

A Novel Filter Bank Design for Enhanced Radio Frequency (Rf) Harvesting and Energy Synthesis

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Abstract: The demand for green and sustainable energy has grown significantly in recent years. Traditional energy sources, such as fossil fuels and nuclear power, pose serious environmental risks, driving the adoption of renewable alternatives. [1] While solar energy has seen substantial advancements, other technologies—including piezoelectric, radio frequency (RF) harvesting, and gyroscopic energy harvesting—remain underdeveloped. Among these, RF energy harvesting holds immense potential to revolutionize low-power applications, particularly for Internet of Things (IoT) devices such as sensors, wearables, smartphones, and unmanned aerial vehicles (UAVs). However, current RF harvesters suffer from inefficiencies in energy synthesis, resulting in low voltage output and limited practical use. For instance, Powercast's state-of-the-art solution achieves 75% efficiency but only within a 24-meter range. [2]

To address these challenges, this paper introduces novel **filter bank architecture** for RF energy harvesting, leveraging microstrip, passive, and active filters to achieve wider bandwidth and improved efficiency. Filters play a critical role in signal processing, and while modern digital filters excel in reconfigurability, analog filters remain essential in RF harvesting to mitigate noise and enhance voltage stability. Our proposed design integrates four specialized filters, rigorously tested through MATLAB and AWR simulations. The results demonstrate significant improvements in energy synthesis, paving the way for self-powering devices that could eventually eliminate the need for traditional chargers and charging ports. [2] [3]

Keywords: Piezo, microstrip, software defined systems, wearable devices.

I. Introduction

Radio Frequency (RF) energy travels through the air as electromagnetic waves, carrying distinct properties such as electric and magnetic fields, polarization, and momentum—all governed by Maxwell's equations. [4] These waves come from both natural and man-made sources. Nearly everything, including living organisms, emits some form of frequency. Certain minerals, like uranium-bearing uraninite (UO₂) and thorium-rich thorite (ThSiO₄), naturally radiate energy. Even tectonic shifts, lightning, and cosmic activity generate electromagnetic waves. On the human side, everyday electronics—radios; engines, and wireless devices—flood our surroundings with untapped RF signals.

For decades, RF energy harvesting remained an underdeveloped concept, but the rise of 5G and 6G networks has reignited interest. The need for sustainable, maintenance-free power has never been greater. Traditional energy systems rely on wired charging, face environmental concerns, and struggle with inefficiencies. RF harvesting offers a breakthrough: the ability to convert ambient waves into usable electricity, [5] enabling self-powered sensors, wearables, and IoT devices.

Yet, current RF harvesters fall short. Most suffer from narrow bandwidth, weak signal selectivity, and inefficient energy conversion, leading to disappointingly low power output. [6] [7]. The core issue lies in outdated rectenna and filter designs, which fail to fully capture and process the scattered RF energy around us. This paper explores how smarter engineering—particularly in filter and rectifier technology—can unlock RF harvesting's true potential, paving the way for a wirelessly powered future.

II. Literature review

The dream of wireless energy is over a century old. Nikola Tesla first proved that power could travel through the air without wires, while Friis later gave us the math to calculate how much energy reaches a receiver based on distance—a fundamental equation still used today:

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi R} \right)^2 \quad [7] [8] \quad 1$$

Despite this early vision, progress has been slow. In 2016, Dr. K. Umapathy and his team [9] designed a dual-band RF harvester capable of extracting energy from weak ambient signals. Their system produced over 1V—enough to trickle-charge a battery—but efficiency remained low. Still, their work sparked new interest in the field.

By 2021, Nicholas Taruvinga (Midlands State University) built a simpler harvester using a Schottky diode rectifier, tuned to 900 MHz cellular signals [6]. His prototype, etched onto an FR-4 PCB with basic L-matching components, claimed 68% efficiency. But the harvested power was tiny—a reminder that single-frequency, single-antenna designs struggle to capture meaningful energy.

Other researchers tried hybrid approaches. Kayhan Celik [10] combined solar cells with a leaf-shaped antenna for Wi-Fi and cellular bands. Yet even with a strong 25 dBm RF source just a meter away, the system barely scraped 100 mV.

A pattern emerges: past designs—whether narrowband, single-antenna, or hybrid—all suffer from weak filtering and poor impedance matching. This leads to pitifully low voltages and wasted energy [3] [11].

Our Solution: A Smarter Filter Bank

This research tackles those flaws head-on. Instead of settling for basic filters, we propose a **tailored filter bank** that boosts signal capture, minimizes losses, and maximizes conversion efficiency. By blending passive filtering and voltage doublers, with optimized rectenna design, we push beyond the limitations of earlier work.

If successful, this could finally make RF harvesting practical—powering IoT sensors, wearables, and other low-energy devices without wires or batteries. This advancement promises a cleaner, maintenance-free alternative to current energy-intensive technologies

System overview

The complete RF energy harvesting system, illustrated in Figure 1, consists of six key components:

- Antenna Array
- Impedance Matching Network
- Filter Bank
- Voltage Rectifier
- Voltage Doubler
- Current Booster

Antenna Array

An antenna (AE) acts as a transducer, converting incoming electromagnetic waves into electrical signals. Its design depends on the wavelength of the target frequency, while its sensitivity varies based on antenna type and operational band.

This system employs four antennas:

AE1 & AE2: Quarter-wavelength dipole antennas (terminated with 50Ω resistors) optimized for lower frequency bands.

AE3 & AE4: Broadband antennas designed for very high (VHF) and ultra-high (UHF) frequencies.

Proper impedance matching between the antenna and incoming signal is critical. Mismatches create standing waves (SWR), causing signal cancellation and zero power transfer. To prevent this, simple LC matching networks are implemented.

Filter Bank

The filtered signal then passes through a four-stage Butterworth bandpass filter bank, where each filter isolates a specific frequency sub-band. This selective processing ensures optimal energy extraction from ambient RF sources.

Rectification & Power Boosting

Since the filtered output voltage remains low, the final stages include:

Voltage Rectifier/Doublers: Converts AC RF signals to DC and amplifies voltage.

Current Booster: Enhances power delivery for practical applications.

