INTERNATIONAL JOURNAL OF MICROWAVE AND OPTICAL TECHNOLOGY,
VOL.19, NO.3, MAY 2024

A Compact Double Comb Shape Slotted Rectenna for Ambient RF Energy Harvesting

Saranya N*, Raja P, Jayanthi S, Vighneshwara B, Janani R, Raghavardhini K

Department of Electronics and Communication Engineering
Sri Manakula Vinayagar Engineering College, Puducherry, India.
Email: saranyawinmile@gmail.com

***Abstract*- This article presents a novel 2.45 GHz compact double comb-shaped slotted rectenna system designed to capture RF energy from the environment. The proposed rectenna integrates two comb-like structures into a square patch antenna, and a voltage doubler rectifier circuit with a small footprint, measuring 48x31x1.5mm^3. The design features semi-circular slots at the patch center to improve bandwidth and impedance matching, while the double comb structures enhance antenna return loss characteristics and radiation performance. The rectenna prototype was constructed on a 1.5 mm thick, cost-effective FR-4 substrate. Both modeling tools and measurements were used to analyze the rectenna harvesting capacity. The analysis results show a return loss (S11) of -10 dB across a fractional bandwidth of 17.14% between 2.3 GHz and 2.48 GHz. The rectifier circuit achieves a maximum energy conversion efficiency of 83% at 2.45 GHz and an output voltage of 2.2V with a 2 kΩ load resistance. The analysis of experimental data demonstrates that the proposed rectenna efficiently harvests RF energy from the surrounding environment.**

***Index Terms*- Double comb antenna, impedance matching, partial ground plane, rectenna, RF energy harvesting**

I. INTRODUCTION

Efficient use of radio frequency (RF) power is a major concern in modern wireless communication systems. The demand for self-sustainable devices and energy-efficient wireless systems has significantly impacted RF energy harvesting research and development. An RF energy harvesting system captures RF energy from various ambient sources, such as cellular towers, WiFi transmitters, and mobile transmitters, and converts it into electrical energy [1-2].

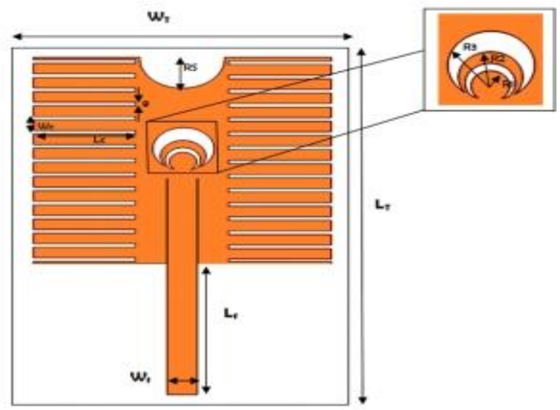
A rectenna, short for "rectifying antenna," is a key component in RF energy harvesting systems. It converts electromagnetic energy into usable DC power. The challenge lies in efficiently harvesting low-power-density RF signals while maintaining high RF-to-DC conversion efficiency. The choice and design of the receiving antenna along with the impedance matching between the antenna and the rectifier circuit and rectifier modeling are fundamental parameters for achieving high conversion efficiency of the rectenna. The antenna gain, polarization, and resonance frequency are crucial for maximizing the energy harvesting capability of the rectenna [2-4].

Over the past few decades, researchers have proposed various receiving antenna structures and rectifier circuit models to address the challenges in energy harvesting systems. For example, a dual-band circular patch microstrip antenna with a circular slot ground plane structure achieved gains of 8.3 dBi at 1.95 GHz and 7.8 dBi at 2.45 GHz [5]. Additionally, a multiband four-cross dipole rectenna demonstrated a maximum conversion efficiency of 41% when exposed to an incident power of 1.8 mW/cm²[6]. A microstrip patch array rectenna achieved a conversion efficiency of 44% at 5.8 GHz [7]. In a CPW quad-band rectenna design, conversion efficiencies of 42% and 30% were achieved at 0.9 GHz and 2.45 GHz, respectively, with overall dimensions of 48 x 42 mm² [8]. Other rectenna designs, such as a differentially slotted rectenna and printed monopole antenna fed with a CPW (coplanar waveguide) ground plane, have exhibited conversion efficiencies of 53%, 13%, and 15.56% at different frequency bands [9-10]. Furthermore, researchers have explored dual-band, multiband, wideband, and broadband rectennas, achieving conversion efficiencies of 40%, 30%, and 26% for applications involving the harvesting of ambient RF energy [11-18].

