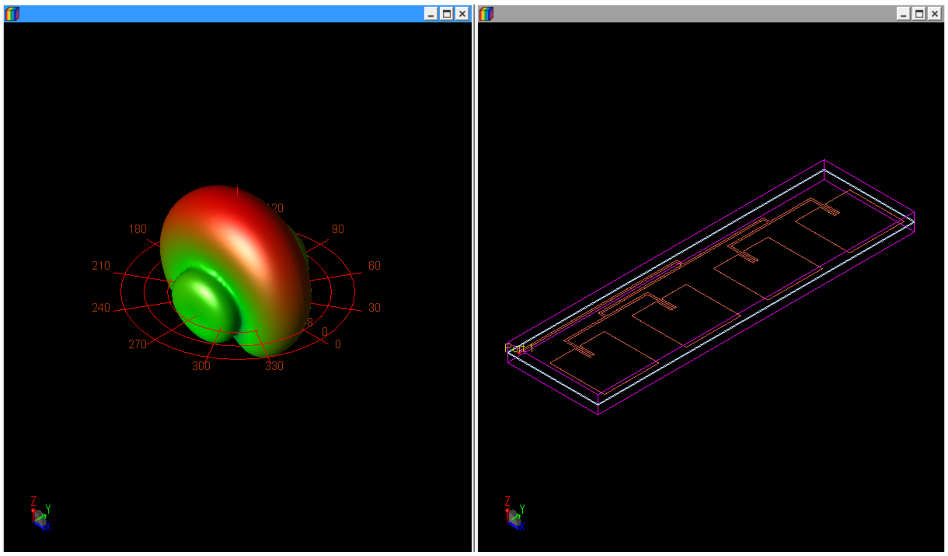
(b) Simulation of Receiver Antenna

Figure 18: Receiver Antenna Design

The transmitting antenna array will feature four base patch antennas in a phase array vertically, with wavelength between each patch. This is done to give additional gain for the signal at the cost of a narrower beam. Four of these vertical phase arrays are arrayed horizontally next to each other, $\frac{1}{2}$ wavelength apart, to form the design's steerable phase array. Ideally all transmitting patches would be printed on one large circuit board. However, under advisement by Endeavor's print service they have been separated into 4 individual boards for ease of printing. To enable these now separated antennas to be arranged in close physical proximity (for optimal distancing) the feed-lines have been redirected downwards to narrow the width of each board. Figure 19a features the vertical phase array antenna. Figure 19b shows the simulated lobes that form as a result of the phase array. This restricts the beam vertically, giving us additional directivity and gain.



(a) Transmitter Antenna Design



(b) Simulation of Transmitter Antenna

Figure 19: Transmitter Antenna Design

2.5 Receiver/Rectifier (Ryan Lucas)

The receiver is made up of three main components which include the antenna,the rectification circuit, and load. The antenna has been designed by another group member and is connected to the rectifier PCB through male-to-male SMA adapter. The rectification circuit utilizes the PCC110 power harvesting chip for rectification of the signal received from the antenna. The rectification circuit's transmission line from the SMA adapter to PCC110 chip will have to be matched to 50ohms that way there will be max power delivery from antenna to load. There will also be a capacitor in parallel with the load on the dc side to make a cleaner and more stable dc signal. The load consists of a low power LED and a resistor to make sure the LED doesn't blow when the antennas are placed close together. When the LED lights up it will indicate power transmission. If the power transmitted is not large enough to light the LED there will also be test points on the DC side that can be used to test the voltage level. The goal is to get the receiver the farthest distance possible from the transmitter possible while still having enough power delivered to the LED for light to be visible. The biggest obstacle from the rectifier standpoint to get the maximum distance is finding the most efficient and low power parts.