This structured approach maximizes energy capture while minimizing losses—key for efficient RF harvesting.

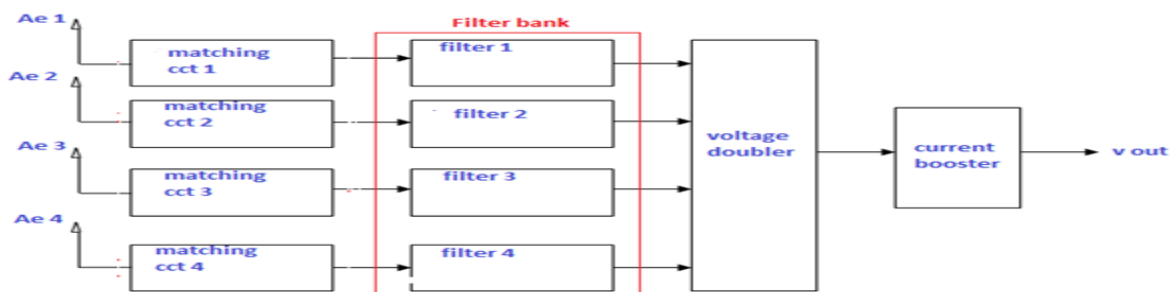


Figure: 1 system block diagram

System Modeling

Antenna design

Table: 1 Antenna array design specification

Antenna	Operating band	frequency	model	impedence	length	polarization
AE 1	Low frequency	1.8 KHz	$\frac{1}{4}$ wave dipole	50 Ω	12 m	horizontal
AE 2	High frequency	30 MHz	$\frac{1}{4}$ wave dipole	50 Ω	7 m	horizontal
AE 3	Very high frequency	56 MHz	Broad band	50 Ω	1 m helix	vertical
AE 4	Ultra high frequency	1.4 GHz	Broad band	50 Ω	1 m helix	vertical

Impedence Matching Network design

Each antenna was terminated with an impedance-matching network, as illustrated in Figure 2. The circuit comprises a simple two-port network with a capacitor (C) and an inductor (L) [13, 14]. The values of C and L are determined using Equations 2 and 3, respectively, while the gain G is expressed by Equation 4.

$$C_1 = \frac{1}{\omega R_s} \sqrt{\frac{R_s}{R_L - R_s}} \quad [5] \quad 2$$

$$L_1 = \frac{R_L}{\omega} \frac{1}{\omega R_s C_1 + \frac{1}{\sqrt{\frac{R_s}{R_L - R_s}}}} \quad [5] \quad 3$$

$$G = \frac{V_L}{V_s} = \frac{1}{2} \sqrt{\frac{R_s}{R_L}} \quad [5] \quad 4$$

In this circuit, C1 represents the shunt capacitor, while L denotes the series inductor. R_s corresponds to the antenna's resistance, and V_s is the input voltage from the antenna. Meanwhile, R_L and C_L represent the resistance and capacitance of the rectifier circuit, with V_L as the output voltage delivered from the LC network to the filter and rectifier stages. Finally, G signifies the gain of the system.

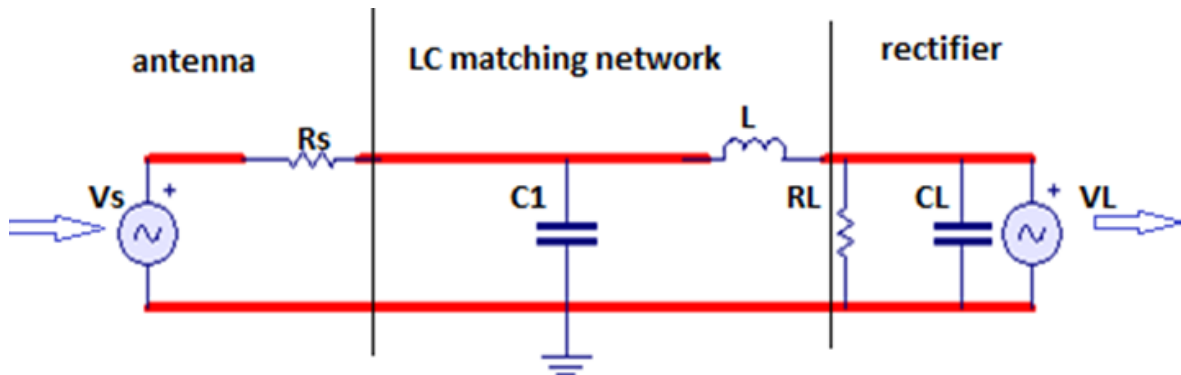


Figure: 2 LC matching network [5]

We designed the matching circuits for the dipole antenna using AWR Design Environment (AWR DE), leveraging its tuning tools and Smith chart capabilities. The design process followed these steps:

Initial Setup: We connected a 100-j50 ohm grounded resistor to a 50 ohm port (Figure 3a). Simulation on the Smith chart showed the cursor positioned at 2-j1 (Figure 3b).

Inductor Tuning: We added a shunt inductor of unknown value to the circuit. Using the tuning tool, we adjusted the inductor value to move the cursor upward until reaching the desired SWR position (Figure 4). At 30 MHz, this yielded an optimal inductor value of 387 nH.

Capacitor Determination: We then moved the cursor downward to the center line where the SWR circle intersects, obtaining a required series capacitor value of 91 pF (Figure 5). This configuration resulted in proper termination of the 50 ohm, 30 MHz antenna (Figure 6).

Performance Verification: Finally, we simulated the insertion loss (S11 parameters) to validate the design (Figure 7). We applied this same methodology to model all subsequent impedance matching circuits for the system.