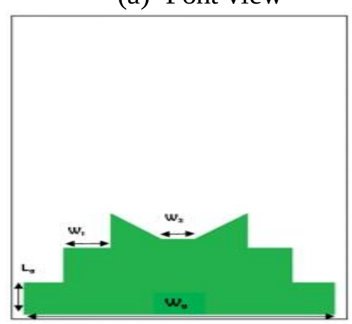
In this article, a compact double comb-shaped slotted rectenna system operating at 2.45 GHz is proposed and implemented for ambient RF energy harvesting of wireless LAN applications. The ISM (industrial, scientific, and medical) band refers to a range of radio frequencies allocated internationally for industrial, scientific, and medical purposes. The primary purpose of the ISM band is to provide a frequency range where unlicensed devices can operate without interfering with licensed radio communication services. The ISM band varies in frequency allocation across different regions, but the most commonly used ISM bands are the 2.45 GHz ISM band (WiFi) and the 5.8 GHz band. The proposed design focuses on a rectenna for the 2.45 GHz ISM band. The rectenna includes a dual-comb like structure incorporated onto a microstrip square patch antenna and a voltage doubler rectifier circuit. The rectenna occupies an area of 48x31x1.5mm^3 and is simulated and fabricated on a low cost FR-4 substrate with a thickness of 1.5 mm.

A comb antenna, also known as a toothed antenna or a comb-shaped antenna is an antenna design that consists of multiple parallel radiating elements or dipoles composed of n-parallel conducting elements fed by a microstrip line. The double comb structure improves the return loss characteristics of the antenna while maintaining a compact size and better radiation characteristics. Semi-circular slots are introduced at the center of the patch to further enhance the bandwidth and impedance matching of the antenna. The Cockcroft-Walton voltage doubler rectifier circuit with an L-type microstrip line impedance matching network is used as the rectifier circuit efficiently converts the RF energy into DC power. The organization of the paper is as follows: Session 2 covers the antenna design and parametric analysis. Session 3 discusses the implementation of the voltage doubler rectifier circuit. Session 4 presents the results and discussion. Session 5 conclude the proposed design.

II. ANTENNA DESIGN AND PARAMETER STUDY



(a) Font view



(a) Back view

Fig.1. Physical dimension of the proposed antenna with design parameters

The proposed double comb-shaped slotted antenna configuration is illustrated in Fig. 1. The antenna consists of a microstrip patch with a comb-like structure on both sides. The comb structure features multiple parallel radiating elements or dipoles that are evenly spaced. The double comb structures enhance the antenna's return loss characteristics, resulting in a compact size and improved radiation characteristics. Semi-circular slots at the center of the patch further improve the antenna's bandwidth and impedance matching. The use of a defected ground structure is a widely employed technique to improving the performance of patch antennas, boosting gain, bandwidth, and reducing cross-polarization.

The proposed antenna is made of 1.5mm thick FR-4 material with a dielectric constant of 4.6. The use of a high dielectric constant material allows for a compact design by reducing the aperture area as the dielectric constant (ε_r) increases. Bandwidth enhancement in the microstrip patch antenna is achieved by incorporating a defected ground plane on the bottom side.

A. Antenna Feeding System

The proposed antenna uses a microstrip insert feeding technique to feed the antenna system. A 50 Ω microstrip transmission line serves as the feeding element, supplying input power to the antenna. The insert feeding technique allows for control of the antenna's impedance through adjustments to the insert gap and inset feed length and width. This technique is straightforward to implement and enables control of the antenna's characteristics.

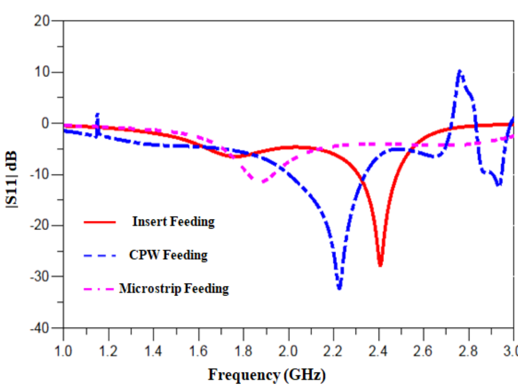


Fig.2. Comparison of reflection coefficient of antenna with different feeding techniques

Different types of feeding techniques such as microstrip feeding, CPW and insert feeding techniques have been implemented in the proposed antenna structure. The reflection coefficients of various feeding techniques are plotted in Fig.2. Analysis reveals that insert feeding techniques offers higher impedance matching at the resonance frequency compare to other techniques. The proposed insert feeding system acts as impedance matching network between the input and the antenna. Microstrip insert feeds provide excellent impedance matching capabilities, which are crucial for minimizing signal reflections and maximizing power transfer between the feed line and the antenna elements. In proposed antenna impedance matching highly depends on microstrip feed-line length and insert gap. The inset feed introduces a junction capacitance that influences the resonance frequency of the antenna. As the feed point shifts towards the centre of the patch from the edge, the input impedance decreases and tends to zero at the centre. In this proposed work, the insert feed width is (W_f) =2.9 mm, feed length (L_f)=18.5 mm and the value of inset feed distance is 11.9 mm.

