DOI: https://doi.org/10.52756/ijerr.2024.v46.002 *Int. J. Exp. Res. Rev.*, Vol. 46: 19-30(2024)

Original Article | Peer Reviewed | Open Access

International Journal of Experimental Research and Review (IJERR)

ISSN: 2455-4855 (Online)
www.iaph.in

Design of Compact Triple-Band Antenna with Dual-Band Rectifier for RF Energy Harvesting

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Article History:

Received: 02nd Jun., 2024
Accepted: 06th Dec., 2024
Published: 30th Dec., 2024

Keywords:
Antenna with reflector, Compact antenna, Dual-band Rectifier, RF Energy Harvesting, Rectenna, Triple-band antenna

How to cite this Article:
A. A. Trikolikar and Swapnil Lahudkar (2024). Design of Compact Triple-Band Antenna with Dual-Band Rectifier for RF Energy Harvesting. *International Journal of Experimental Research and Review*, *46*, 19-30.
DOI: https://doi.org/10.52756/ijerr.2024.v46.002

Abstract: A rectenna is a device that converts electromagnetic energy into direct current electricity. An antenna and rectifier are the main components of a rectenna; the antenna serves the purpose of receiving radio frequency energy that exists in the environment, & rectifier is utilized for converting captured RF energy into DC power. This paper presents an edge-fed triple band (2.4, 3.5, & 5.8 GHz) semicircle arc-shaped patch antenna designed using a low-cost FR4 substrate. The antenna has compact dimensions of 31 mm*28 mm*1.6 mm ($0.25\lambda_0$ * $0.22\lambda_0$ * $0.013\lambda_0$), suitable in the context of harvesting radio frequency energy from ambient environments. The configuration of a high-gain antenna involves situating a reflector positioned 18.5 mm beneath the antenna, thereby achieving gain levels of 3.49 dB, 7.48 dB, and 8.78 dB at designated frequencies. An equivalent circuit of the antenna was accomplished by utilizing ADS, and the results were analyzed in comparison to the reflection coefficient values derived from HFSS at the relevant frequencies. Furthermore, a rectifier capable of dual-band operation at 1.80 GHz and 2.45 GHz has been developed and fabricated. The outcomes for both the proposed antenna and rectifier are then analyzed in relation to findings documented in the current literature. The innovation presented in this study is characterized by the unique design of the antenna, which allows for the manipulation of its resonance frequency. The proposed antenna offers significant benefits, including reduced dimensions and enhanced gain performance.

Introduction

The method of collecting and turning radio frequency energy from the environment into electrical energy is known as 'RF energy harvesting (RFEH)' (Fang et al., 2022). Systems that use such a method can generate energy from nearby radio frequencies, such as those using cellular networks, Wi-Fi and Bluetooth. There is no longer a requirement for conventional batteries or cable power sources because this captured energy may be utilized to recharge batteries or operate low-power gadgets and sensors. Among the advantages of RF energy harvesting are: longer device lives, lower operating costs, greater flexibility and enhanced security (no need to change batteries in dangerous conditions). Nevertheless, RF energy harvesting still has inadequate efficiency and a restricted capacity for power gathering.

Many rectennas have been introduced earlier for single-frequency, dual-band and triple-band operations. A high gain (7.31 dBi) patch antenna with HSMS-2850-based voltage doubler designed to operate at 2.4 GHz was developed by Khan et al. (2024). The developed rectenna achieved an efficiency of 64% for an input power of 0 dBm. In (Ribadeneira-Ramírez et al., 2023) an insert-feed microstrip antenna and HSMS-2850 Schottky diode-based rectifier are presented, which operate at 2.45 GHz. In their research, Prashad et al. (2023) and Sharan et al. (2024) developed a circular microstrip antenna that functions at 2.45 GHz, achieving a gain of 2.38 dBi. They also incorporated a voltage doubler based on the HSMS2852 diode, which demonstrated an efficiency of 52% when powered at 0 dBm. Manjunath and Reddy (2024) developed a Multiband Elliptical Patch Octagon

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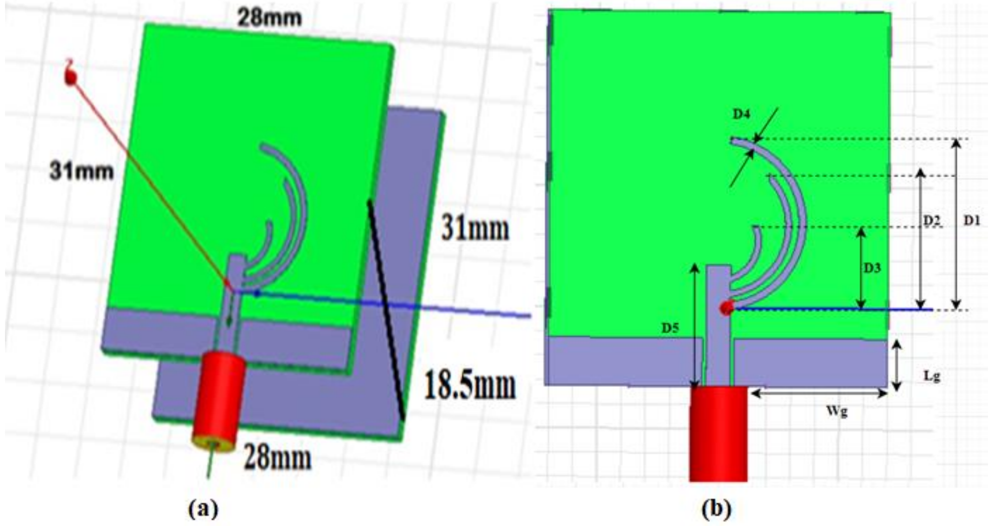

Figure 1(a). Schematic diagram of semi-circle arc-shaped antenna (b) Dimensions of Semicircle arc (D1=13.25 mm, D2=10.65 mm, D3=6.32 mm, D4=0.5 mm, D5=10 mm, Lg=4mm, Wg=12.7 mm).