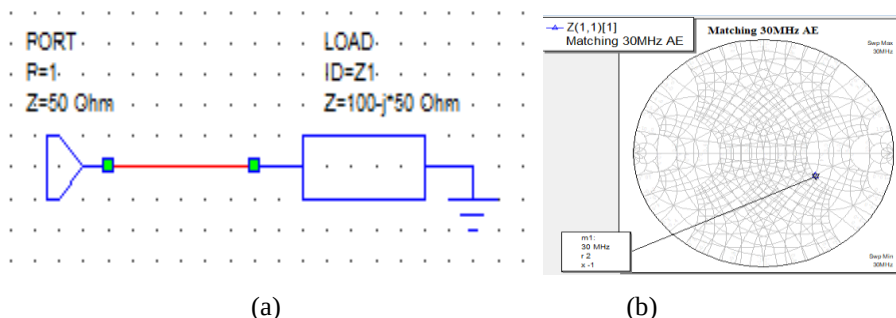


Figure: 3 (a) impedance of 100-j50 cct (b) simulated normalised impedance on smith chart . stage 1

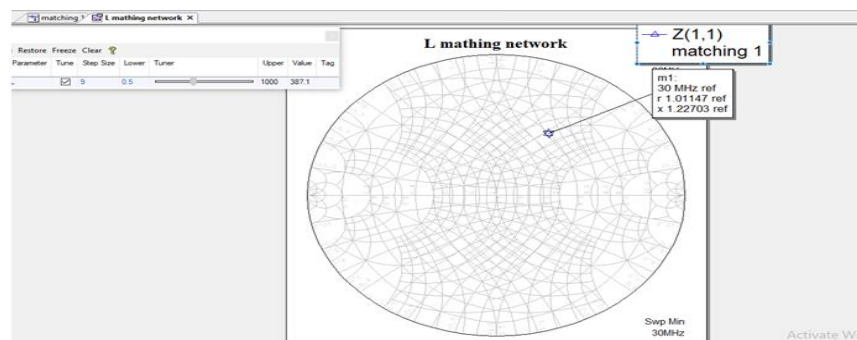


Figure: 4 inductor tuning stage 2

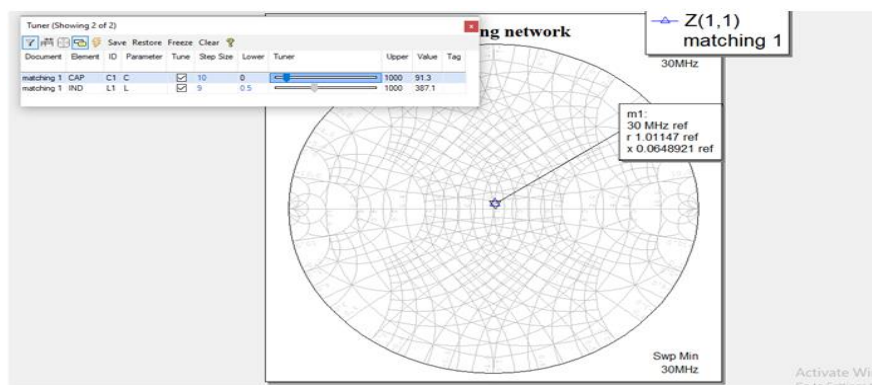


Figure: 5 capacitor tuning stage 2

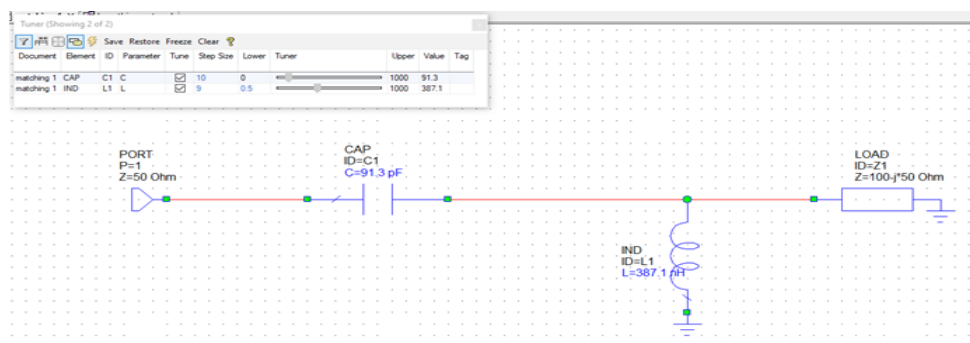


Figure: 6 schematic of a matched antenna impedance of 100-j50 ohm

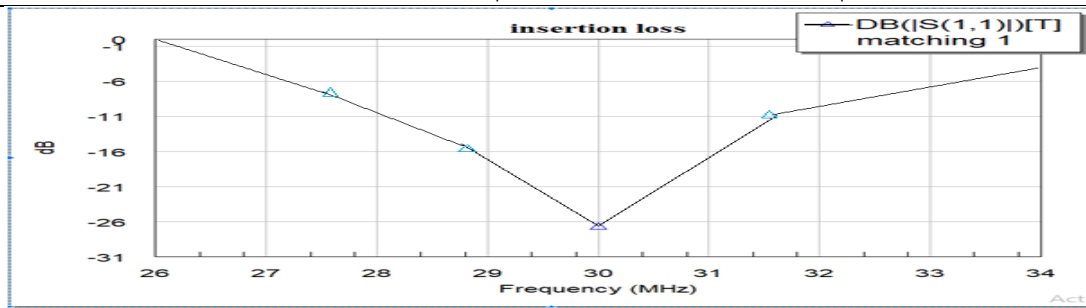


Figure: 7 insertion loss at 30 MHz

Filter Bank design

The fundamental requirement for filter design is determining the appropriate cutoff frequencies. We based our frequency selection on spectrum analyzer measurements conducted during a field survey in Cranborne, Harare Zimbabwe. The survey identified the strongest signal peaks across the frequency spectrum, which we attributed to commercial broadcast stations, radio transmissions, and television signals.

For the upper frequency bands, our measurements revealed dominant signals originating from Wi-Fi networks and cellular base stations. To maximize energy harvesting potential, we intentionally designed both low-pass and high-pass filters with wider bandwidths than strictly necessary. This approach allows the system to capture energy from additional, unidentified RF sources that may be present in the environment.