B. Antenna Equivalent Circuit Analysis

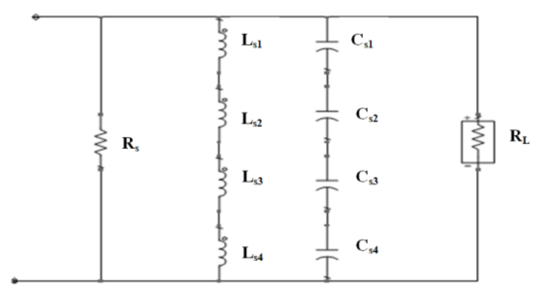


Fig.3. Equivalent circuit diagram of the proposed antenna with 4 vertical rectangular splits

The equivalent circuit diagram of the proposed antenna is illustrated in Fig.3. Initially derived from a square microstrip patch antenna, the proposed design is modeled with an RLC circuit. Through fine-tuning, the RLC parameter achieve the desired resonance frequency. The antenna's performance is further enhanced by incorporating a comb-shaped structure onto the square patch. This structure comprises 16 vertical rectangular slits, denoted as jX_s, positioned in parallel on both sides of the patch. Each vertical slit is composed of inductance (L_s) and capacitance (C_s), resulting in a combination of variable inductance and capacitance. The resonance is achieved due to the parallel combination of R, L and C element. These components contribute to size reduction and enable operation at a lower frequency. The equivalent circuit parameters are determined through simulations conducted using Advanced Design simulation software.

The resonant frequency (f_r) of the microstrip patch antenna can be determined using Eq. (1). The resonance frequency of the patch antenna depends on the length of the patch. As the patch length increases, the aperture area, effective dielectric constant (ε_{eff}) and fringing field also increase. Consequently, the resonance frequency decreases and the input impedance plot shifts towards the lower impedance values.

$$f_r = \frac{C}{2L\sqrt{\varepsilon_{eff}}} \quad (1)$$

where, L is the length of the microstrip patch, C is the speed of the light ($3*10^8$ m/s), ε_{eff} is the effective dielectric constant of the substrate. The width (W) and length (L) of the microstrip patch antenna are calculated using Eqs. (2)-(6). Based on the characteristic impedance (Z_0) of 50Ω, a dielectric constant o (ε_r) of 4.6 and a resonance frequency of 2.45 GHz.

$$W = \frac{C}{2f_r}\sqrt{\frac{2}{\varepsilon_r + 1}} \quad (2)$$

where, μ_0 is the permeability of the free space (4π x 10^{-7} N/A^2), ε_0 is the permittivity of the free space (8.854 x 10^{-12} F/m).

$$L = L_e + 2\Delta L \quad (3)$$

$$L_e = \frac{C}{2f_r\sqrt{\varepsilon_{eff}}} \quad (4)$$

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{h}{W}\right]^{-\frac{1}{2}} \quad (5)$$

$$\Delta L = 0.412\left\{\frac{(\varepsilon_{eff} + 0.33)\left[\frac{W}{h} + 0.26\right]}{(\varepsilon_{eff} - 0.033)\left[\frac{W}{h} + 0.26\right]}\right\}h \quad (6)$$

The dimensions of the partial ground plane are determined based on finite ground plane condition of the microstrip patch antenna. Specifically, the width of partial ground plane matches that of the finite ground plane, while the length is 0.12 times the operating wavelength (λ). The optimal values for all dimensional parameters are presented in Table 1.

Table 1: Dimension of the proposed antenna

Parameters	Physical Dimension (mm)	Parameters	Physical Dimension (mm)
WT	30	Rs	4.3
LT	50	R1	1.3
Wf	2.9	R2	2.9
Lf	18.5	R3	4.8
Wc	1.5	Wg	30
Lc	10	Lg	5
g	0.5	W1	4.8
W2	3	-	-

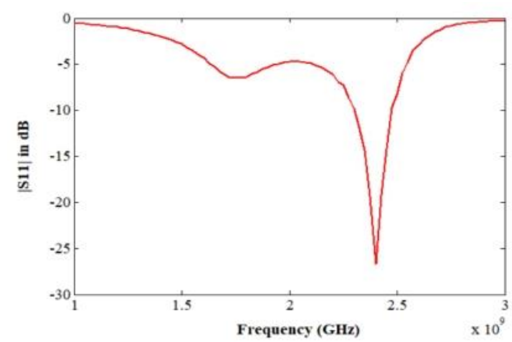


Fig.4. Simulated reflection coefficient ($|S_{11}|$) of the proposed antenna

The proposed antenna's reflection coefficient has been thoroughly analyzed and is depicted in Fig. 4. The graph demonstrates that the antenna operates effectively at 2.45 GHz with a remarkable reflection coefficient of -28 dB. As illustrated in Fig. 5 the antenna's surface current density plays a pivotal role in determining the overall efficiency of the antenna system. To enhance the surface current density, it is important to increase the ratio between the flow of current in the surface element (dI) and the length of the conducting element (dL). Therefore,

INTERNATIONAL JOURNAL OF MICROWAVE AND OPTICAL TECHNOLOGY,
VOL.19, NO.3, MAY 2024

to achieve a significant boost in surface current density, semi-circular slots and a gap 'g' have been strategically incorporated into the proposed antenna design.