Antenna with and without proximity coupling. Pramono et al. (2021) proposed an array-based rectenna at 2.45 GHz with a voltage multiplier circuit utilizing HSMS2850 diode and achieve a conversion efficiency of 77.5%. A rectenna working for 5.8 GHz is reported by Abdellah et al. (2019), which contains a patch antenna & HSMS2820 diode voltage multiplier.

The research presented in the references introduces dual-band rectennas designed primarily for the frequency ranges of 2.2–2.45 GHz & 5.2–5.8 GHz (Patil et al., 2023; Elkhosht et al., 2023; Deng et al., 2023; Said et al., 2021). Nevertheless, these rectennas exhibit considerable dimensions. A dual-band (3.1 GHz & 5.75 GHz), high gain (>4dB) Vivaldi antenna with HSMS2850-based rectifier is reported by Hosseini et al. (2024) & achieved efficiency of 50.8% for 5 dBm input power.

A triband (2.3, 3.5, and 5.7 GHz) rectenna is reported by Aboualalaa et al. (2023), which offers a PCE of 69.7% for 2 dBm power. Another slotted multiband (6.3, 7.4 & 9.1 GHz) antenna and rectifier having PCE of 56.7% was reported by Kashyap et al. (2023). Alaoui et al. (2023) propose a CSR-based MSA working for 2.4, 3.5, & 5.6 GHz and achieve a gain of 7 dB for 3.55 GHz. A slot antenna working in the range of 2.4 to 3.5 GHz, 4.8 to 5.5 GHz, & 5.7 to 7.9 GHz was reported by Behera et al. (2023). Fatima et al. (2022) developed a triple band (1.8, 2.4 and 3.5 GHz) monopole antenna with SMS7630 rectifier with a maximum conversion efficiency of 39.2% at the 1.8 GHz frequency.

This paper focuses on designing and fabricating a semi-circular arc-shaped antenna that operates effectively in three frequency bands and a dual-band rectifier for harvesting RF energy (Trikolikar et al., 2021).

The subsequent sections of the paper are structured in the following manner; the specifications of the recommended antenna scheme are outlined in Section 2. Section 3 elaborates on the design of the rectifier circuit. Section four describes the antenna, rectifier, measurement and analysis. However, the final section presents the conclusions.

Materials and Methods

Design of Triple-Band Semicircle Arc-Shaped Antenna

The diagram of the planned antenna is presented in Fig. 1 (a & b), containing a semicircle arc-shaped patch. The patch and ground plane are produced with FR4 substrate, which is sized at 28*31*1.6 mm^3. A reflector is positioned 18.5 mm under the antenna to increase the gain of the antenna, as displayed in Figure 1.

Figure 2 illustrates the semicircular arc antenna design procedure, which says that antenna 1 is created using an edge feeding technique with a single arc, antenna 2 is created with two arcs, and antenna 3 is formed with three arcs.

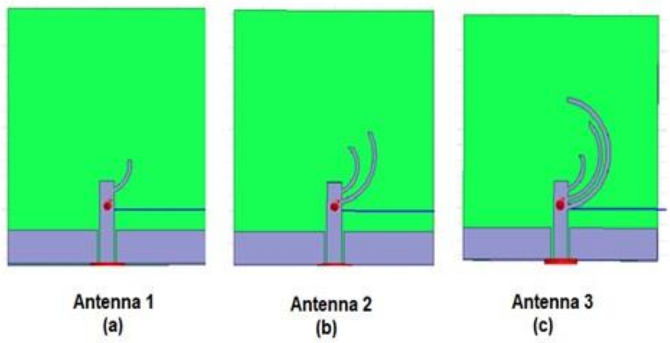

Figure 2. Development of planned antenna (a) antenna 1 (b) antenna 2 (c) antenna 3.

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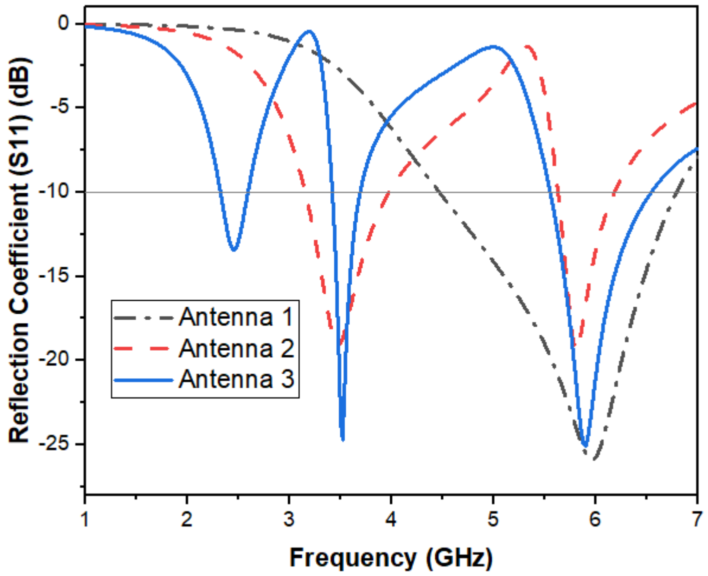

Figure 3. Plot of Reflection Coefficient (S_{11}) of 3 different antennas.

