Radio Frequency Energy Harvesting

A wide spectrum of radio frequency signals are present in atmosphere, the idea here is to explore, research, simulate and test the concept of harvesting energy from these radio frequency signals.

RF Energy harvestable bands:

Source	Representative Frequency Bands
AM Radio	530–1,700kHz
FM Radio	88–108MHz
TV Broadcast/DTV	550–600MHz
GSM-900	850–910MHz
GSM-1800	1,850–1,900MHz
WiFi/ISM	2,400–2,450MHz, 5,150–5,825MHz
BLE (Bluetooth Low Energy)	2,402–2,480MHz
UMTS/LTE	2,150–2,200MHz, 700–800MHz
UWB	3,100–10,600MHz
WLAN	3,100–4,400MHz
C-Band	4,400–5,000MHz

Design Strategy for RF Energy Harvester:

The choice of design of an RF energy harvester should be guided by three key performance factors: **frequency band, output voltage, and power conversion efficiency (PCE)**. The process begins with selecting the appropriate frequency bands from which ambient RF energy will be harvested. This selection is based on the availability and strength of RF signals in the environment, such as GSM-900, GSM-1800, LTE, Wi-Fi, and DTV bands. Once the bands are identified, the next step involves evaluating whether the harvester should be designed as a **narrowband, broadband, or wideband system**. This decision depends on the number of bands targeted and the trade-offs between size, efficiency, and complexity. A practical approach is to first design and test individual harvesters for each selected band, analyzing their output voltage and PCE. Based on these results, a multiband or unified design can be developed to optimize performance across multiple frequency bands. This staged methodology ensures that the final harvester design is both efficient and tailored to the ambient RF environment.

Research paper's with various designs were explored and three main focus areas were decided.

1. 900MHz Frequency band
2. 2.4GHz Frequency band
3. Broadband based design

The above frequency designs were explored from research papers.

Frequency band(s)	Paper	Link
2.4–2.45 GHz ISM	Development of 2400–2450 MHz Frequency Band RF Energy Harvesting System for Portable Gadgets and Low-Power Devices (authors include N. U. Khan)	National Library of Medicine (full text): **https://pmc.ncbi.nlm.nih.gov/articles/PMC11125279/**
2.1 GHz and 5.8 GHz Dual-band	A dual band rectifying antenna for RF energy harvesting (Neeta Singh et al., 2018)	Springer (record): **https://dl.acm.org/doi/abs/10.1007/s10825-018-1241-6**
GSM-900 downlink (~935–960 MHz)	DESIGN OF RF ENERGY HARVESTING SYSTEM FOR ENERGIZING LOW POWER DEVICES (N. M. Din et al., 2012)	PIER PDF: **https://www.jpier.org/ac_api/download.php?id=12072002**
800 MHz–2.5 GHz (CDMA, GSM900, GSM1800, 3G)	Broadband RF Energy Harvesting System covering CDMA, GSM900, GSM1800, 3G Bands with Inherent Impedance Matching (Arrawatia, Shojaei Baghini, Girish Kumar)	Semantic Scholar record: **https://www.semanticscholar.org/paper/Broadband-RF-energy-harvesting-system-covering-3G-Arrawatia-Baghini/d7eb30f01bc19df674a0b9f60da2d56e98769d2c**
1.8–2.5 GHz broadband	A High-Efficiency Broadband Rectenna for Ambient Wireless Energy Harvesting (Chaoyun Song, Yi Huang, et al., IEEE TAP 2015)	University of Liverpool repository (PDF link inside): **https://livrepository.liverpool.ac.uk/3005519/**
2.4 GHz and 5 GHz (ISM/WLAN)	Dual Band Rectenna for Electromagnetic Energy Harvesting at 2.4 GHz and 5 GHz Frequencies (L. Prashad, H. C. Mohanta, A. J. A. Al-Gburi, 2024)	PIER B article page: **https://www.jpier.org/issues/volume.html?paper=24072102** and PDF: **https://www.jpier.org/ac_api/download.php?id=24072102**

Design's chosen to work on:

1. **RF Energy Harvesting - Design for GSM-900 frequency band**
   Antenna Specifications: Thickness of substrate 1.6mm, the thickness of copper 0.035mm, the dielectric constant 3.9, and the loss tangent 0.01.

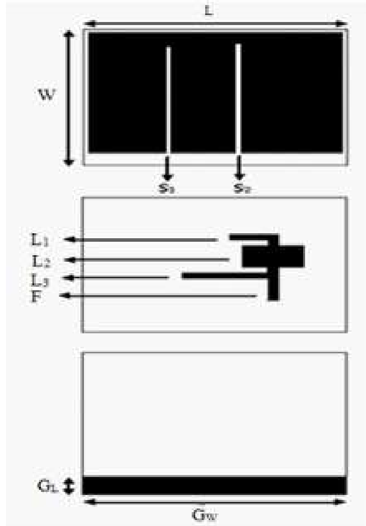


Figure 1. Configuration of E-shaped patch antenna with pi matching network and partial ground plane.