Table: 2 filter bank design

Filter type	Cut-off frequency	Source	Filter name	Order	Elements
1. low pass	1.8 KHz	Commercial Broadcast	Butterworthy	4 th	Lumped
2. Band pass	24 MHz,36 MHZ	Commercial Broadcast	Butterworthy	9 th	Stubs
3. Band pass	52 MHz,120 MHZ	TV & Radio broad cast	Butterworthy	9 th	Stubs
4. High pass	1.4 GHz	LTE, WI-FI	Butterworthy	12 th	Stubs

Low pass filter modeling

The first filter in our bank is a low-pass filter designed for capturing low-frequency transmissions, particularly shortwave radio broadcasts. This passive filter uses a ladder configuration of reactive components (inductors and capacitors), which exhibit negligible losses at these low frequencies.

The cutoff frequency (f_c) is a critical design parameter, representing the frequency at which the filter begins attenuating signals above this threshold. As shown in Figure 7, this corresponds to the point where the output voltage drops to 70.7% of its maximum value (-3 dB). For our design, we set the cutoff frequency at 1.8 kHz.

The fundamental cutoff frequency equation is:

$$f_c = \frac{1}{2\pi LC}, \quad 5$$

Where:

L represents the equivalent inductance

C represents the equivalent capacitance

The component values (L and C) are determined by solving the polynomial roots that define the filter's response curve. This mathematical approach ensures optimal filter performance for our target frequency range. The values of g are also provided, where:

$g_1 = L_1$, $g_2 = C_2$, $g_3 = L_3$, $g_4 = C_4$. Then

$$L_k = \frac{R_0 L_k}{\omega_c}, \quad 6$$

$$C_k = \frac{C_k}{R_0 \omega_c},$$

ω_c is the cut-off frequency, R value of resistor and c capacitor

Voltage is given by:

$$|V_{out}| = |V_{in}| \frac{1}{\sqrt{1+w^2 L^2 C}} \quad , [8] \quad 7$$

We implemented the circuit design using AWR Design Environment, utilizing passive components for the filter structure. The schematic (Figure 8) shows the complete configuration with the following component values:

Inductors: L1 = 9.25 mH, L2 = 3.85 mH

Capacitors: C1 = 1.54 μ F, C2 = 3.7 μ F

For voltage measurements, we employed M1 and M2 probes to monitor the input and output signals respectively. This setup allowed us to verify the circuit's performance characteristics and validate the design parameters.

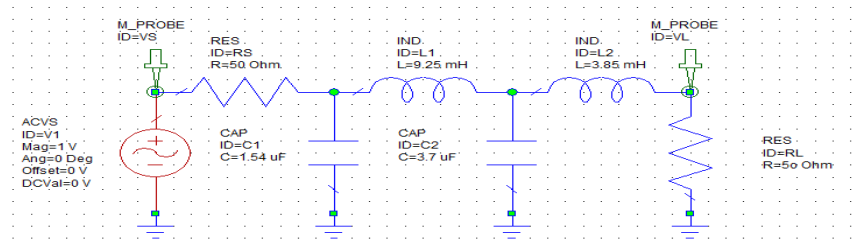


Figure: 8 Fourth order Butterworth low pass passive filter.

The circuit in figure 8 was simulated and the results shown in figure 9. The voltage in and out harmonic index was set to 1. At 100Hz -20,83 dB and the cutoff at -3dB, frequency of 1809Hz. The slope is -145dB/decade.

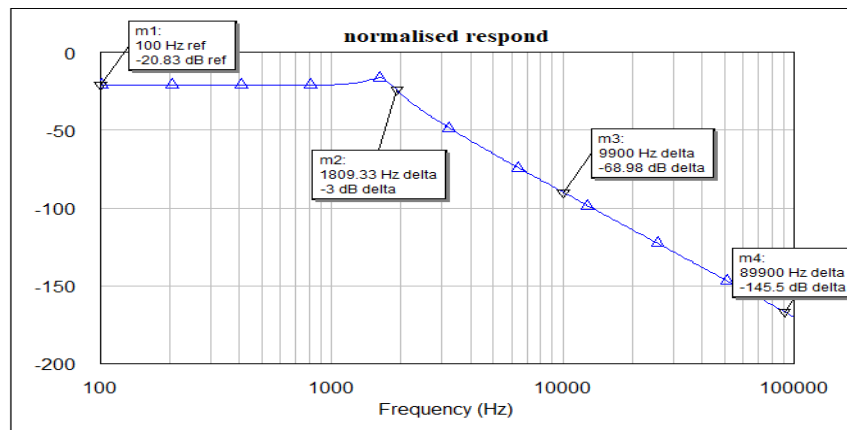


Figure: 9 low pass filter S parameter characteristics curve

Voltage gain. The frequency responds is found by the laplace responds. Transfere function $H(s)$ is given by:

$$H(s) = \frac{V_{out}(s)}{V_{in}(s)} = \frac{w_0}{s+w_0} \quad , \quad 8$$

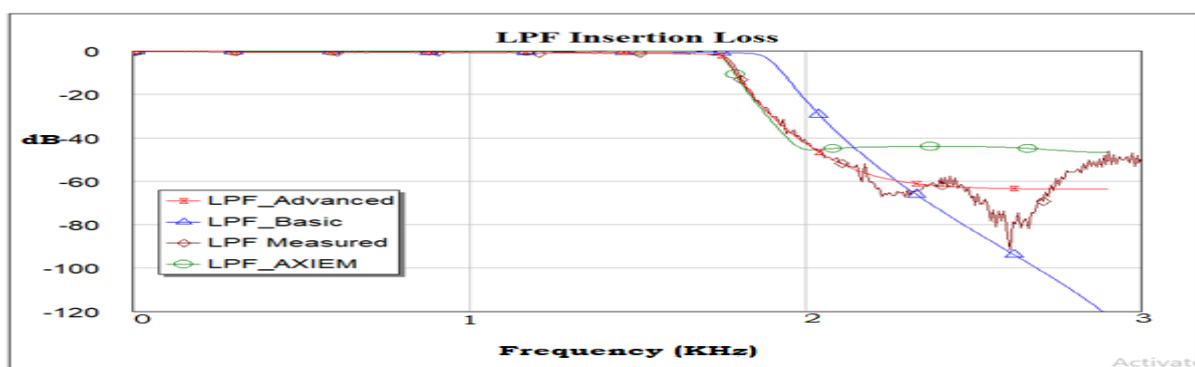


Figure: 10 Comparison of insertion loss.