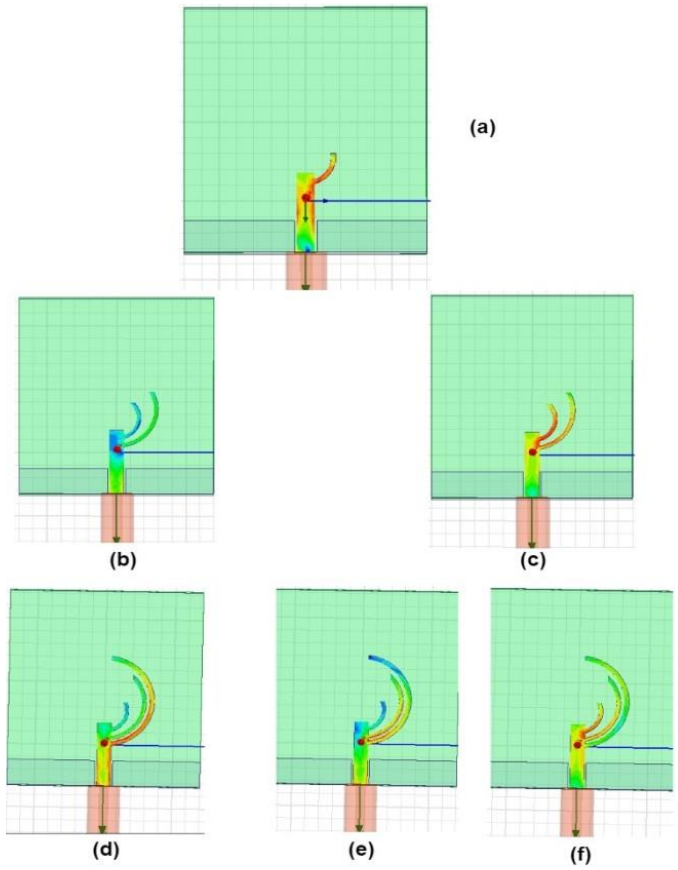

Figure 4. Current distribution of 1) antenna 1 (a) 5.8GHz; 2) antenna 2 (b) 3.5GHz, (c) 5.8GHz, 3) antenna 3 (d) 2.4GHz, (e) 3.5GHz, (f) 5.8GHz.

The data presented in Figure 3 indicates that antenna 1 exhibits resonance exclusively at 5.8 GHz, as illustrated by the reflection coefficient measured across all three antennas. The operational frequencies of antenna 2 are confined to 3.5 GHz and 5.8 GHz. In contrast, the newly proposed antenna, referred to as antenna 3, resonates for 2.4 GHz, 3.5 GHz, and 5.8 GHz. As shown in Figure 3, antenna 1 has S_{11} value of -25 dB at 5.8 GHz, and antenna 2 has -18 dB value of S_{11} for 3.5 GHz & 5.8 GHz frequencies. The planned antenna resonates at 2.45, 3.5, & 5.8 GHz with S_{11} values of -13 dB, -24 dB, & -25 dB, respectively.

Figure 4 depicts the current distribution of all antennas, demonstrating that antenna 1 has a superior current distribution at 5.8 GHz along the feeding path and arc. As shown in Figure 4(c), antenna 2 has a higher current flowing at 5.8 GHz and a lower current at 3.5 GHz along the feeding path and arcs [Figure 4(b)] for antenna 3, the current is stronger for the outer arc at 2.45 GHz [Figure 4(d)], stronger at the middle arc at 3.5 GHz

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[Figure 4(e)], and strongly distributed at the arc joining point for 5.8 GHz [Figure 4(f)], respectively.

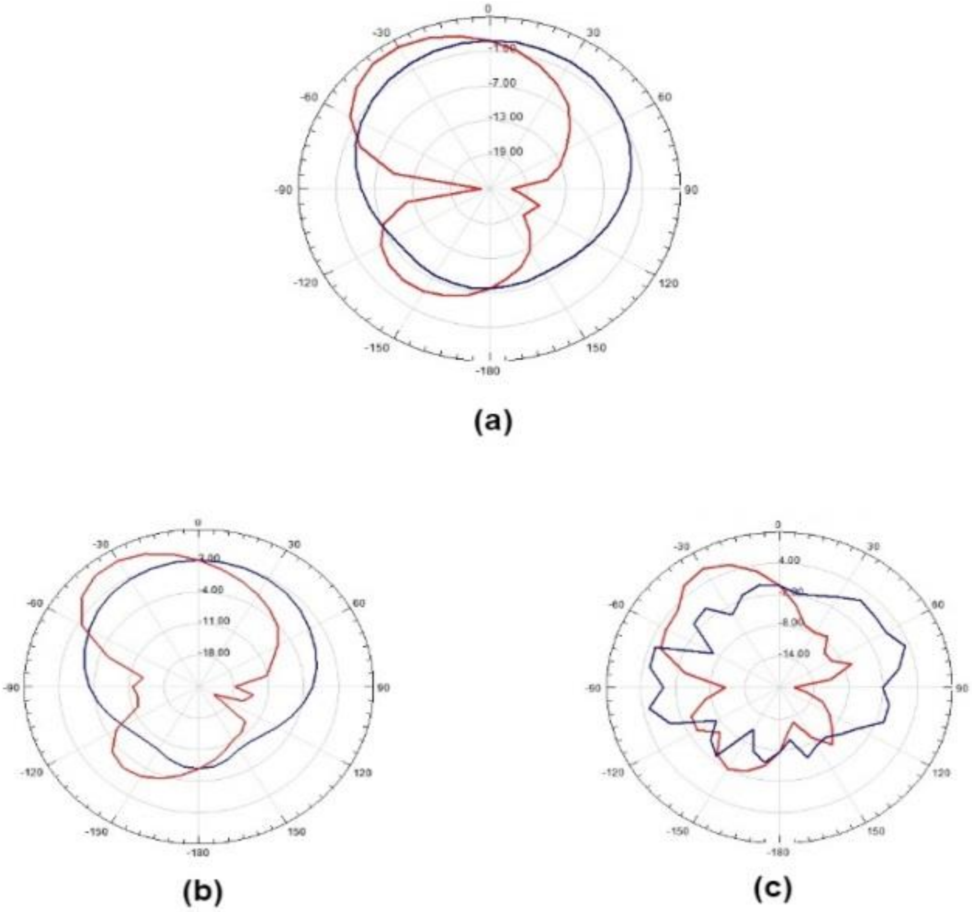

Figure 5. Radiation pattern of antenna 3 (a) 2.4GHz (b) 3.5GHz (c) 5.8GHz (In this figure red line indicates E plane pattern and the blue line indicates H plane pattern).