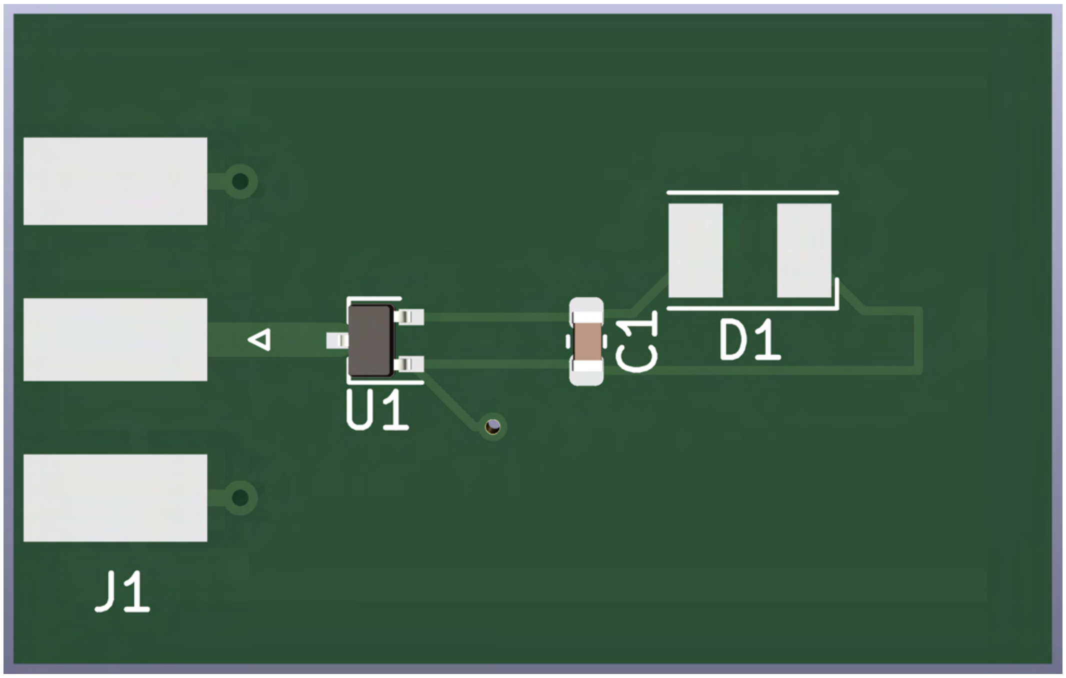


Figure 20: Rectifier PCB

The rectifier PCB shown in figure 20 is made up of the SMA connector,PCC110 chip, capacitor, and LED. The LED component in this design was chosen for its low power dissipation properties as well as its affordability. The capacitor is there to smooth out any ripples in the voltage outputted from the PCC110.

3 Design Details

3.1 Switch (Josh Kusbel)

To test the switch, the FieldFox VNA was calibrated, then used to supply a 2.4GHz signal into the input port. First, RF_out port 1 was tested. When V1 and V2 are set to 0, then all other ports should be matched, while port 1 achieves total transmission. This was then verified for each output port. Figure 21 shows the breadboard used to supply the 3.3V VDD and voltage to pins V1 and V2.