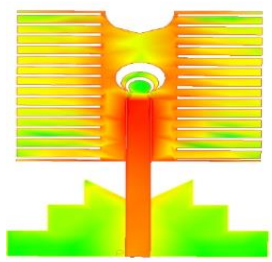


Fig.5. Performance of the surface current distribution at 2.45 GHz

III. RECTIFIER CIRCUIT DESIGN METHODOLOGY

The proposed rectenna system uses a Cockcroft-Walton voltage doubler circuit that employs HSMS-2850 Schottky diodes. These diodes are particularly suitable for low-power RF applications due to their relatively low forward bias voltage of 0.15V and fast switching at high frequencies. The topology of the rectifier circuit is illustrated in Fig.6.

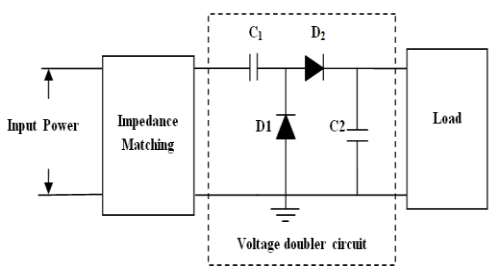


Fig.6. Equivalent circuit of the proposed rectifier

The voltage doubler circuit consists of two Schottky diodes D_1 and D_2, charging capacitors C_1 and C_2 and an AC input voltage source. When the input signal is applied during negative half cycle, diode D_1 becomes forward biased and allows the current to flow through the capacitor C_1 which charged to the peak value of the input voltage (Vps). Meanwhile, diode D_2 becomes reverse biased and does not conduct. During the positive half cycle, diode D_1 become reverse biased and does not conduct, while diode D_2 become forward biased and allows current to flow through the capacitor C_2. At the beginning of the negative half cycle, capacitor C_2 is discharged, but capacitor C_1 remains charged up to Vps. During the positive half cycle, capacitor C_2 charged to twice the input peak voltage ($2V_{ps}$).

$$C = I.\frac{dt}{dv} \tag{7}$$

Here C represents the charging capacitors, I is branch current and dt/dv is the ratio of change of voltage with respect to frequency variation. The values of the charging capacitors C_1 and C_2 are calculated using Eq. (8). The calculated values of the charging capacitors C_1 and C_2 are equal to 150 pF. The another important block in the rectifier circuit design is the DC pass filter which blocks any AC signal enters into the resistive load.

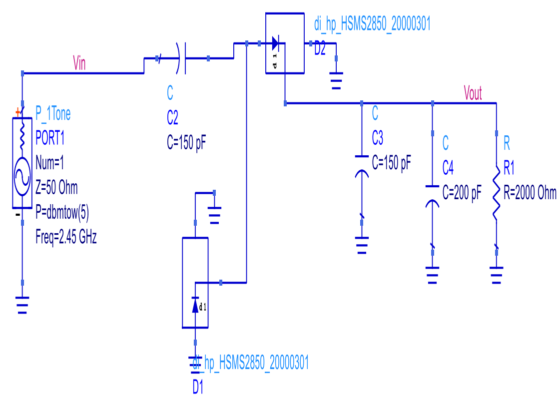


Fig.7. Topology of the proposed rectifier circuit

The proposed voltage doubler rectifier circuit is designed using ADS 2015.01 software as shown in Fig.7. In the rectifier circuit, the receiving antenna is considered as a sources element with input impedance (Z_{in}) of 50Ω, while the voltage doubler rectifier circuit is considered as a load element with output impedance (Z_L) of 7.85-102.6Ω. When there is an impedance mismatch between the rectifier circuit and the receiving antenna, the system's efficiency decreases due to the reflected power inside the circuit. To achieve maximum RF-to-DC conversion, an L-type impedance matching network is incorporated between the antenna and the rectifier circuit as depicted in Fig.8.

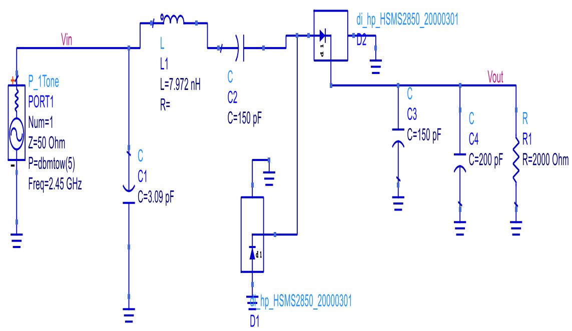


Fig.8. Proposed configuration of voltage doubler rectifier circuit

IV. RESULTS AND DISCUSSION

The prototype of the proposed antenna was meticulously fabricated using an FR4 dielectric substrate with a thickness of 1.5 mm, as shown in Fig. 9. The overall physical dimension of the antenna is $48x31x1.5mm^3$. The fabricated prototype of the dual comb slotted antenna underwent rigorous experimental verification using a Vector Network Analyzer. As shown in Fig. 10, there is an excellent match between the simulated and measured reflection coefficients of the proposed antenna, confirming its well-engineered design and high-performance capabilities. With a remarkable return loss of -31 dB, the antenna demonstrates minimal signal reflection. Additionally, the antenna provides impedance bandwidth spanning from 2.3 GHz to 2.48 GHz, encompassing a notable fractional bandwidth of 17%.