As shown in Figure 5, the radiation pattern of antenna 3 varies with frequency, being omnidirectional for 2.4GHz and 3.5GHz and transitioning to a quasi-omnidirectional pattern for 5.8GHz. This shows that the antenna can collect RF energy from every possible orientation.

Table 1 compares the gain of antenna 3 with and without the reflector, demonstrating an apparent gain boost with the reflector.

Table 1. Gain of antenna 3 with & without reflector.

Sr. No.	Antenna 3	Operating Frequency (GHz)	Gain (dB)
1	Without Reflector	2.53	1.78
		3.55	4.92
		5.73	7.60
2	With Reflector	2.46	3.49
		3.52	7.48
		5.84	8.78

The influence of the reflector on the gain of the antenna is also illustrated through the analysis of the current distribution both with and without the reflector, as depicted in Figure 6. The data presented in Figure 6 indicates a decrease in backward radiation, which subsequently reduces the current flow and enhances the antenna's gain.

The proposed antenna's equivalent circuit is represented in Figure 7, where it is modeled as parallel RLC circuits at resonance frequencies. This model is based on the impedance data analyzed in ADS (Keysight, n.d.) software. For a multi-band antenna, bandwidth can be considered as the result of several adjacent resonances, and each one can be represented by a parallel RLC circuit (Elabd et al., 2024), indicated using Figure 7.

A graphical representation in Figure 8 contrasts the S_{11} values for antenna 3, as simulated by HFSS (Sliusar et al., 2020) and ADS, and it is evident that there is a significant agreement between the results from both simulation tools.

Design of Dual-Band Rectifier

This paper discusses the development of a dual-band rectifier that functions for 1.80GHz & 2.45GHz. The rectifier's circuit diagram, presented in Figure 9, comprises a transmission line-based impedance matching network and a voltage doubler that incorporates SMS7630 (Skyworks, n.d.) diodes, implemented on a 1.6 mm thick FR4 substrate characterized by ε_r = 4.4 and tanδ = 0.02.

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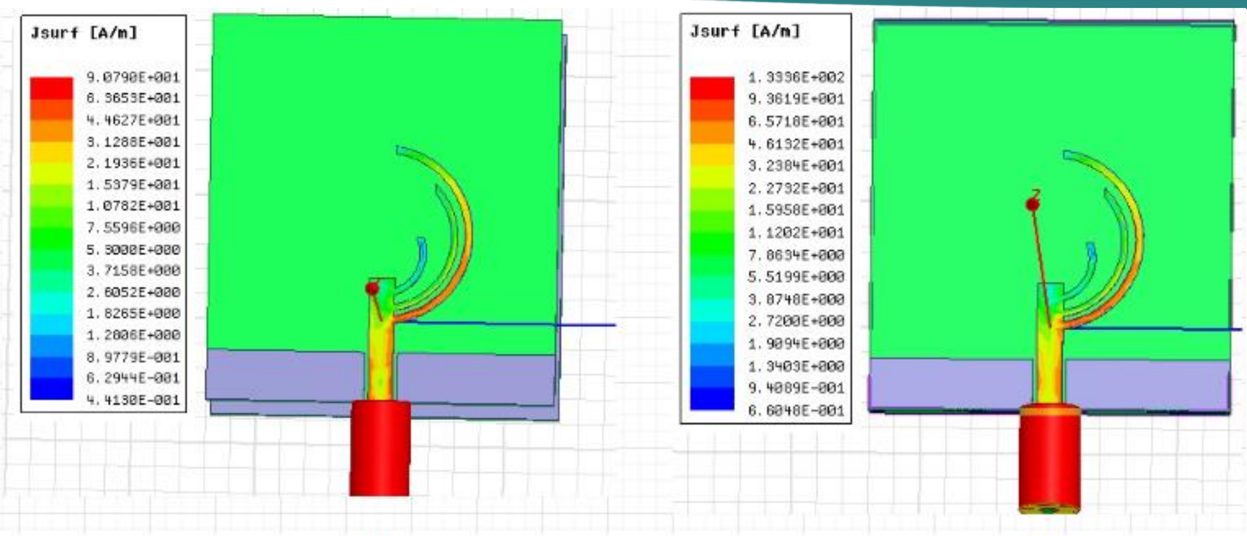

(a) **(b)**

Figure 6. Current distribution of antenna 3 (a) With reflector (b) Without reflector.

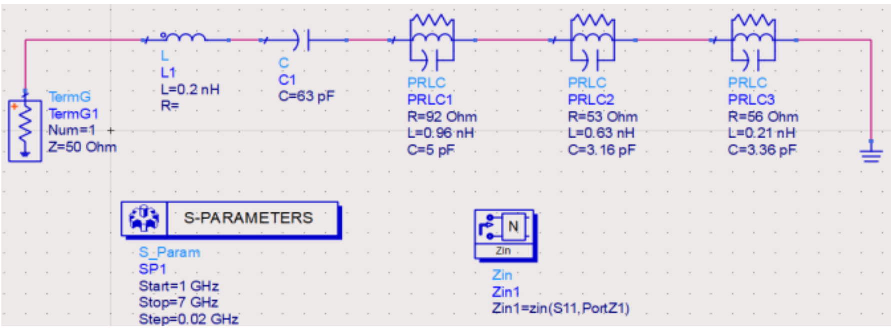

Figure 7. Equivalent circuit of the proposed antenna.