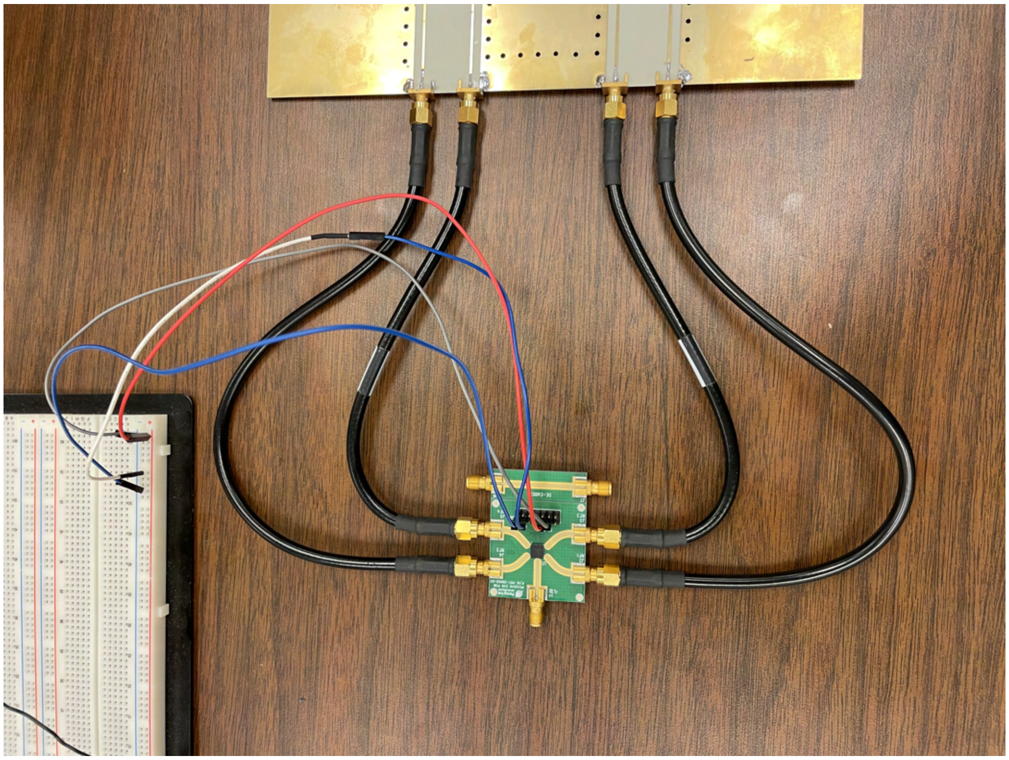


Figure 21: Implementation of breadboard with supply voltage with the PE42441 evaluation kit.

3.2 Butler Matrix (Nick Loeffelholz)

Once the Matrix arrived from the manufacturer we added SMA connectors to it in order to test and integrate it into the switch. Our primary focus was in confirming the S parameters of the Matrix with the VNA, specifically the dB drop at the center frequency and the phase shift. We discovered that our dB drop was closer to 10 dB than 6 which was still usable for our purposes. The relative phase shift, while significantly less ideal proved to still be highly usable. Once this was ensured we assimilated with the switch, retested, into the rest of the project at large.

3.3 Amplifier (Josh Kusbel)

Once the amplifier boards were received from JLCPCB, the components were soldered into their respective places using the pick-and-place machine in the Endeavor Labs. This proved to be very difficult due to the minuscule size of the capacitors and inductors used. None of the amplifiers behaved as desired once they were all soldered. In the soldering process, some of the pads might have bridged together, thus shorting the circuit. However, the most realistic explanation for the amplifiers not performing as expected is a poor solder connection of the VDD input. Therefore, the amplifiers were ultimately scrapped from the final design. However, as with all design projects, more time and more testing would have allowed for design changes that could have proved to be the difference.

3.4 Antenna (Chris Bird)

Once ADS had confirmed adequate results, we had Endeavor print off two of the receiver antennas. This was done to test that the design and print method was satisfactory. The test prints turned out great see Figure 22. However, due to this decision and Endeavor's slower than expected turn around, additional antennas were substantially delayed. This would have been acceptable, if not for Endeavor's laser blowing a fuse and being unable to complete the batch of antennas. All in all only the four receiver antennas were printed. Fortunately, we were able to source four omni-directional 3DBI wifi antennas to substitute for the missing transmitter antennas. The reduction in antenna gain, 14DBI from the original design to 3DBI substitute antennas, would substantially reduced the expected range we could expect.