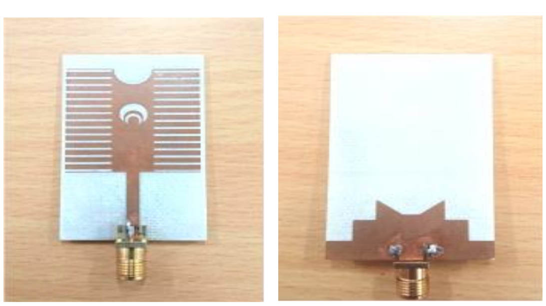


Fig.9. Fabricated dual comb antenna with defected ground plane structure

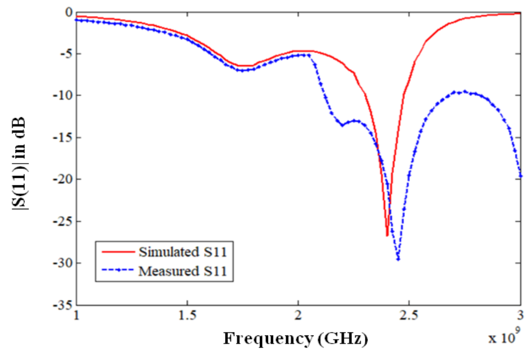


Fig.10. Reflection coefficient characteristics of the antenna

The input impedance for antenna with partial ground plane structures is calculated as Z_{in}= 50*(1.030+j0.077)Ω. It matches the characteristic impedance of 50Ω with a small reactive component, as shown in the results. This impedance signifies the antenna's efficiency as a radiator, ensuring maximum power transfer from the input port to the antenna.

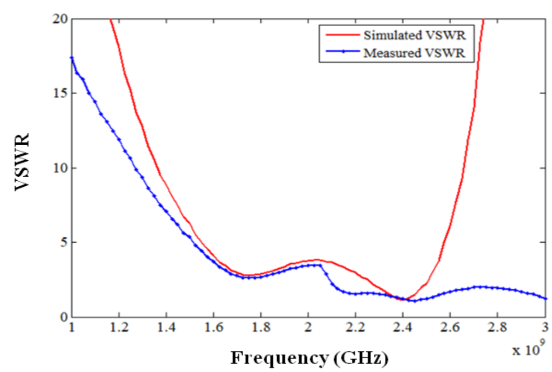


Fig.11. VSWR of the proposed antenna structure

In Fig. 11, both the simulated and experimental VSWR of the proposed antenna are depicted. The graph confirms the excellent matching between the antenna's input impedance and the load impedance with slight deviations due to fabrication discrepancies, material loss and free space testing losses such as temperature fluctuations, humidity and the influence of nearby metallic objects on the RF system's performance. The maximum peak to peak gain of

INTERNATIONAL JOURNAL OF MICROWAVE AND OPTICAL TECHNOLOGY,
VOL.19, NO.3, MAY 2024

4.2 dBi is achieved at 2.45 GHz can be inference from Fig. 12.

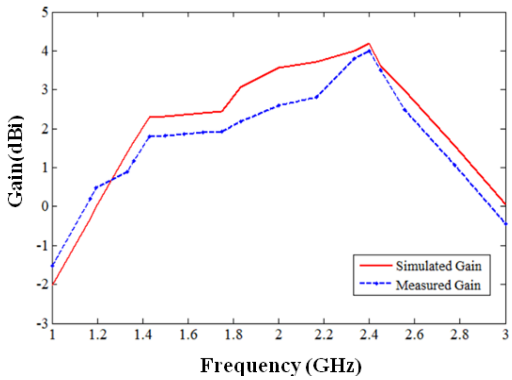
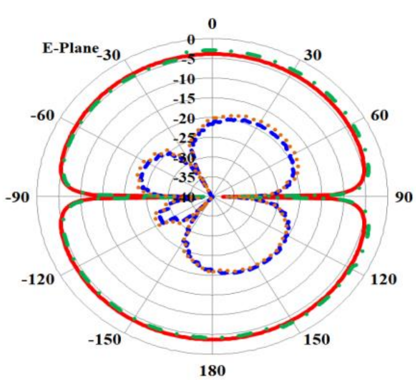


Fig.12. Gain characteristics of the proposed antenna

The antenna shows good agreement between the simulated and measured gain. The radiation efficiency plays a crucial role in the antenna performance analysis. The proposed antenna provides the high radiation efficiency exceeding 85% at the operating frequency range of 2.4 GHz evidenced by both simulation and testing results. The simulated E and H plane co and cross polarization characteristics are shown in Fig. 13. The simulation & measured results indicates that the antenna has a very low cross polarization level with a cross polarization value of -25 dB achieved at the operating frequency. The antenna exhibits nearly isotropic radiation pattern in the H-plane (YZ Φ=90˚) and an omni-directional radiation pattern in the E- plane (XZ plane, Φ=0˚) as evident from the 2D radiation graph. Based on the simulation and measured results, the suggested antenna is ideally suited for capturing 2.45GHz ambient energy.