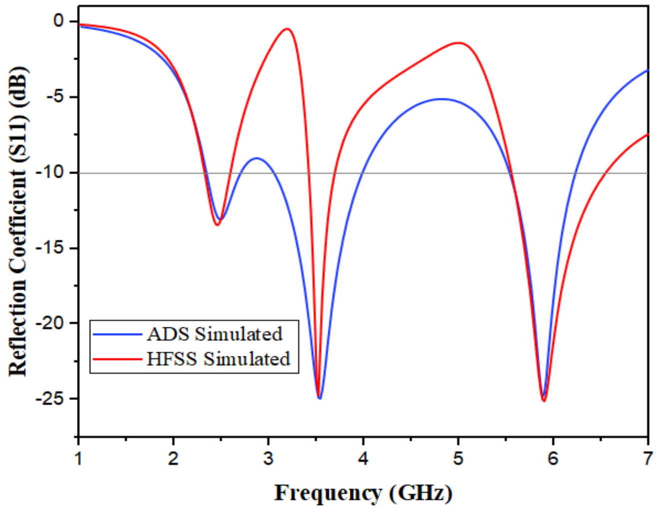

Figure 8. Comparison between ADS simulated & HFSS simulated values of S_{11}.

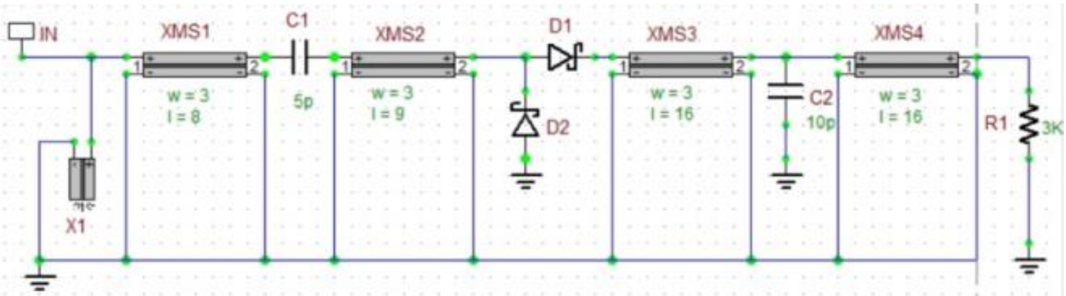

Figure 9. Circuit Diagram for rectifier.

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The voltage doubler comprises transmission lines XMS2 of length 9 mm, XMS3 and XMS4 of length 16 mm, each with a width of 3 mm for all lines, capacitors C1 (5 pf) and C2 (10 pf), along with two SMS7630 diodes. The impedance matching network is designed using a single stub (XMS1) having a length of 8 mm & width of 3 mm. The load of 3 KΩ is utilized in the circuit for optimal efficiency and the whole system has been fine-tuned to match the rectifier at the needed frequencies.

The graph of the simulated S_{11} for the rectifier is revealed in Fig.10, which shows the resonance of the rectifier at 1.80 GHz and 2.45 GHz. The value of S_{11} depends on parameters such as the input power provided and the load resistance connected to the circuit. Figure 11 & Figure 12 indicate variations in S_{11} for changes in input power and load resistance, respectively. As indicated in Figure11 & 12, S_{11} has minor variations due to changes in Pin and RL in all cases, its value is less than the standard -10 dB value for interested frequencies.

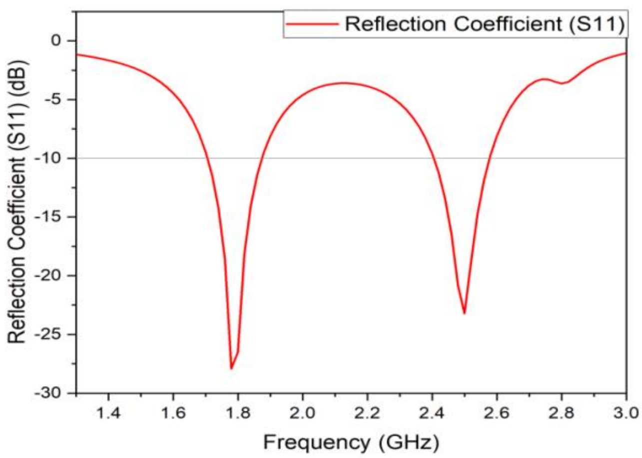

Figure 10. Graph of Simulated Reflection Coefficient (S_{11}) of rectifier.

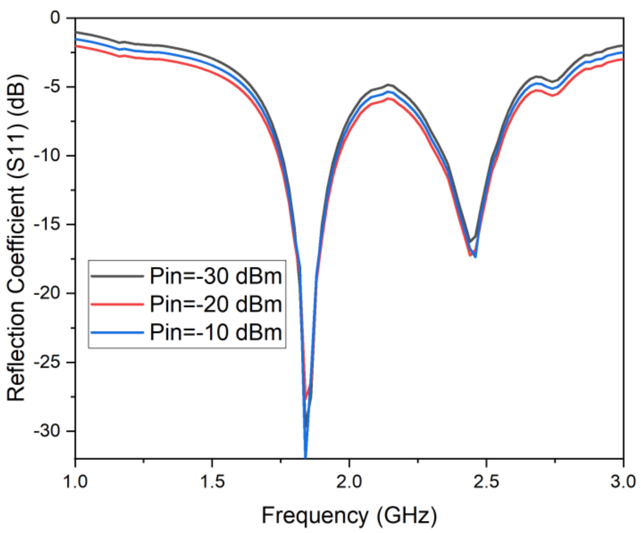

Figure 11. Effect of input power (Pin) on S_{11}.