Table 1. Dimensions of antenna geometry.

Basic Configuration	Patch antenna						Pi matching network						Feed line		Ground plane	
Variable	W	L	S_1		S_2		L_1		L_2		L_3					
			W	L	W	L	W	L	W	L	W	L	W	L	G_W	G_L
Dimensions **(mm)**	85	106	79	2	81	3	2	10	13	8	2	20	8	3	8	110

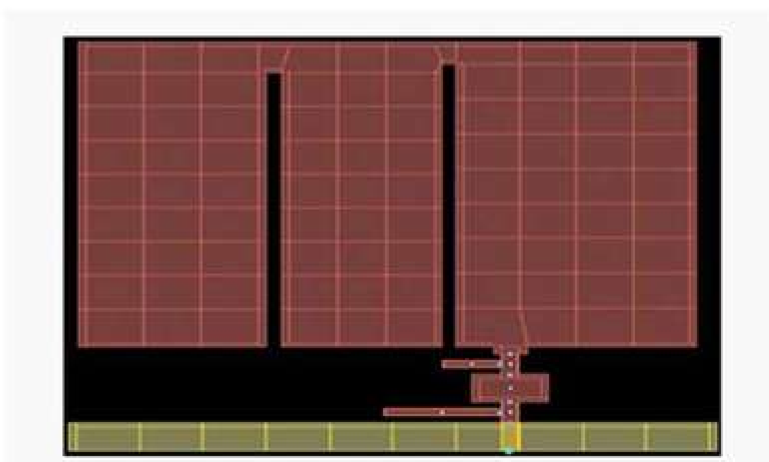


Figure 3. Screen capture of E-shaped patch antenna.

Impedance Matching and Rectifying Circuit:

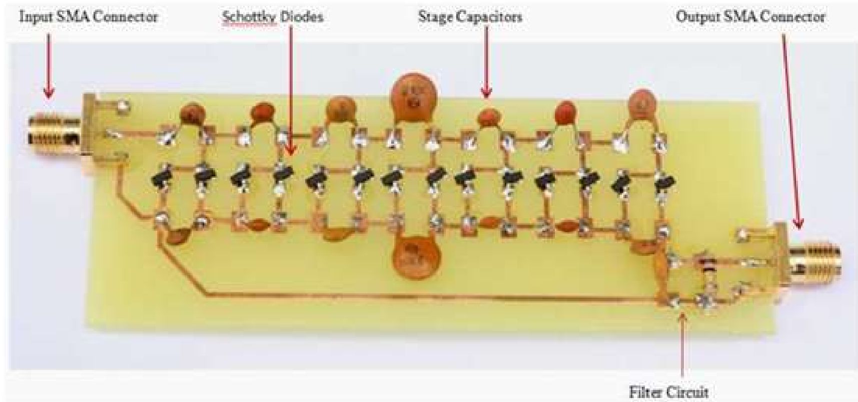


Figure 6. Photograph of assembled circuit board of 7-stage voltage doubler.

Components:

Description	Value
Schottky Diode	HSMS-2850
Capacitance	-
Load Resistance	-

2. **RF Energy Harvesting - Design for 2.4GHz frequency**
   Antenna Specifications:

- Antenna - a rectangular metallic patch which is placed on the top of another metallic sheet called ground plan.
- Substrate - FR-4, whose dielectric constant is 4.3 A patch made up of copper and a substrate of FR-4 sheet having a thickness of 1.6 mm.

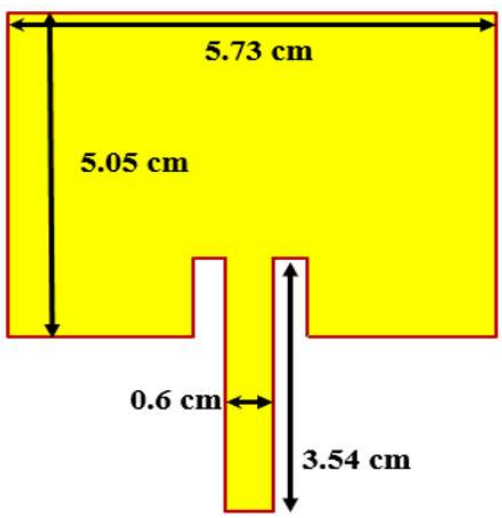


Fig. 2. Designed patch antenna

Impedance Matching and Rectifying circuit:

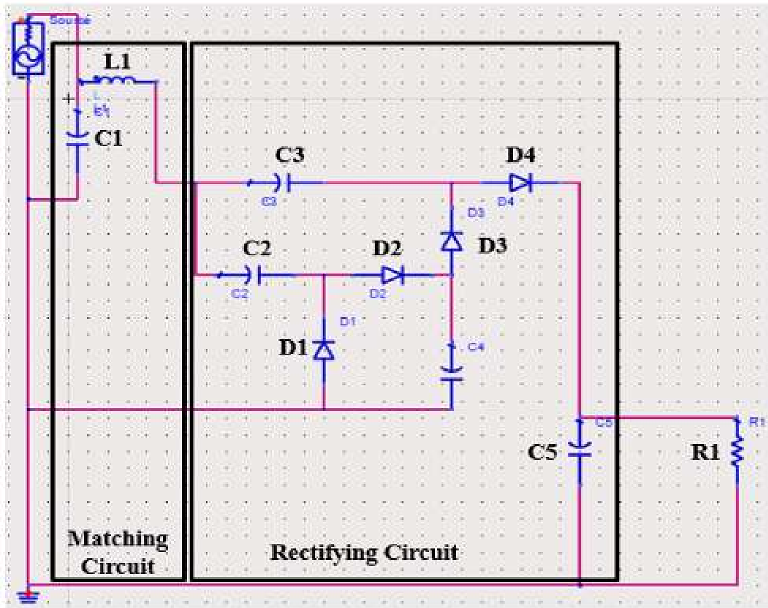
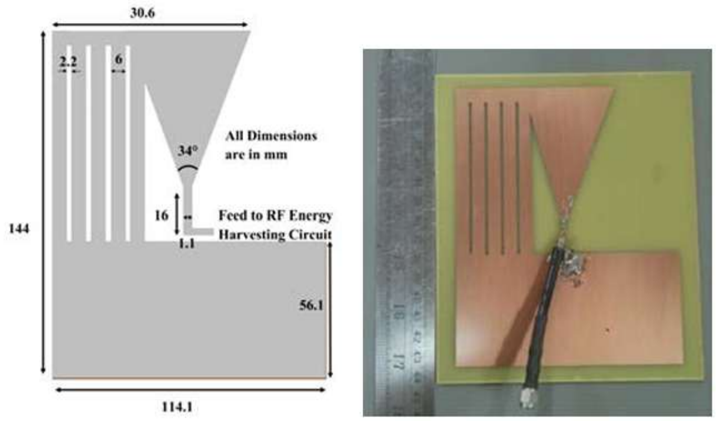


Fig. 4. Designed matching and rectifying circuit

Components:

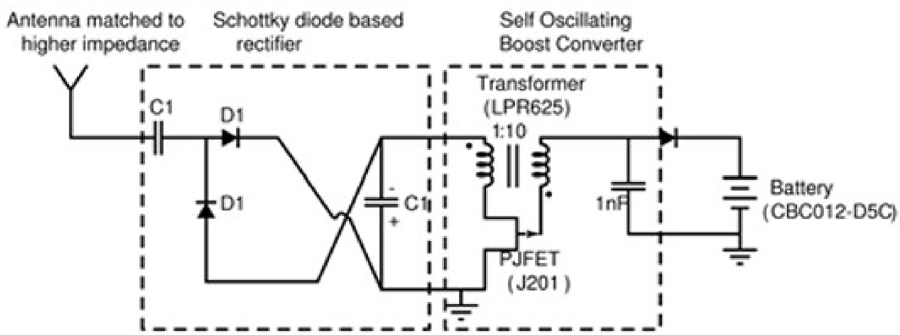
Description	Value
Matching Inductor L1	14 nH
Matching Capacitor C1	2pF
Rectifier Capacitor C2	15pF
Rectifier Capacitor C3	15pF
Rectifier Capacitor C4	15pF
Load Capacitor C5	5pF
Load Resistor R1	50kΩ
Diode	HSMS2850

3. **RF Energy Harvesting - Design for Broadband frequency range 800MHz to 2.5GHz**
   Antenna Specifications: The antenna is designed on 1.6mm thick FR4 substrate (r =4.4, tan = 0.02).



(a) (b)

Impedance Matching and Rectifying circuit:



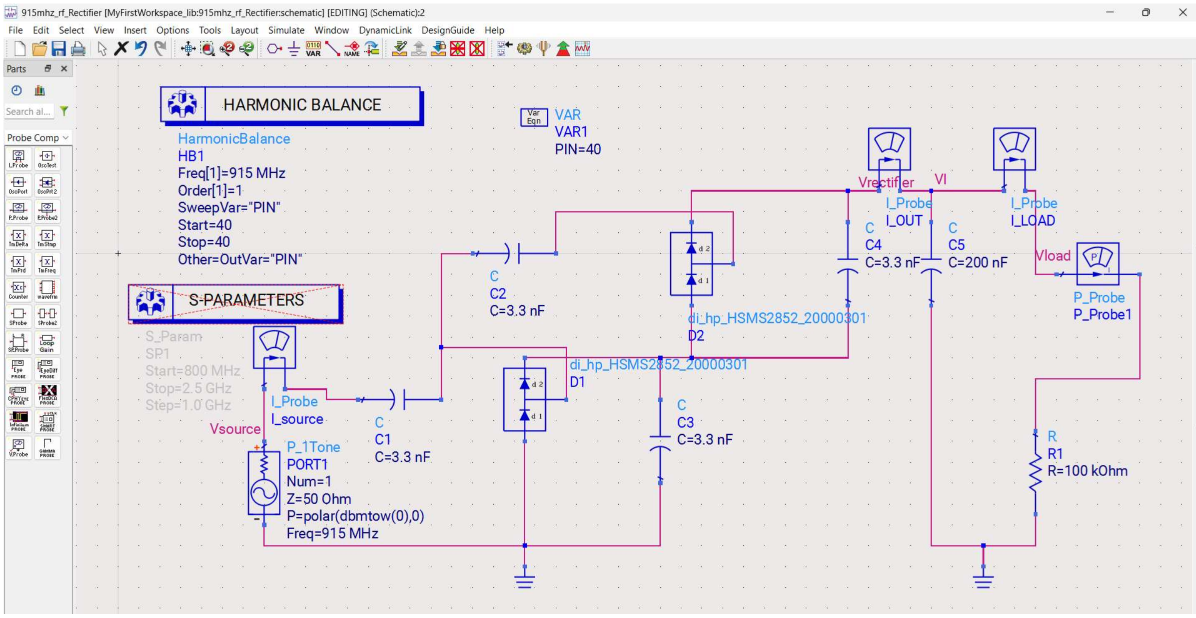
(a)

Components:

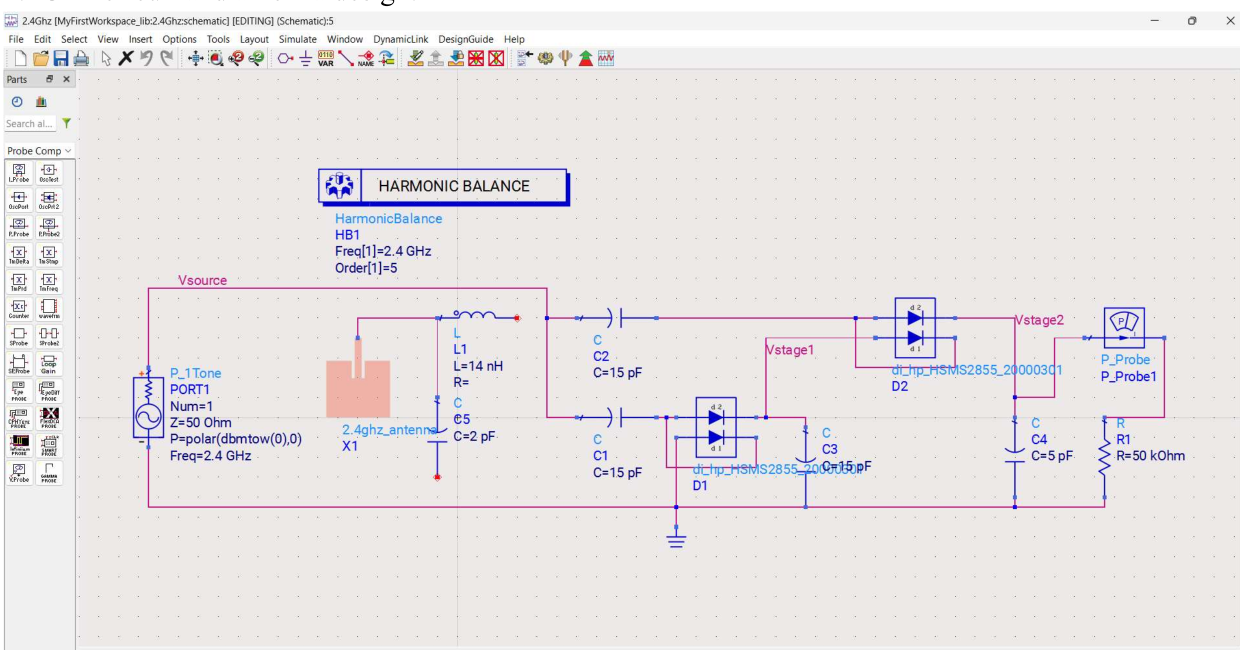
Description	Value
Matching capacitance C1	-
Diode D1	Schottky Diode
Boost circuit capacitance	1nF
PJFET	J201

Simulations carried out:

1. 915MHz circuit design:



2. 2.4GHz circuit and antenna design:



Power generated values per above designs for different input power:

1. 915MHz:

- 40.1µW
- 146.9µW

2. 2.4GHz:

- 0.006554µW

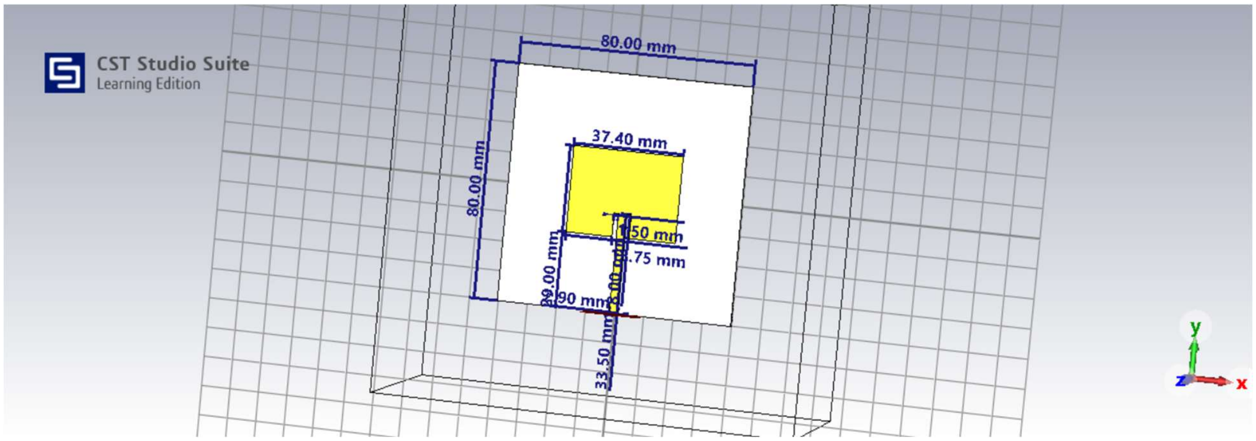
Power output values seen as mentioned in research papers:

Frequency Band	Paper Name	Max Power Output (measured)	Max Voltage Output (measured)
2400–2450 MHz ISM	Development of 2400–2450 MHz Frequency Band RF Energy Harvesting System for Portable Gadgets [Nasir Ullah Khan]	4.60 µW (lab), 0.47 nW (WiFi field)	5.2 V DC (lab), 1.3 V DC (field)
935–960 MHz GSM-900	DESIGN OF RF ENERGY HARVESTING SYSTEM FOR ENERGIZING LOW POWER DEVICES [Din et al.]	21.67 µW @ −16.64 dBm (cell tower, 50m)	2.9 V DC (field, 50m tower), 5 V DC (lab)
800–2500 MHz (CDMA, GSM900, GSM1800, 3G)	Broadband RF Energy Harvesting System covering CDMA, GSM900, GSM1800, 3G Bands [Arrawatia, Shojaei Baghini, Kumar]	~10–40 µW (typical, various bands)	1–5 V (varies by band and input, bench/field)
2.1 GHz, 5.8 GHz	A dual band rectifying antenna for RF energy harvesting [Neeta Singh et al.]	1.26 mW @ 2.4 GHz, 1.82 mW @ 5.8 GHz (sim, −3 dBm)	2.2 V DC (sim/bench)
1.8–2.5 GHz broadband	A High-Efficiency Broadband Rectenna for Ambient Wireless Energy Harvesting [Chaoyun Song et al.]	55% RF-DC efficiency @ −10 dBm (−35 dBm sensitivity, output power ~6.3 µW, lab)	~1.4 V DC @ −10 dBm input (lab)
2.4 GHz & 5 GHz	Dual Band Rectenna for Electromagnetic Energy Harvesting at 2.4 GHz and 5 GHz [Prashad, Mohanta, Al-Gburi]	315 µW @ 2.4 GHz (sim/bench); 170 µW @ 5 GHz (sim/bench)	~1.7 V DC @ 2.4 GHz (sim)