Band pass filter modeling

The second and third stages of our filter bank consist of two bandpass filters. We implemented 9th-order Butterworth bandpass filters, with one optimized for the High Frequency (HF) band and the other for the Very High Frequency (VHF) range.

To overcome the limitations of lumped elements at higher frequencies (which become increasingly lossy), we employed Richard's Transformation [16] to convert lumped components into transmission line equivalents, followed by Kuroda's identities to derive their equivalent values. The distributed parameters are characterized by:

For closed-circuit stubs:

$$X_l = \omega_c L = Z_0 \sin \varphi, \quad (17) \quad 9$$

The distributed parameters of open stubs are given as:

$$X_c = \frac{1}{\omega_c C} = Z_0 \cos \varphi, \quad (17) \quad 10$$

Using AWR Design Environment, we successfully replaced the conventional lumped L and C components with microstrip stubs that maintain equivalent electrical properties. This distributed-element approach offers superior stability and easier tuning compared to discrete components. As illustrated in Figure 12, the design implements:

Series stubs to represent inductors

Shunt stubs to represent capacitors [16]

Our spectrum analysis revealed particularly strong RF activity at 30MHz in Harare, Zimbabwe, with significant signal peaks observed. This abundant transmission activity in this frequency band makes it especially suitable for energy harvesting applications.

The complete microstrip implementation (Figure 12) was designed using the following parameters calculated in AWR Design Environment (Figure 11):

Substrate dielectric constant: 4.5

Conductor material: Copper

Input/output impedance: 50Ω

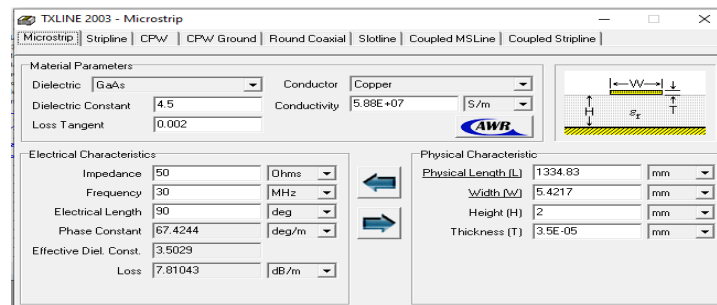


Figure: 11 AWR Microstrip calculations

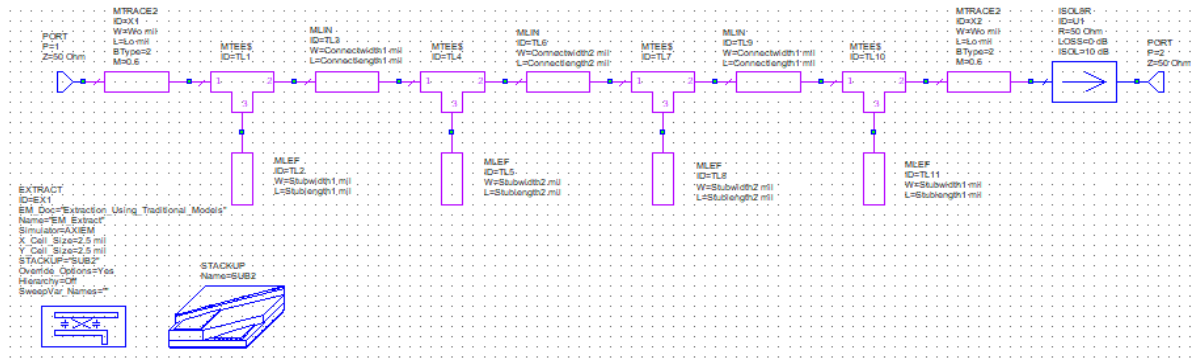


Figure: 12 Showing the 30MHz band pass filter using stubs.

S-parameter simulations were performed using a conventional method on AWS. The center frequency was set to 30 MHz, with the two corner frequencies at 24.8 MHz and 36.1 MHz, respectively. The substrate material selected was Flame Retardant 4 (FR4), with a relative permittivity of 4.5 [6]. (See Figure 13.)

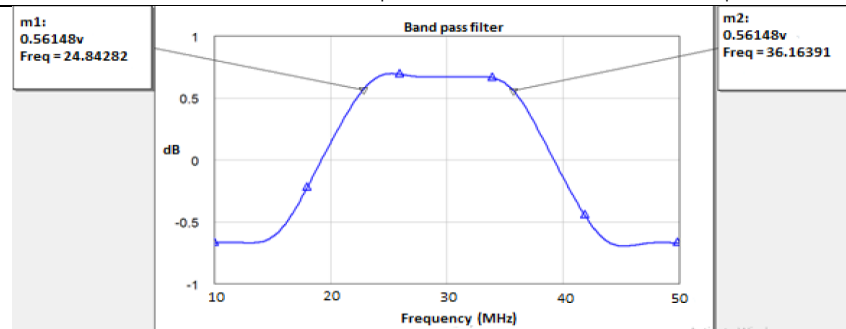


Figure: 13 Band pass filter characteristics curve

We conducted comprehensive simulation and analysis of the second band-pass filter to evaluate its performance. Three distinct modeling approaches were compared to identify the optimal response:

EM uBend Simulation - Our initial simulation using electromagnetic bending analysis

Closed Form Model - An analytical solution based on theoretical equations

Full EM Simulation - A complete electromagnetic field solution

All simulations were performed using Microwave Office software. As shown in Figure 14, the Closed Form model demonstrated superior accuracy, maintaining perfect alignment with the target center frequency of 56 MHz without any frequency shift - a significant advantage over the other modeling approaches.