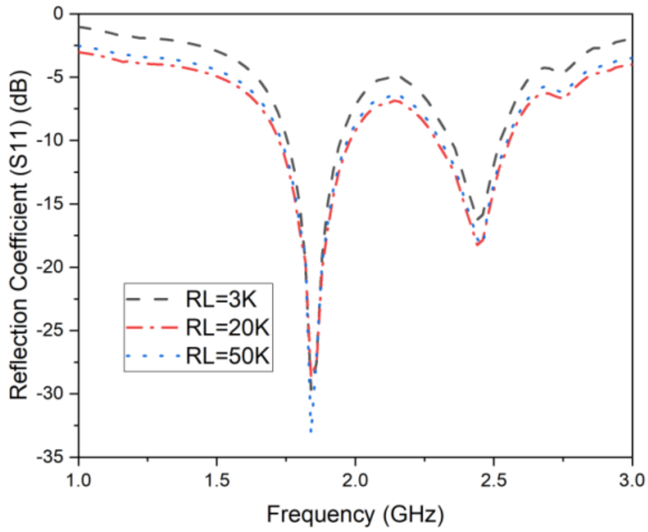

Figure 12. Effect of load resistance (R_L) on S_{11}.

The simulated value of power conversion efficiency for the rectifier is described using Figure 13, which displays that efficiency is 70% at 1.85 GHz & 65% at 2.45 GHz for a Pin of -5 dBm.

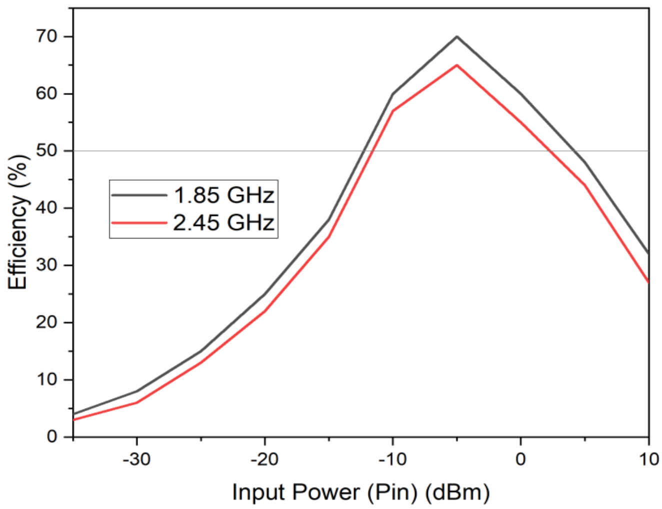

Figure 13. Plot of conversion efficiency for rectifier.

The rectifier exhibits greater efficiency at -5 dBm, closely approximating the power generated by common sources like Wi-Fi, cell phones, and digital TV broadcasts. Figure 13 also indicates that the rectifier's design results in an efficiency surpassing 50% across a significant Pin range, applicable to both resonance frequencies, from -10 dBm to 4 dBm.

Result and Discussion

Measurement & Analysis

Measurement of Antenna

The fabricated model of the proposed antenna is presented in Figure14. Its performance is measured using the Keysight N9923A VNA (Keysight, n.d.), as demonstrated in Figure 15. Figure 16 indicates a plot comparing the simulated and tested results for S11 of the suggested antenna. We observed that, for 2.4 GHz

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frequency band, we obtained a better value of measured S_{11} compared with the simulated one, and for other frequencies, the value of S_{11} is nearly equal in both cases.

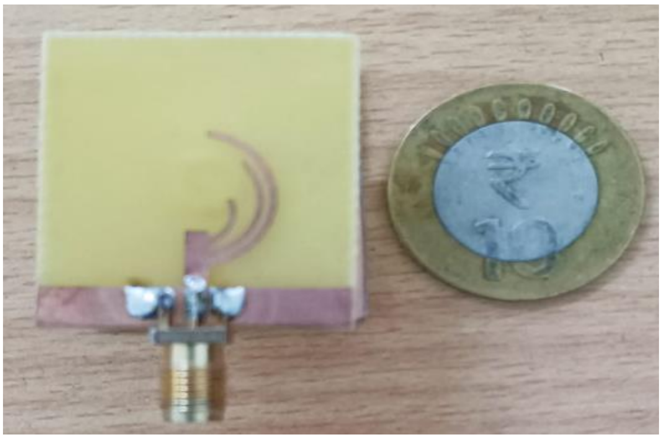

Figure 14. Fabricated model of antenna.

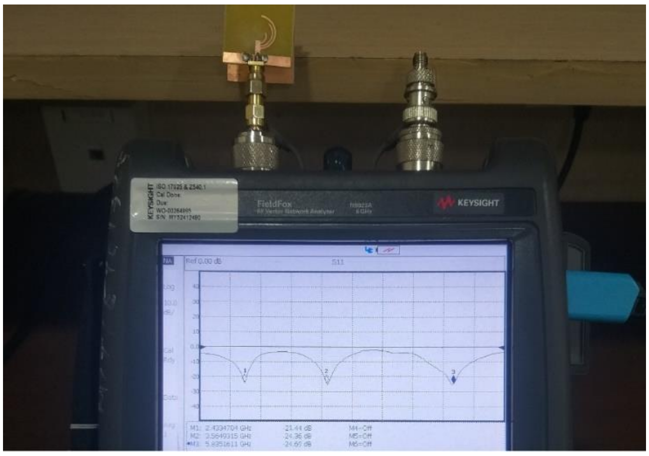

Figure 15. Performance Measurement of Antenna using VNA.