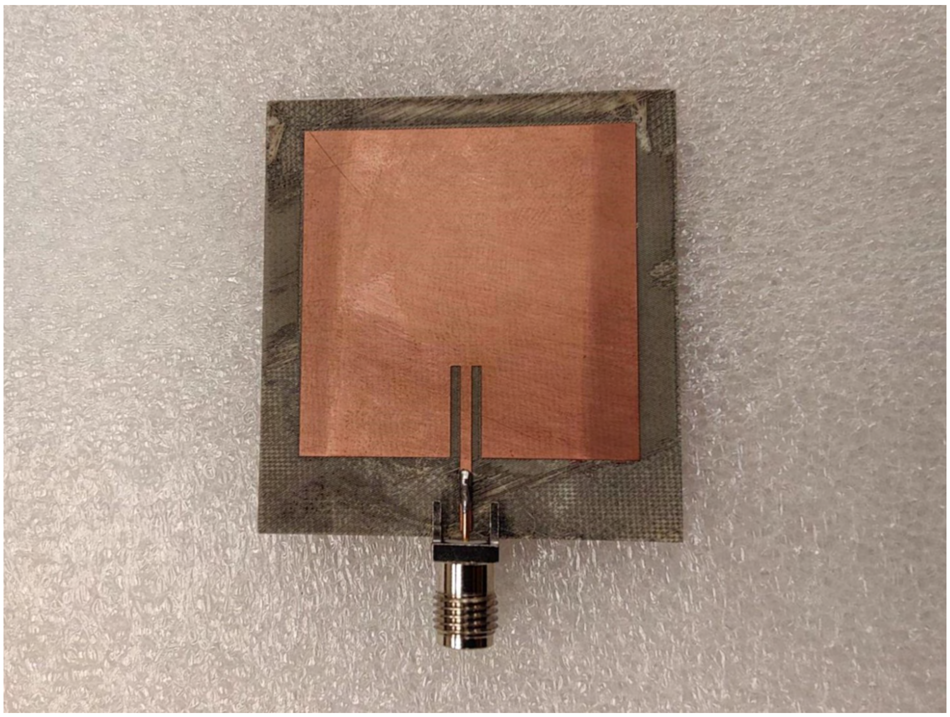


Figure 22: Printed Receiver Antenna with SMA Connector

3.5 Receiver/Rectifier (Ryan Lucas)

The Receiver/Rectifier circuit was manufactured by sending the design off to JLCPCB to get printed. Once this board came in the components were placed on the boards by utilizing the Endeavors pick and place and re-flow machines. Once constructed, the first design was tested to make sure the designed circuit would function as expected at low frequencies which would then indicate if it would work at higher frequencies. When the circuit passed this sanity check the next step was to test to see if the LED would light up when given a 2.4 GHz signal. Which the rectification circuit failed to light up the LED and every indication points to insufficient power levels. A solution to this issue was to put test points on the DC side of the receiver to then be able to test for changes in voltage. This would be a sufficient indication of power delivery as well as assist in finding the effect that beam steering has on power delivery.