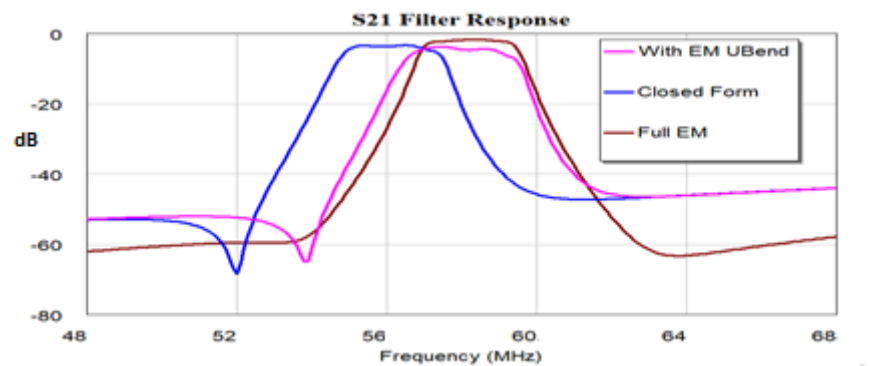


Figure: 14 Comparing the frequency responds S21 characteristics .

Using EM simulator integrated within the Microwave Office, we produced the models in figure 15. The substrate parameters are not changed. These models are then printed and etched on the FR4 substrate during fabrication.

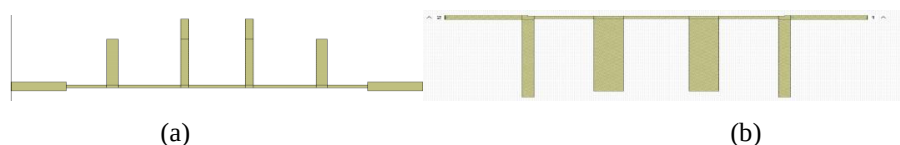


Figure:15 Band pass models created by AWR Design Environment (not to scale) (a) 30MHz, (b) 56MHz

High pass filter modeling

The fourth stage in our filter bank consists of a high-pass filter specifically designed for:

Cellular and WI-FI transmissions (primarily in the 2.4-5 GHz range)

Stray frequencies from natural RF sources

Our spectral analysis revealed significant energy concentration around 3 GHz, prompting us to set the filter's cutoff frequency at 1.4 GHz for optimal performance. The circuit was implemented using microstrip block elements within AWR Design Environment (Figure 16).

We analyzed the filter's frequency response through S-parameter simulations (Figure 17) and verified the physical implementation through electromagnetic (EM) printouts (Figure 18).

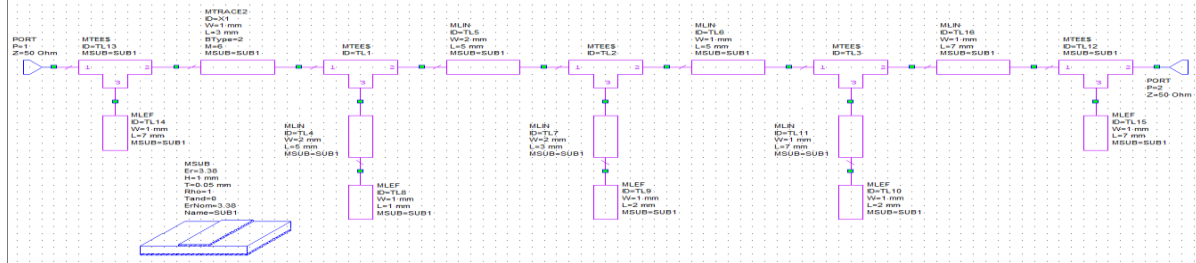


Figure: 16 Schematic diagram of a high pass filter using stubs

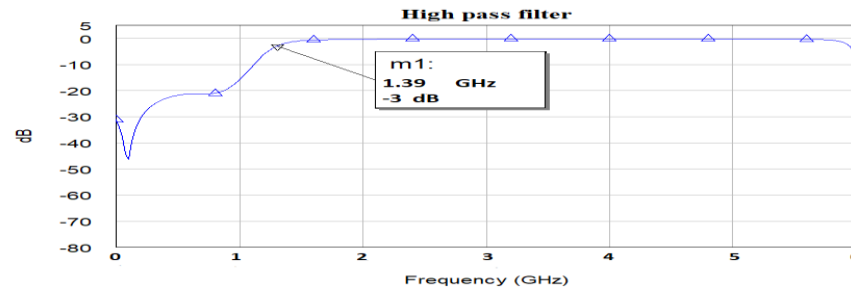


Figure: 17 Frequency characteristics curve of a high pass filter

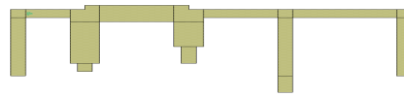


Figure: 18 high pass model, print on microstrip substrate (not to scale)

Rectifier and Voltage Doubler Circuit Design

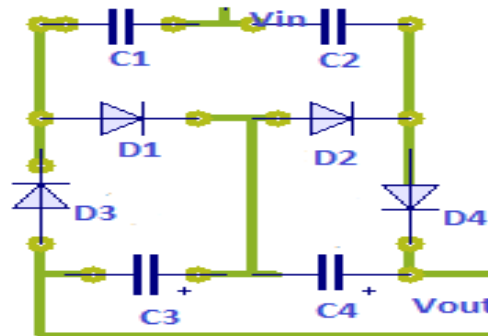


Figure: 19 rectifier and voltage doubler circuit

For optimal performance, the rectifier's input impedance must be approximately 100Ω (both real and imaginary components) to ensure proper impedance matching [18]. The resonant LC tank circuit is critical, as it determines the cutoff frequency (f_c), which defines the upper limit for efficient rectification. Beyond f_c , the rectified signal's power diminishes by a factor of $(f_c)^2$ [7].

We selected an **ultra-fast diode (1N4148)** over conventional Schottky diodes (commonly proposed in literature) due to its superior characteristics.

Faster switching for improved RF signal capture

Lower impedance, enabling weak-signal rectification

Circuit Operation (Figure 19):

Positive half-cycle: D_1 and D_2 forward-bias, charging capacitors C_3 and C_4 .

Negative half-cycle:

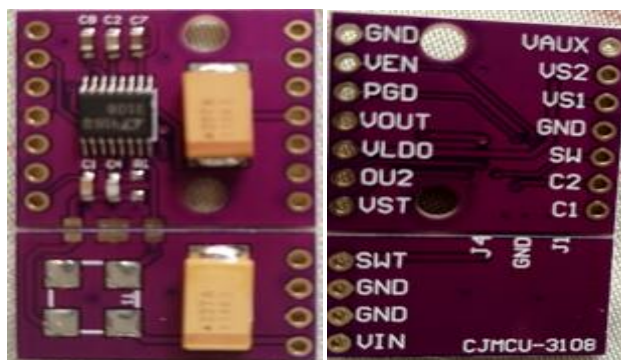
D_3 conducts through C_1 , charging C_3 .