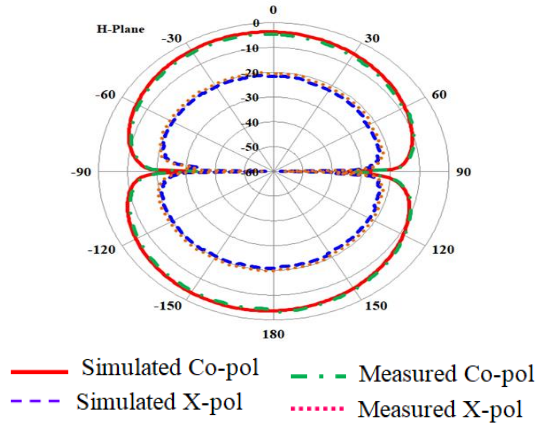


Fig. 13. Simulated & measured (a) E and (b) H-plane 2D radiation pattern at 2.45 GHz

The fabricated prototype of the proposed rectifier circuit with the impedance matching configuration is presented in Fig.14. The test results demonstrate the circuit capability to achieve a return loss exceeding -10 dB, as shown in Fig.15. Both the simulated and measured S11 parameters consistently indicate a superior return loss exceeding -10 dB. Figs 16 and 17 presents the performance of the proposed rectenna circuit when subjected to an input power range from -10 dB to +10 dB. The analysis includes assessments of output voltage and RF-to-DC conversion efficiency.

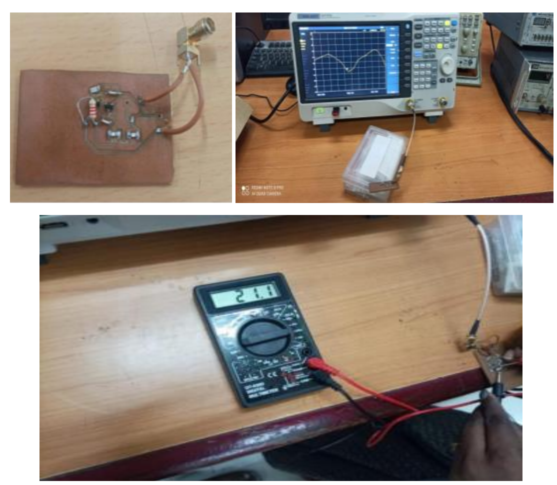


Fig.14. Fabricated prototype and testing of the rectifier circuit

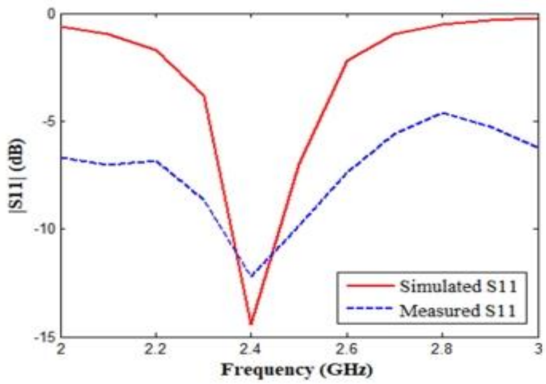


Fig.15. Simulated and measured return loss in dB of the proposed rectifier

The simulated or measured results illustrate the rectenna efficiency in harvesting ambient RF energy. At a load resistance of 2KΩ, the rectenna achieves a maximum output voltage of 2.2V and a maximum conversion efficiency of 83%. This analysis emphasizes the proposed rectifier circuit as an efficient system for RF energy harvesting. A performance comparison of proposed work with existing system is presented in Table.2. The parameters involved in the comparison include the antenna structure, rectifier type, return loss (S11), gain, resonant frequency, output voltage and the size of the antenna.

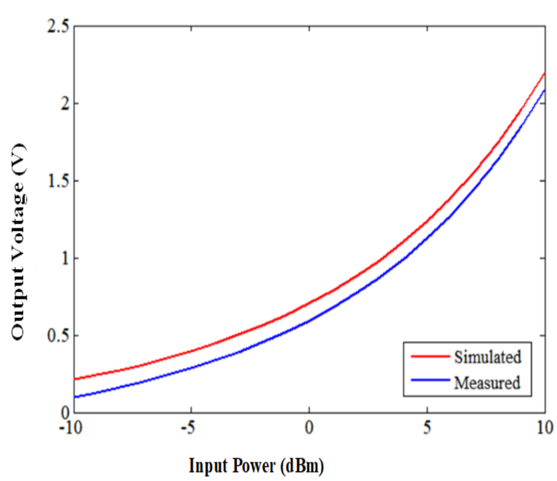


Fig.16. Output voltage for simulated and measured circuit

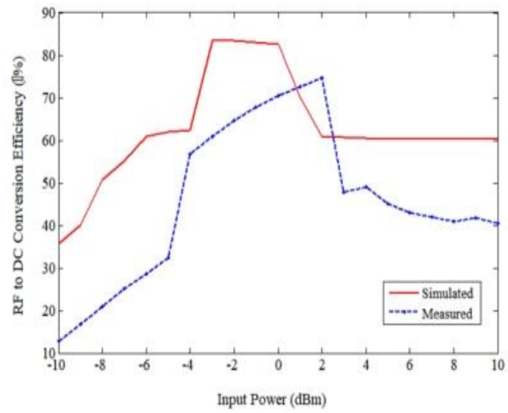


Fig.17. RF to DC conversion efficiency for simulated versus measurement

In [19-21], a study focused on pairing a basic microstrip patch antenna with a half-wave rectifier circuit. However, the inherent limitations of the half-wave rectifier resulted in a low output voltage. In another study [22], a rectenna structure based on a Yagi antenna was introduced, demonstrating improved performance metrics. However, the larger overall size of the Yagi antenna makes it less suitable for applications requiring compactness, such as self-powered handheld devices. In [23], a rectangular patch antenna with a U-slot rectenna was investigated. Despite the potential of the design, its output power was found to be lower compared to the proposed antenna. This discrepancy can be attributed to differences in antenna characteristics, including impedance matching and gain, which play crucial roles in determining overall performance.