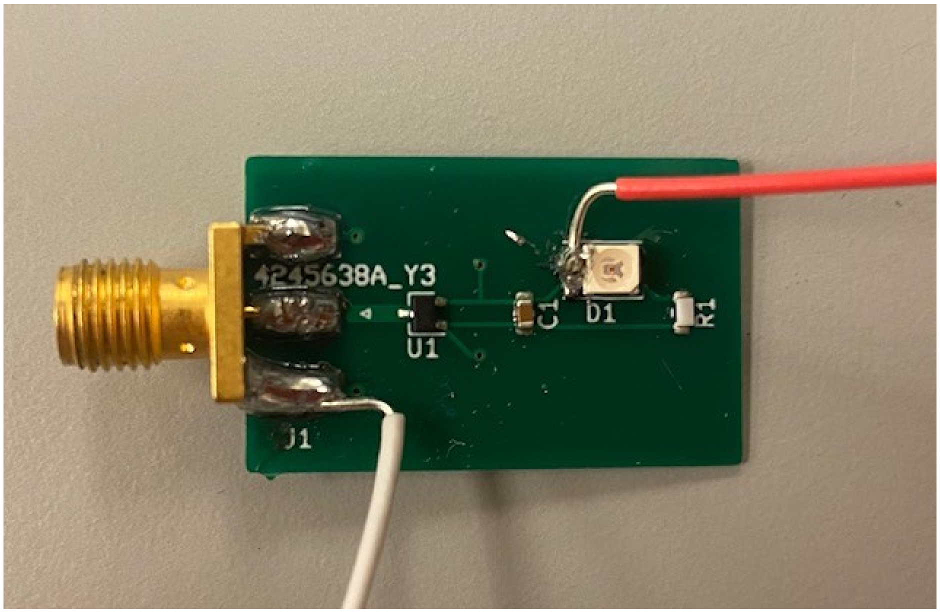


Figure 23: Rectifier PCB with test points

Results that were found when testing the rectifier circuit individually using the VNA as the source indicates that the PCC110 is a very effective rectifier at the frequency we were using. When a 3mW signal was put at the input of the circuit the voltage at the output of the rectifier chip was .95V. Which is very efficient rectification. Although this is not a high enough voltage to actually power the LED. The next step of testing the rectifier circuit was to integrate it with the antennas as well as to mount the combination of the two. Which after that the combination of the antenna and rectifier was combined with the rest of the design.