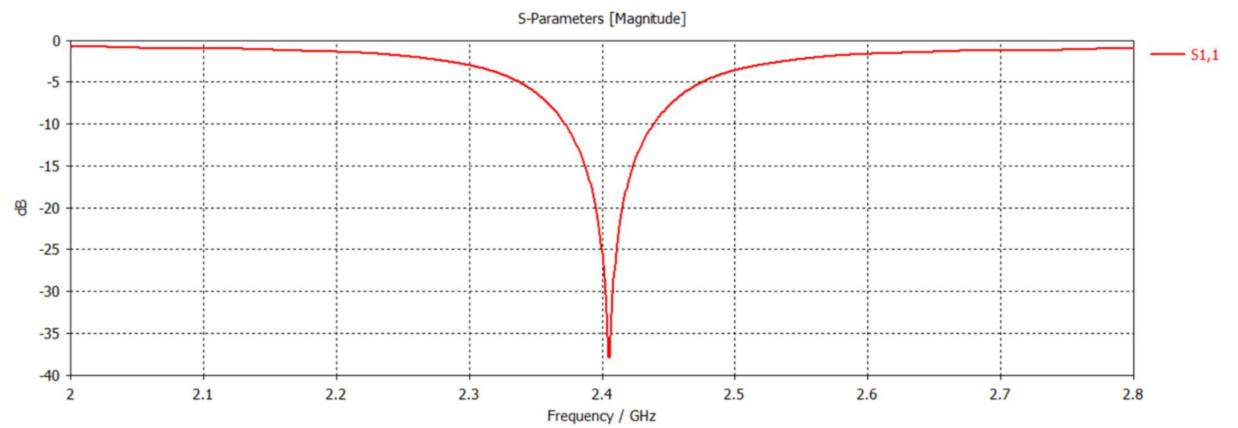
Design Implementation in Lab:

With the idea to implement the concept and verify the power output, voltage values, the 2400–2450 MHz ISM band RF energy harvesting system from the paper 'Development of 2400–2450 MHz Frequency Band RF Energy Harvesting System for Portable Gadgets' by Nasir Ullah Khan was chosen. In the lab, the antenna design and circuit layout have been carried out according after simulations and optimization of antenna in CST Studio software for antenna. PCB layout was designed in KiCAD.

Antenna Design for 2.45GHz:

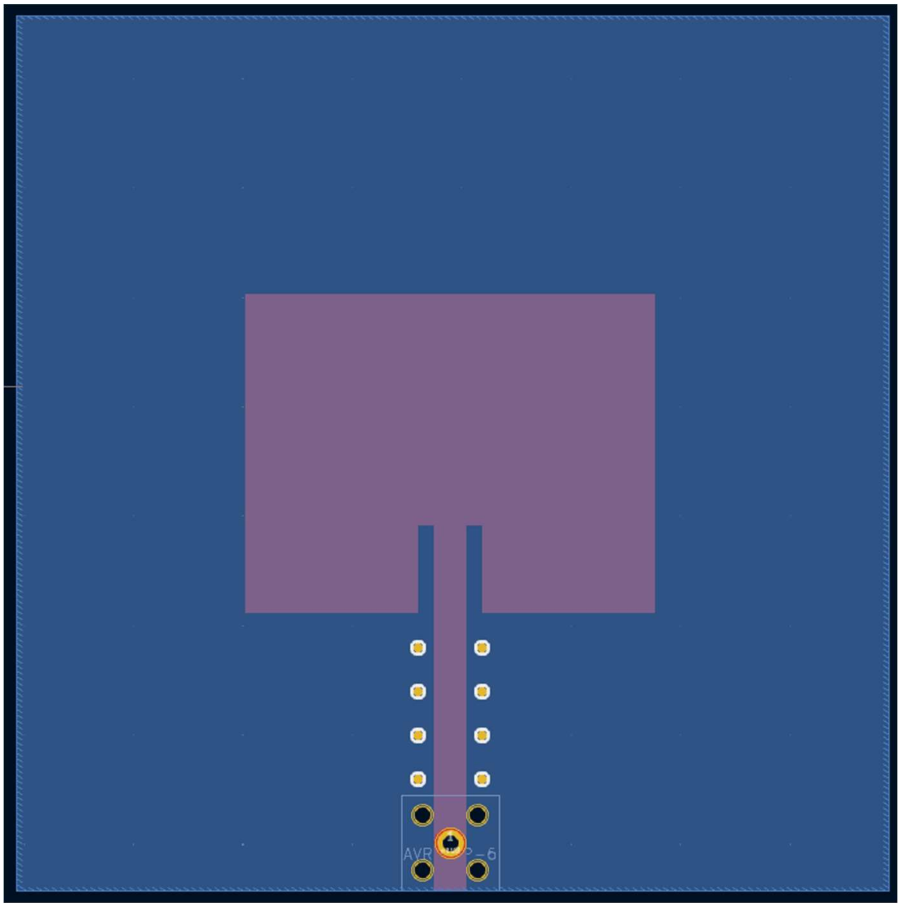


After initial design, S11 parameter analysis and Impedance calculation of antenna using the tool, further optimizations were required and parameter sweep analysis was performed to find best design.



S11 characteristics graph

The antenna design measurements were taken and designed in KiCAD, and the PCB was printed.