The proposed compact double comb-shaped slotted rectenna coupled with a voltage doubler circuit and operating at 2.45 GHz demonstrates notable advancements in several key aspects compared to previously published designs. These includes improvements include enhanced return loss characteristics, impedance matching, gain, RF-to-DC conversion efficiency, and output voltage. Overall, the proposed antenna structure offers significant improvements over existing design.

Table 2: Performance comparison of proposed rectenna with related research finding

Ref	Antenna Structure	Rectifier Type	Frequency (GHz)	Antenna Dimension (mm)	S_{11} (dB)	BW	VSWR	DC Output	Gain (dBi)
[19]	Microstrip Patch Antenna	Half Wave Rectifier	2.45	37 x29	-18	8 MHz	1.228	50mV	-
[20]	Microstrip Patch Antenna	Rectifier	1.8	39 x30	-25.339	Narrow band	1.11	0.459 V	5.88572
[21]	Microstrip Patch Antenna	Half Wave Rectifier	900	-	-21	Narrow band	1.19	32 mW.	3.9
[22]	Yagi Antenna	Cockcroft Walton Rectifier	2.45	60 x 60	-21.6	Narrow Band	1.18	2.32 V	7.8
[23]	Rectangular Patch Antenna With U Slot	Bridge Rectifier	2.45	24.9 x 18.6	-20	20 MHz	1.22	97 mV	2.89
Propose work	Compact double comb-shaped slotted	Voltage Doubler Circuit	2.45	48 x 31	-31	280 MHz	1.05	2.2 V	4.2 dBi

These enhancements include lower S11 values indicating better impedance matching, broader bandwidth, lower VSWR, which suggests reduced signal loss. The design achieves comparable or superior DC output, and competitive gain performance. These improvements align with the objectives outlined in the introduction, showcasing the advancements made in the antenna design. The innovative double comb-shaped structures employed in the antenna contribute to enhanced return loss characteristics, even within a compact size, while also improving radiation characteristics. Moreover, the design of the rectifier, combined with the double comb structure, synergistically boosts the overall performance of the proposed system, ensuring efficient RF-to-DC conversion and maximizing the output voltage.

V. CONCLUSION

This article presents a 2.45 GHz compact double comb-shaped slotted rectenna system designed for RF energy harvesting in wireless LAN applications. The design integrates two comb-like structures into a square patch antenna, with the voltage doubler rectifier circuit occupying a small footprint of $48 \times 31 \times 1.5\ mm^3$. Design improvements, such as semi-circular slots at the patch center, double comb structures, and an L-type impedance matching network, enhance bandwidth, impedance matching, and return loss. A prototype of the rectenna was constructed using a cost-effective FR4 substrate, allowing for performance evaluation through both simulations and physical measurements. The analysis shows an impressive return loss (S11) of -10 dB across a fractional bandwidth of 17.14% from 2.3 GHz to 2.48 GHz. Additionally, an L-type impedance matching network-based voltage doubler circuit achieved a maximum energy conversion efficiency of 83% at 2.45 GHz and delivered an output voltage of 2.2 V with a 2 KΩ load resistance. These results demonstrate the proposed rectenna's ability to efficiently capture RF energy from its surroundings, making it a promising solution for wireless LAN applications and advancing the field of energy harvesting technology.

INTERNATIONAL JOURNAL OF MICROWAVE AND OPTICAL TECHNOLOGY,

VOL.19, NO.3, MAY 2024

REFERENCES

[1] Y. Zhou, B. Froppier and T. Razban, "Radio frequency ambient level energy harvesting". *Wireless Power Transfer*, Vol. 2, pp. 121-126, Dec. 2015.

[2] N. Shinohara, "Wireless Power Transfer via Radiawave", John Wiley & Sons, New York, Jan. 2013.

[3] M. Aboualalaa, A. B. Abdel-Rahman, A. Allam , H. Elsadek and R. K. Pokharel, "Design of a dual-band microstrip antenna with enhanced gain for energy harvesting application", *IEEE Antennas Wirel Propag Lett*., Vol. 16, pp. 1622-1626, Jan. 2017.

[4] A. Okba, A. Takacs, H. Aubert, S. Charlot and P. F. Calmon, "Multiband rectenna for microwave applications rectenna multi-bands pour des application micro-ondes", *C. R Physique*., Vol. 18, pp. 107-117, Dec. 2016.