Figure 24: Rectifier PCB and Antenna Mounted on Stand

3.6 Final Assembly (Josh Kusbel)

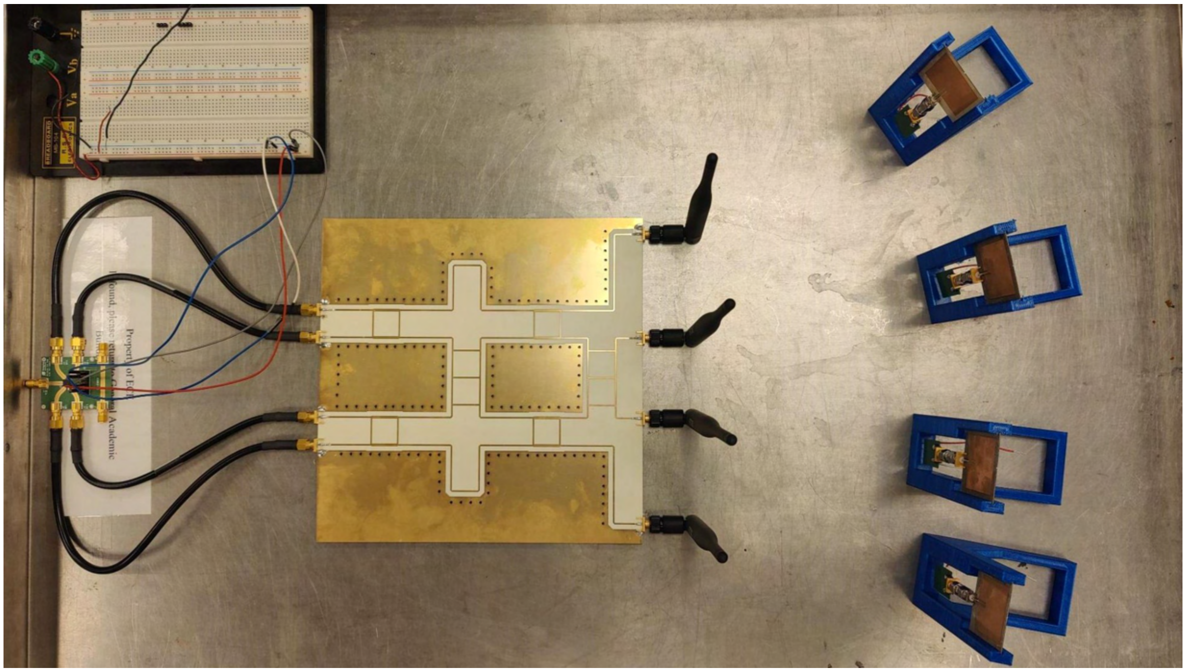


Figure 25: Final Assembly of each component

The image shown in 25, is not the original design. Through difficulty in ordering parts, supply chain issues, and other unforeseen hiccups along the way, this was the final product. However, the image shown demonstrates the testing setup that was ultimately used to successfully demonstrate beam steering. To test and prove that beam transmission was successfully occurring, a small voltmeter was attached to the test probes on the rectifier and when the correct output port was chosen on the switch, it was verified that power was being successfully transmitted to different receivers. Had the amplifier worked, and had the antennas been printed, we would have been able to increase the distance that power was being transferred over, and ultimately been more successful.

4 Schedule (Chris Bird)

As shown in the following gantt charts, 26 and 27, the project did not end on schedule. There were many factors that contributed to us being behind schedule. Early on, we were briefly inhibited by our need to acquire ADS software licenses, this was solved in approximately a week. We were further setback after both the Initial Presentation and the Critical Design Review as we took feedback from those presentations into consideration and revised our designs.

Lastly, we encountered delays while attempting to manufacture our components. Manufacturing the Butler Matrix in China and having it shipped took a few weeks. Some minor delays were a result of testing. Testing had revealed that the receiver boards required test points. For the Antenna, deciding to print two test antennas before committing to the full batch resulted in almost two weeks lost as Endeavor services were at first, slow, and later totally incapable. As a result of these delays, we were pushed uncomfortably close to the deadline for working prototype.