D_2 conducts through C_2 , charging C_4 .

The **output voltage** is the sum of C_3 and C_4 , with their large capacitance values ensuring capture of high-amplitude transients.

Current Booster

The last circuit is the current booster see (figure 15) (a) and (b). This module is capable of accepting 0.5 vdc 1 uA to 5 vdc 0.5 A



(a) (b)
Figure 20 – (a) current booster (b) pin out

RF Haverster Prototype fablication

The schematic diagram was designed using Circuit Wizard (Figure 21). The track layout was modified to incorporate the microstrip filters, as shown in Figure 22.

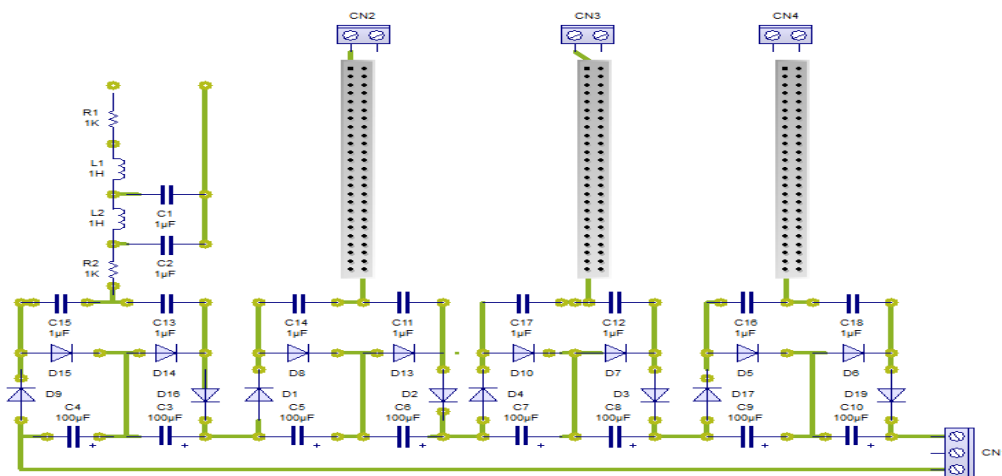


Figure: 21Schematic diagram for the RF energy Harvester

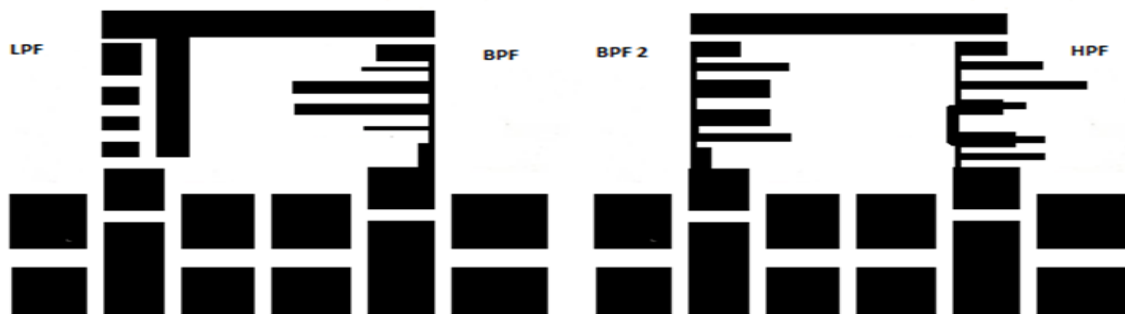


Figure: 22 Track layout of the RF energy Harvester

In the next phase, we fabricated the circuit on double-sided FR4 substrate, as illustrated in Figure 23b, with all components properly soldered (shown in Figure 23c). Additionally, we implemented a Butterworth stepped-impedance low-pass filter (Figure 23a) for simulation and comparative analysis.

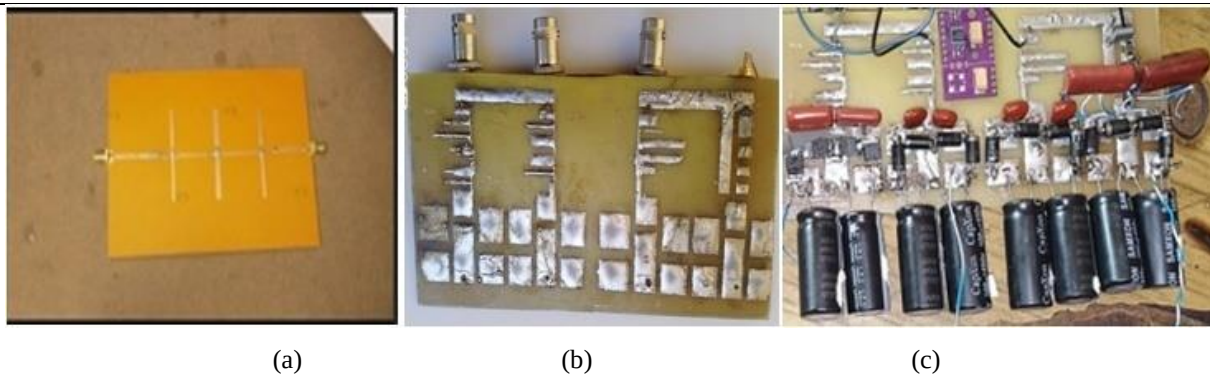


Figure: 23 (a) butterworthy steeped impedance low pass filter, (b) track layout of the harvester on FR4, (c) Complete harvester prototype.

Field simulation of prototype

A test bench was established in the laboratory to evaluate the filter performance. Each filter was systematically characterized using both a system analyzer (Figure 24a) and an oscilloscope (Figure 24b), with the complete experimental setup shown in Figure 24c.