[5] T. Matsunag, E. Nishiyama and I. Toyoda, " 5.8 GHz stacked differential rectenna suitable for large-scale rectenna array with DC connection", *IEEE Trans Antenna Propag*., Vol. 63, pp. 5944-5949, Oct. 2015.

[6] A. Sachine, M.S. Parihar and P. N. Kondekar, " A quad-band antenna for multi-band radio frequency energy harvesting circuit", *Int J Electron Commun (AEU)*., Vol. 85, pp. 99-107, Feb.2018.

[7] S. Chandravanshi, S.S. Sarma and M.J. Akhtar, " Design of triple band differential rectenna for RF energy harvesting", *IEEE Trans Antennas Propag*., Vol. 66, pp. 2716-2726, Mar. 2018.

[8] A. Khemar, A. Kocha, H. Takhedmit and G. Abib, "Design and experiments of a dual-band rectenna for ambient RF energy harvesting urban environment", *IET Microwaves, Antennas Propag*., Vol.12, pp. 49-55, Dec. 2017.

[9] H. Sun, Y.X. Guo, M. He and Z. Zhong, "A dual-band rectenna using broadband Yagi antenna for ambient RF power harvesting", *IEEE Antennas Wirel Propag Lett*., Vol. 12, pp. 918-921, Jul.2013.

[10] K. Niotaki, S. Kim, S. Jeong, A. Collado, A. Georgiadis and N.M. Tentzeri, "A compact dual-band rectenna using slot-loaded dual band folded dipole antenna", *IEEE Antennas Wirel Propag Lett*., Vol. 12, pp. 1634-1637, Dec. 2013.

[11] S. Neeta , B. K. Kanaujia, T. B. Mirza, K. Taimoor and A. Sachin Kumar, "Dual polarized multiband rectenna for RF energy harvesting", *Int J Electron Commun.*, Vol. 93, pp. 123-031, Sep. 2018.

[12] C. Song, Y. Huang, P. Carter, J. Zhou, S. D. Joseph and G. Li, "Novel compact and broadband frequency-selectable rectennas for a wide input-power and load impedance range", *IEEE Trans Antennas Propag.*, Vol. 66, pp. 3306-3316, Apr. 2018.

[13] V. Palazzi, J. Heste, J. Bito, F. Alimenti, C. Kalialakis, A. Collado, P. Mezzanotte, A. Georgiadis, L. Roselli, M.M. Tentzris, "A novel ultra-lightweight multiband rectenna on paper for RF energy harvesting in the next generation LTE bands", *IEEE Trans. Microwave Theory Tech.*, Vol. 66, pp. 366-379, Jan. 2018.

[14] T. Shanmuganantham and S. Ashok Kumar, "Design of an implantable CPW fed dual dipole antenna for dual band biomedical applications", *Int J Biomed Engg Techno*., Vol. 14, pp. 46-59, Feb. 2014.

[15] C. Song, Y. Huang, P. Carter, J. Zhou, S. Yuan, Q. Xu and M.A. Kod, "Novel six-band dual CP rectenna using improved impedance matching technique for ambient RF energy harvesting", *IEEE Trans Antennas Propag.*, Vol. 64, pp. 3160-3171, Jul. 2016.

[16] S. Agrawal, D. G. Ravi, S. P. ManoJ and N. K. Pravee, " A wideband high gain dielectric resonator antenna for RF energy harvesting application", *Int J Electron Commun*., Vol. 78, pp. 24-31, Aug. 2017.

[17] Y. Shi, J. Jing , Y. Fan, L.Yang, Y. Li and M. Wang, " A novel compact broadband rectenna for ambient RF energy harvesting", *Int J Electron Commun*., Vol. 95, pp. 264-270, Oct. 2018.

[18] C. Song, Y. Huang, J. Zhou, J. Zhang, S. Yuan and P. Carter P, "A high-efficiency broadband rectenna for ambient wireless energy harvesting", IEEE *Trans Antennas Propag*., Vol. 63, pp. 3486-3495, Aug. 2015.

[19] N. Abdullah, A. M. Shire and E. Mohd " Rectenna for RF energy harvesting", in *Proc. IEEE Int. Conf. Adv.Elec.Electron. sys Eng*., Nov 2016, Putrajaya, Malaysia, pp.318-321.

[20] Nikhil Purohit and Imaculate Rosaline, " Novel RF energy harvesting using rectenna", *J. Phys*., Vol. 2070, pp. 1-7, Aug. 2021

[21] G. Indumath and K. Karthika, " Rectenna design for RF energy harvesting in wireless sensor network", in *Proc. IEEE Int. Conf. Elec.Comp. Commun. Techno.*, May 2015, India, pp.1389-1392.

[22] M. Aboualalaa and H. Elsadek, " Rectenna system for RF energy harvesting and wireless power transfer", *Recent Wireless Power Tranfer Technologies*, Intech Open, Oct. 2019.

[23] M. Koohestani, J. Tissier and M. Latrach, "A miniaturized printed rectenna for wireless RF energy harvesting", *Int. J. Electron. Commun.*, Vol. 127, pp. 153478, Dec. 2020.