PCB Design of antenna

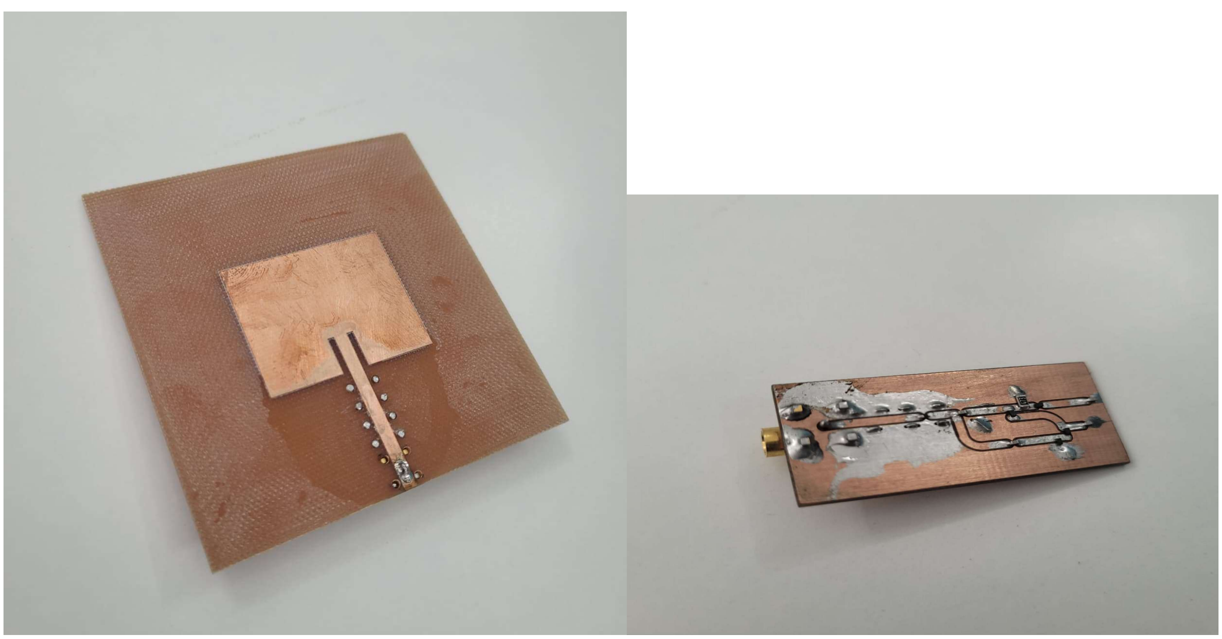
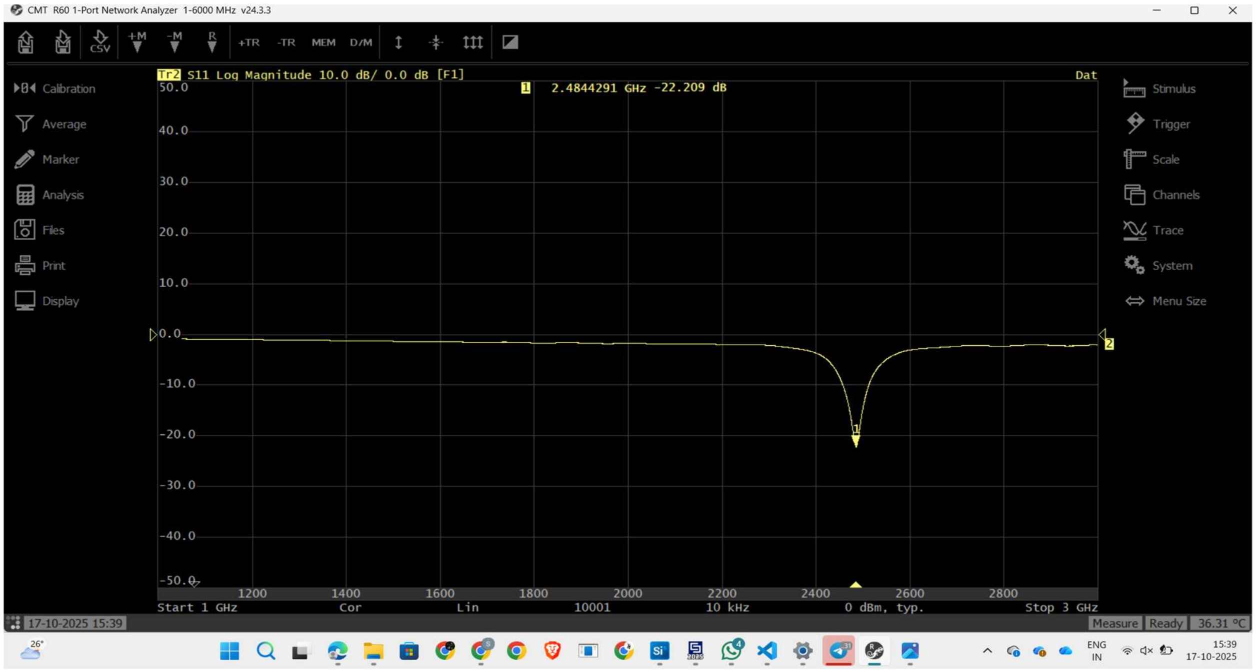