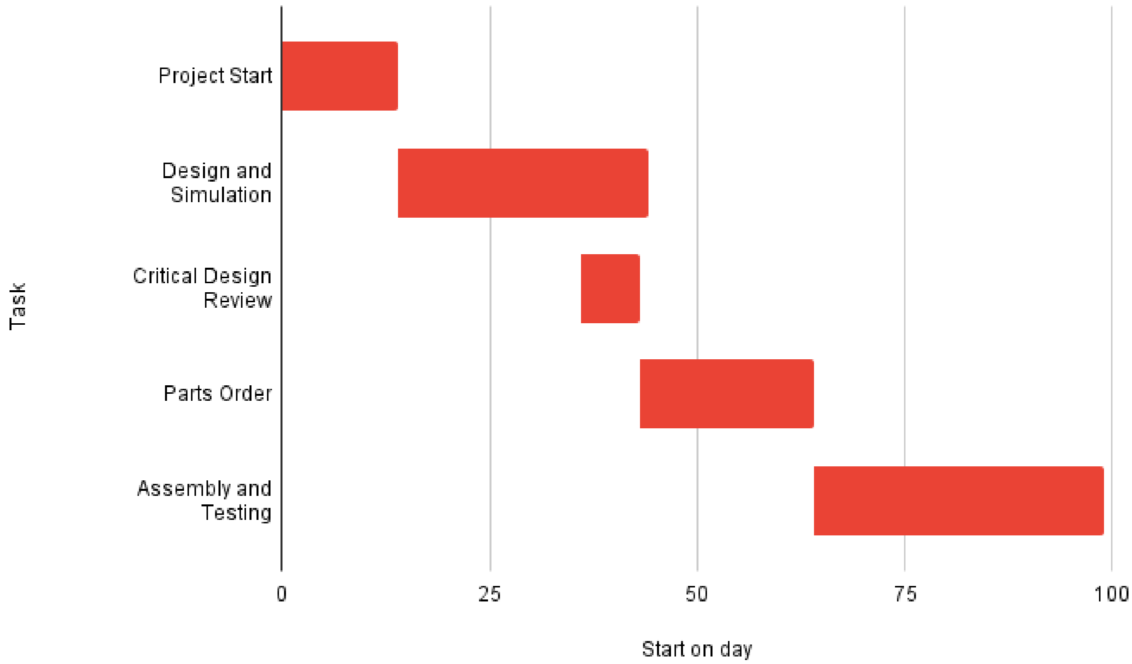


Figure 26: Predicted Project Schedule

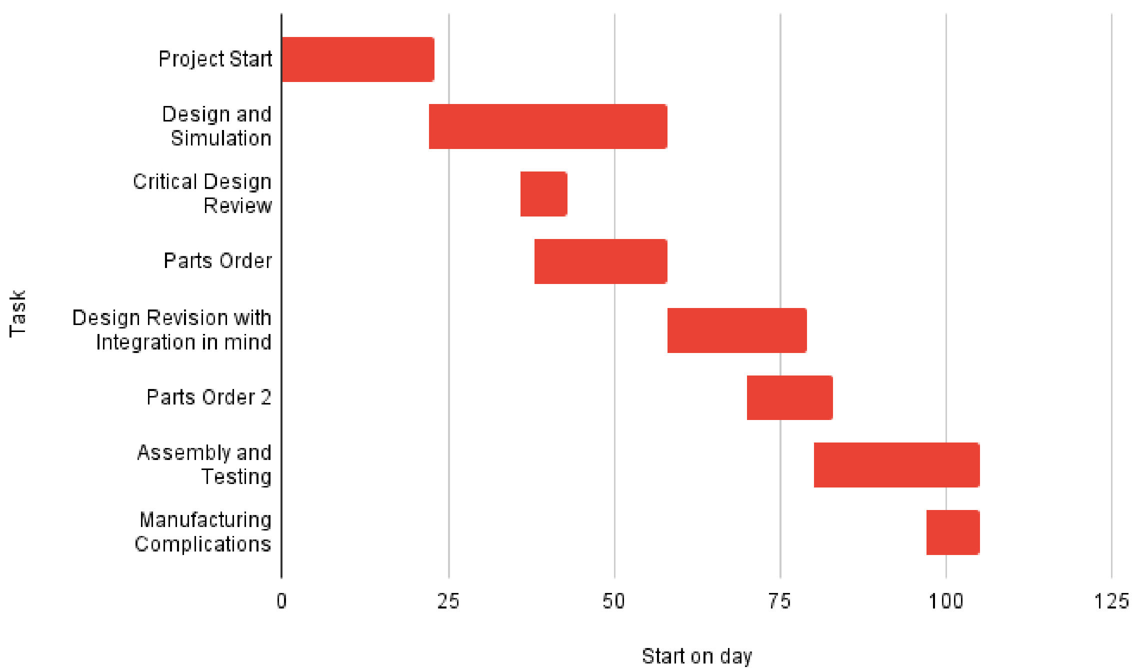


Figure 27: Actual Project Schedule

5 Costs (Nick Loeffelholz)

For the costs our goal was to utilize as many of the previous teams components as possible as well as to use any student discounts as possible. This is shown in Figure 28

Costs					
Quantity	Part	Ordered From	Price Per Unit	Price (Total)	Theoretical Price
1x	SP4T	Stockroom	$105		$105
10x	PCBs (Amplifier)	JLCPCB	$1.54	$15.42	
20x	PHA-102+ RF Amplifier	Mouser	$8.95	$179	
20x	1000pF Ceramic Capacitors	Mouser	$0.05	$1	
20x	100pF Ceramic Capacitors	Mouser	$0.02	$0.40	
20x	.01uF Ceramic Capacitors	Mouser	$0.03	$0.60	
20x	390nH Fixed Inductors	Mouser	$0.34	$6.80	
10x	PCC110	Mouser	$2.48	$24.80	
5x	1uF Ceramic Capacitors	Stockroom	$0.04		$0.20
10x	SMD LED	Mouser	$0.36	$3.56	
5x	PCBs(Rectifier)	JLCPCB	$2.00	$22.78	
1x	butler matrix	ipcb	$198.00	$268.00	
8x	SMA Cables	Stockroom	$2.60	$20.80	
4x	WiFi Antennas	Endeavor	$65.00		$260
4x	Transmitter Antennas	Stockroom	$26.50		$106.00
4x	Reciver Antennas	Stockroom	$5.00		$20.00
				$543	$928