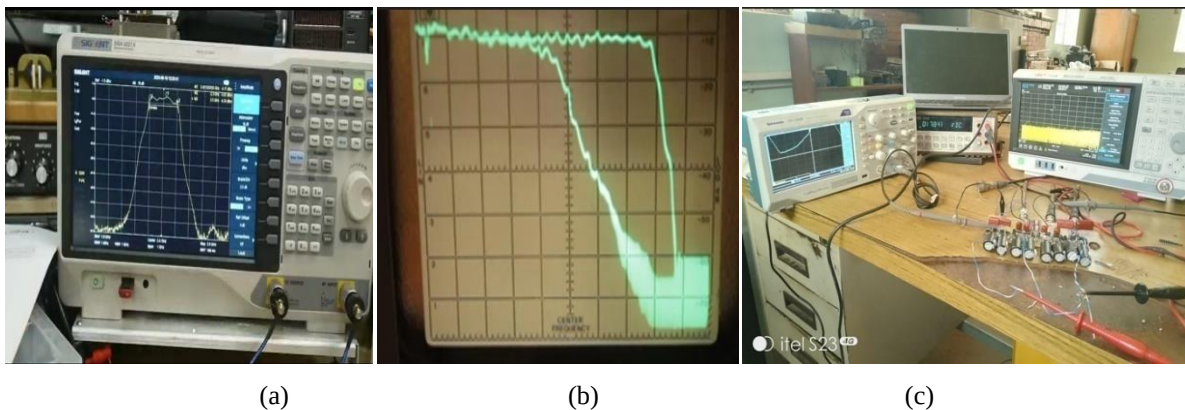


Figure 24- (a) band pass simulation on systems analyser (b) low pass filter on oscilloscope (c) The complete experiment setup and prototype under test. steeped butterworth low pass on FR4 substrate.

III. Discussion of Results and Comparative Analysis

Simulation and practical testing demonstrated excellent system performance, with significant improvements in both efficiency and energy capture. Key results include:

High Efficiency Operation

Measured data (Table 3) confirms minimal energy losses

Maximum energy harvesting capability achieved

Enhanced RF Capture

Substantial increase in harvested RF energy percentage

Improved frequency selectivity observed

Verification

Comprehensive measurement points documented (Figure 25)

Consistent performance across test conditions

The design successfully optimized the energy conversion chain, demonstrating practical viability for real-world RF harvesting applications.

We calculated efficiency using this formula:

$$\eta = \frac{V_{out}}{V_{in}} \times 100 \quad 11$$

For the first antenna, the input voltage measured 0.1 V while the output voltage was 0.07 V measured from the filter output. Substituting these values into Equation 11:

$$\eta = \frac{0.07V}{0.1V} \times 100$$

$$\eta = 70\% \quad \text{Answer}$$

The average total circuit efficiency was measured at 80%. It should be noted that minimal losses occur when using stubs.

$$\text{Circuit efficiency} = \frac{70+84+86+80}{4} = 80$$



Figure: 25 Testing points

Table: 3 Simulation results

band	frequency	Input voltage	Filter voltage	output	efficiency	Voltage booster output
LF	1.8 KHz	0.1	0.07		70%	0.5VDC
HF	30 MHz	0.369	0.31		84%	3VDC
VHF	56 MHz	0.318	0.254		80%	3VDC
UHF	2.4 GHz	0.26	0.224		86%	3.5VDC
All					80%	10VDC

Experimental observations revealed that the load capacitor requires four hours to charge up to 10 VDC, while discharging rapidly under a 270 Ω load (Figure 26). The current booster circuit failed to function as intended.

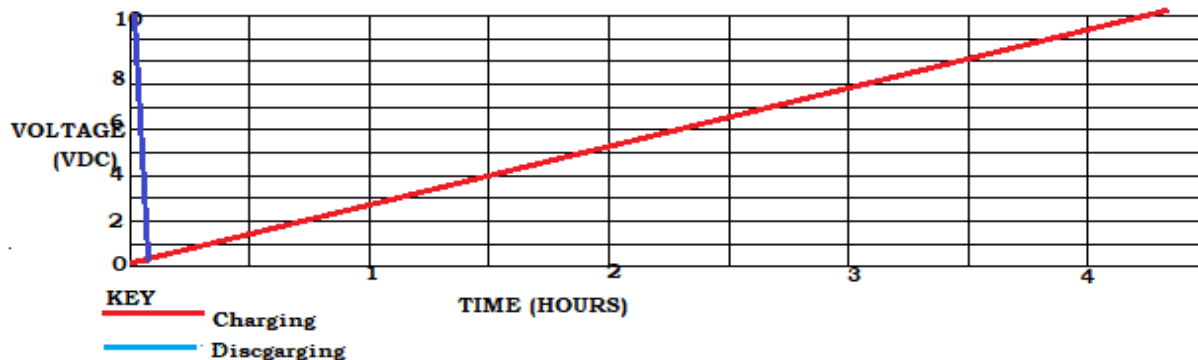


Figure: 26 harvester charging and discharging rate

Table 4 - Comparison of results [5]

Author	year	Frequency/band	Harvested voltage
M. Arrawatiwa [19]	2011	900MHz	0.25VDC
N. Md Din [20]	2012	945MHz	0.2VDC
T. Taris [21]	2012	902MHz	0.3VDC

L. M. Borges [11]	2015	900MHz	0.37VDC
Dr. K. Umapathy [9]	2016	900MHz	1VDC
S. Shen [22]	2019	900, 1800MHz	0.5VDC
Z. Zeng [23]	2020	900 MHZ	0.4VDC
N. Taruvinga [6]	2021	956MHZ	0.3VDC
G. Sinati [This work]	2025	1.8KHz, 30MHz, 56MHz, 1.4 GHz	10VDC

IV. Conclusion

This study successfully achieved its primary objectives, demonstrating significant advancements in RF energy harvesting:

Performance Achievements

Generated **10 VDC open-circuit voltage**, substantially exceeding comparable designs

Achieved **80% conversion efficiency**, validating the system's effectiveness

Prototype Evaluation

The implemented design showed robust operational performance

Current output remains an area for future optimization

Development Potential

Next-phase research will focus on:

Current output enhancement

AI enhancement on RF harvesting

System miniaturization for integration into handheld devices (smartphones, wearables)

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