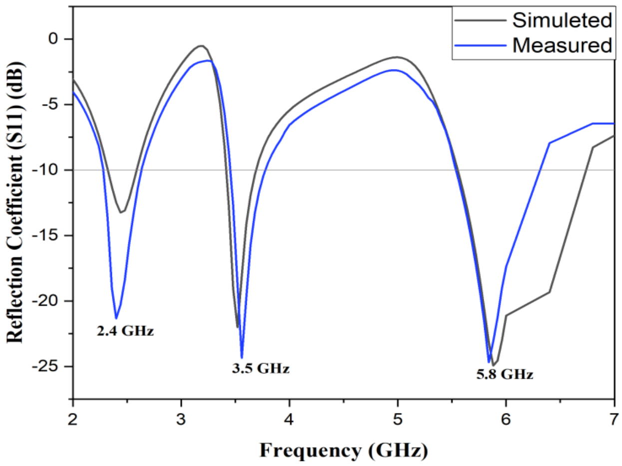

Figure 16. Plot for S_{11} comparison of simulated & measured results for the proposed Antenna.

In Table 2, a comparative evaluation of the proposed antenna with other relevant scholarly works is presented, highlighting that the dimensions of the suggested antenna are notably more compact than those found in earlier research. The above table also confirms that our antenna achieves better gain while employing a simple reflector of the same dimensions.

Measurement of Rectifier

The manufactured sample of the suggested rectifier is depicted in Figure 17, and its effectiveness is evaluated with the Keysight N9923A VNA, as illustrated in Figure 18. The S_{11} of the rectifier is determined with the use of a VNA and then compared to the simulated value. Figure 19 illustrates a significant correlation between measured and simulated values in both circumstances.

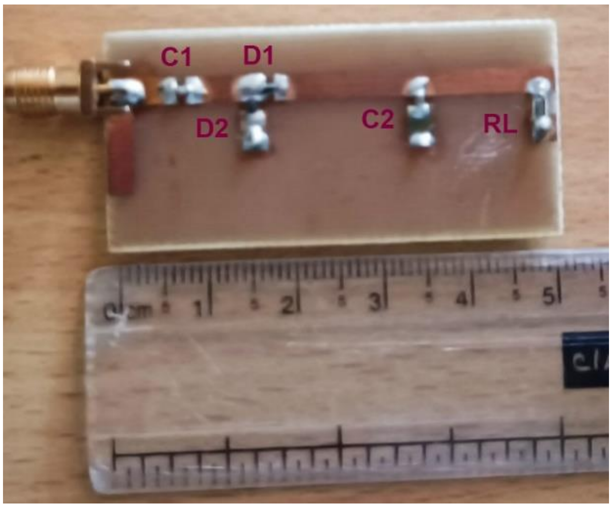

Figure 17. Fabricated prototype of rectifier

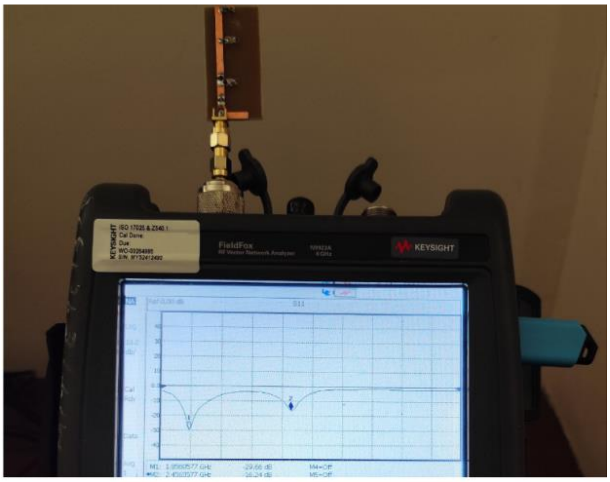

Figure 18. rectifier measurement with VNA

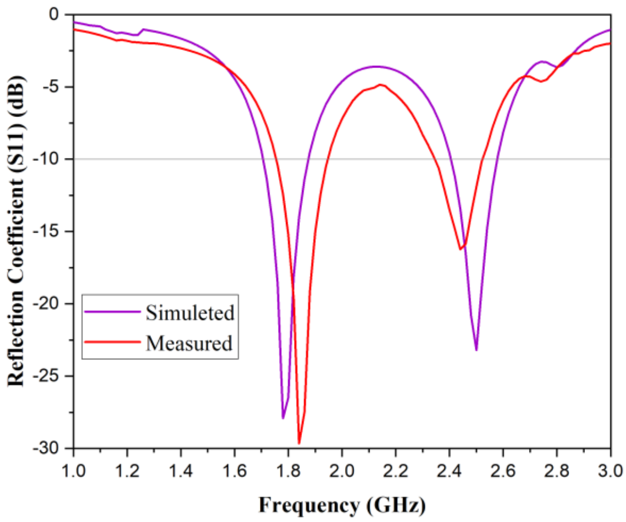

Figure 19. Simulated and measured S_{11} of rectifier.

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Table 2. Comparison of suggested antenna with linked work.