Image of printed antenna and circuit board

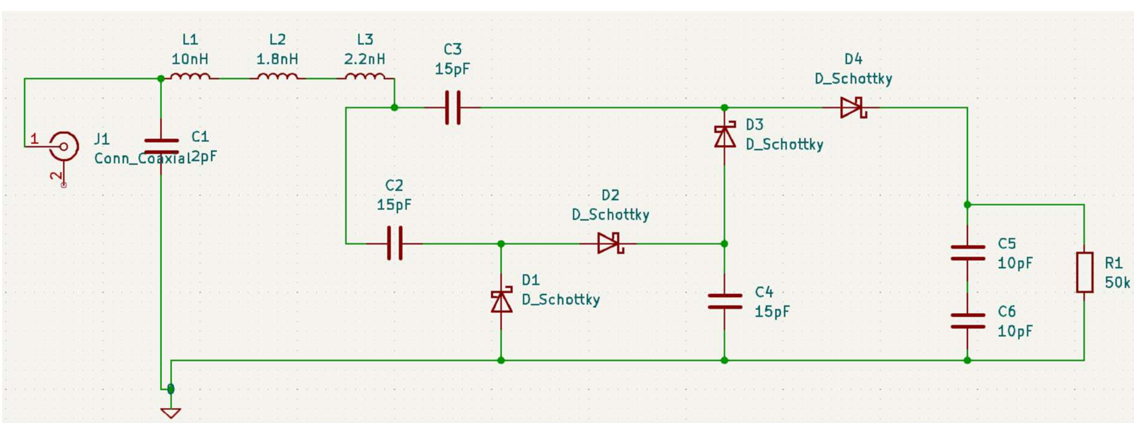
A Vector Network Analyzer was used to find the performance characteristics i.e, the return loss graph across a range of frequencies. RVNA software and R-60 VNA was used. The output graph from this analysis is shown below. We can see that the antenna is well designed for the 2.48GHz point with a return loss of -22.209 dB.

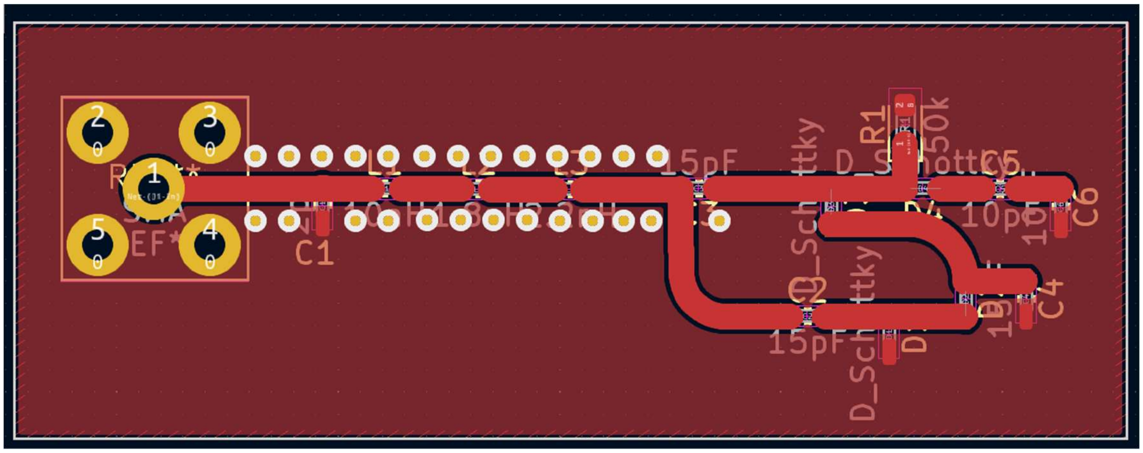


This antenna has a return loss of –10.042 dB at 2.45GHz and a return loss of –10.395 dB at 2.5GHz. Thus making the antenna best suitable for Wi-Fi signals energy harvesting.

Circuit Layout:

Circuit layout in KiCAD modifications based on components available. HSMS 2850 diode was out of production thus with similar characteristics and recent research papers SMS 7621 diode was chosen and replaced in design.





Antenna design and verification are complete. Testing of this circuit with the antenna together by producing Wi-Fi signals using a Wi-Fi board was in process.

Observations:

1. Antenna is working good with return loss shown of –22.209 dB at 2.48GHz.
2. Rectifying circuit is directly connected to antenna, impedance matching is not implemented at this stage.
3. Output voltage for this configuration across resistor should be ~300mV which is not seen in test, further debugging and adding of impedance matching circuit is required. Debugging steps involve
   – figure out tool/method to measure power present in ambient environment.
   - add impedance matching circuit.
   - simulations to include output at each point after signal is received at antenna, post impedance matching circuit point, rectifier output at load.