Figure 28: Final costs

6 Risk Management (Josh Kusbel)

Anything having to do with power transfer has some inherent danger and with exposure to very high RF intensities can result in the heating of biological tissue and an increase in body temperature. This can cause tissue damage due to the human body not being able cope with or to dissipate the heat quick enough. These risks make lab safety even more paramount. Another restriction that all projects face is that we have a budget that we need to keep to. This might have been an issue if multiple iterations were required to get the design correct because shipping costs are expensive as well as the boards themselves. Another factor that we accounted for is time because shipping delays as well as fabrication delays could not be avoided.

7 Work Breakdown Overview (Nick Loeffelholz)

The work breakdown for this project is as follows:

- Nick: Butler Matrix
- Chris: Antenna Design
- Ryan: Receiver/Rectifier
- Josh: Switch and Amplifier

These tasks were divided up in the first week of the project. However, it has been important to the group for transparency to all members on each individual part of the design. We desired for each person in the group to thoroughly understand how each component of this project works and is integrated. In practice, there was significant overlapping of tasks especially as pertained to testing of parts using the VNA.

8 Reflections and Closing Thoughts

8.1 Josh K.

While this project was ultimately a success in terms of demonstrating beam steering there were several things that I would have done differently. For one, I would have started the design process of the amplifier far earlier, and abandoned the idea of designing an amplifier from the ground up. Outside of the problems with the amplifier, one of the main things that I learned over the course of this project was how to ask questions. With a project such as this, there were many things that I was unaware of, and learning to ask as many questions as possible was integral to success.

8.2 Nick L.

If given the opportunity to do this project again, I would have assumed the outsourcing of the butler matrix from the first day of the project. As we have seen now, there are simply too many risks associated with relying on the campus fabrication process. If we had assumed outsourcing on all parts from day one and adjusted our task schedule accordingly we could have saved significant time and simplified design processes.

8.3 Ryan L.

There are several things I would do differently if I was able to start this project again. The first thing that I would do differently would be to find a more efficient LED even if it is more expensive to then minimise power consumption even further. The second isn't really something I can do but is instead something that the department can do which is to have a rigorous course about practical circuit applications involving designing PCBs to meet a goal. Then the last is to have been more efficient with our time to then be able to integrate the rectifier and antenna onto one PCB.

8.4 Chris B.

Looking back on this project there are a few changes I, in hindsight, should have done. Firstly, the resources I used to design the patches (the website and textbook referenced in the bibliography) could've been located earlier in the research phase and would have expedited my progress early on. Secondly, with the time gained, could have worked better to integrate the antennas into other group member's component's designs. For example, the receiver/rectifier could have been printed on one board with the receiving antennas. Another example is that the spacing of the output ports of the Butler Matrix could have been the proper spacing of the arrays to begin with and would have allowed us to avoid the use of cables. Lastly, I was extremely hesitant to outsource the antennas as we already had the boards which meant using Endeavor was essentially free. Had I outsourced these boards, we could have avoided the problems with Endeavor's turn-around speed and eventual laser failure.

References

[1] OSHA, "Radiofrequency and microwave radiation - standards."

[2] Microwaves101.com, "Butler matrix."

[3] A. M. Zaidi, B. K. Kanaujia, M. T. Beg, J. Kishor, and K. Rambabu, "A novel dual-band branch line coupler for dual-band butler matrix," *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 66, no. 12, pp. 1987–1991, 2019.