Ref.	Antenna Type	Frequency of Operation (GHz)	Size of antenna (W*L*H) (mm^3)	Size of Reflector (W*L*H) (mm^3)	Distance Between antenna & Reflector (mm)	Peak Gain (dB)	Gain Improvement Technique
Kumar et al., 2023	CPW fed Monopole	0.97 to 2.77	120*120*1.6 (0.38λ_0 * 0.38λ_0 * 0.005λ_0)	120*120*1.6 (0.38λ_0 * 0.38λ_0 * 0.005λ_0)	40	5.2 @ 2.35 GHz	phase gradient metasurface reflector
Jamal et al., 2023	UWB Planar	2 to 11	26*26*1.6 (0.17λ_0 * 0.17λ_0 * 0.010λ_0)	61*61*1.6 (0.40λ_0 * 0.40λ_0 * 0.010λ_0)	10	7.6 @ 9.6 GHz	FSS reflector
Polaiah et al., 2020	Monopole	1.8	70*80*1.6 (0.42λ_0 * 0.48λ_0 * 0.009λ_0)	120*120*1.6 (0.72λ_0 * 0.72λ_0 * 0.009λ_0)	Not Reported	7.1	Simple reflector
Mansour et al., 2020	Dipole loop	0.97 & 1.5 to 2.58	45*70*0.8 (0.14λ_0 * 0.22λ_0 * 0.002λ_0)	45*70*0.8 (0.14λ_0 * 0.22λ_0 * 0.002λ_0)	50	6.5 @ 2.1 GHz	Simple reflector
Behera et al., 2020	Y shape monopole	3 to 7	80*59.5*1.6 (1.09λ_0 * 0.59λ_0 * 0.016λ_0)	120*99.5*0.2 (1.2λ_0 * 0.99λ_0 * 0.002λ_0)	20	7.1 (Avg.)	PEC reflector
Farias et al., 2019	Patch	2.4 & 5.8	40*40*1.6 (0.32λ_0 * 0.32λ_0 * 0.012λ_0)	81*81*1.6 (0.64λ_0 * 0.64λ_0 * 0.012λ_0)	35.3	7.54 @ 2.4 GHz	FSS reflector
Eid et al., 2017	Slot	2.45	109*82*1.6 (0.89λ_0 * 0.67λ_0 * 0.013λ_0)	118*88*0.035 (0.96λ_0 * 0.72λ_0 * 0.0002λ_0)	17	6.5	Copper sheet as reflector
Prop. Work	**Semicircle Arc Shape**	**2.4, 3.5 & 5.8**	**31*28*1.6 (0.25λ_0 * 0.22λ_0 * 0.013λ_0)**	**31*28*1.6 (0.25λ_0 * 0.22λ_0 * 0.013λ_0)**	**18.5**	**8.78 @ 5.8 GHz**	**Simple reflector**
λ_0 = free space wavelength which is calculated at lower resonance frequency.							

Table 3. Recommended rectifier compared with related work.

Ref.	Operating Frequency (GHz)	Size (W*L*H) (mm^3)	Substrate	Diode	Simulated Efficiency (%)	Input Power for Efficiency (dBm)
Li et al., 2024	2.45 & 5.8	34.7*26*1.016 (0.28λ_0 * 0.21λ_0 * 0.008λ_0)	F4B	HSMS2852	63.6 @ 2.45 GHz 43.8 @ 5.8 GHz	9 11
Mehta et al., 2024	2.45 & 5.5	72*8.5*1.6 (0.58λ_0 * 0.069λ_0 * 0.013λ_0)	FR4	SMS7630	47 @ 2.45 GHz 27 @ 5.5 GHz	-10

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Maher et al., 2023	1.85 & 2.45	33*55*1.57 (0.20λ_0 * 0.33λ_0 * 0.009λ_0)	Rogers 5880	HSMS2850	73 @ 1.85 GHz 69 @ 2.45 GHz	3 2
Nguyen et al., 2023	1.81 & 2.35	35*60*0.8 (0.21λ_0 * 0.36λ_0 * 0.004λ_0)	Taconic TLY	HSMS2860	76.3 @ 1.81 GHz 76.2 @ 2.35 GHz	13 13
Zhang et al., 2022	1.9 & 2.4	3.4cm*4.7cm* 0.8mm (0.21λ_0 * 0.29λ_0 * 0.005λ_0)	Rogers 4350B	GaN HEMT	75 & 76	10
Alhily et al. 2021	1.8 & 2.4	5.5*5 (mm^2) (0.032λ_0 * 0.029λ_0)	Not Reported	HSMS2850	52 for both frequencies	-5
Prop. Work	**1.85 & 2.45**	**25*50*1.6 (0.15λ_0 * 0.30λ_0 * 0.009λ_0)**	**FR4**	**SMS7630**	**70 @ 1.85 GHz 65 @ 2.45 GHz**	**-5**

λ_0 = free space wavelength, which is calculated at lower resonance frequency.

Figure 19 also shows that, for 1.8 GHz, the measured value of S_{11} is better as compared to the simulated value. This is due to the direct connection of the rectifier to the VNA during measurement, thereby avoiding connector losses. Finally, Table 3 illustrates a comparison of the planned rectifier with similar investigations, revealing that the designed rectifier possesses a more compact design and superior efficiency at reduced power levels.

Conclusion

This research paper outlines a compact antenna structure with a semi-circular arc design intended for applications in RF energy harvesting. This antenna is notably compact, measuring 31×28×1.6 mm³, and is fabricated using an FR4 substrate. The antenna design presented demonstrates improved gain, which is accomplished by incorporating a reflector positioned at the lower section of the antenna. The comprehensive outcomes of this antenna design are obtained through HFSS simulations, and these results are validated through an equivalent circuit representation utilizing ADS. The designed antenna is manufactured & evaluated utilizing a VNA, demonstrating a strong correlation with the simulated data.

This study also addresses designing and manufacturing a dual-band rectifier specifically tuned to 1.85 GHz and 2.45 GHz, employing the SMS7630 diode. The rectifier is printed with a cost-effective FR4 substrate and is optimized for a load of 3 KΩ. When the Pin is set at -5 dBm, the rectifier demonstrates 70% and 65% efficiency, respectively. Additionally, the efficiency remains above 50% for power levels extending from -10 dBm to 4 dBm, which renders it appropriate for practical low-power scenarios. The antenna and rectifier design presented here achieves superior performance relative to existing research in the field. The next research phase will focus on integrating the antenna with the rectifier to create a rectenna, which will then be tested in an ambient environment.

Conflict of Interest

None.

Acknowledgement

The authors express their gratitude to the editor and reviewers whose feedback and recommendations improved the manuscript's quality.

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How to cite this Article:
A. A. Trikolikar and Swapnil Lahudkar (2024). Design of Compact Triple-Band Antenna with Dual-Band Rectifier for RF Energy Harvesting. *International Journal of Experimental Research and Review*, *46*, 19-30.
DOI : https://doi.org/10.52756/ijerr.2024.v46.002

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