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Original Article

Design of a High-Gain Reflector-Based Slotted Antenna for RF Energy Harvesting Application

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Abstract *- This study presents the design, analysis, and implementation of a rectenna system (rectifying antenna) optimized for RF energy harvesting in IoT applications. With the exponential growth of low-power IoT devices, sustainable power solutions are increasingly critical. Our work introduces a novel heptagonal patch antenna with strategically placed slots functioning at 2.45 GHz. The design fabricated on FR4 achieves a substantial gain improvement from 2.63 dBi to 6.1 dBi at 2.45 GHz and 11.5 dBi at 2.42 GHz through the integration of a reflector positioned 20 mm behind the antenna. A voltage doubler rectifier circuit utilizing SMS7630-079LF Schottky diodes successfully converts the harvested RF energy to DC power. The proposed rectenna provides a DC output voltage (V_{DC}) of 180.8 mV placed at 45 cm from the commercial Wi-Fi router, demonstrating the solution's suitability for powering low-energy IoT devices. This cost-effective approach addresses key issues in IoT deployment by eliminating dependencies on conventional batteries and providing a sustainable alternative power for smart city applications, including agriculture, healthcare, smart factories, and transportation.*

Keywords *- Antenna, Energy harvesting, IoT, Rectenna.*

1. Introduction

The rapid spread of Internet of Things (IoT) devices has changed several sectors, including agriculture, healthcare, transportation, urban infrastructure, and industrial automation. These smart systems rely on low-power electronic devices and sensors that require uninterrupted and reliable power sources. To provide a continuous supply to billions of low-power IoT sensors is a challenge. Conventional battery-based solutions have significant limitations, including limited life, maintenance overhead for frequent replacement, and environmental concerns related to disposal [1, 2]. To address this problem, continuously available, long-life, low-cost, maintenance-free, and sustainable alternative energy sources are needed. Energy harvesting from ambient sources such as solar, thermal, kinetic and RF has emerged as a promising sustainable substitute to traditional batteries. Among various energy harvesting systems, Radio Frequency (RF) energy harvesting offers unique advantages due to the ubiquity of RF signals in modern environments. These signals emanate from various sources such as cell towers, television transmitters, and mobile devices, Wi-Fi routers, creating an omnipresent energy resource that can be captured and utilized [3, 4]. Rectennas (rectifying antennas) represent the cornerstone technology for RF energy harvesting systems. These devices combine an antenna for electromagnetic wave reception with a rectifier that converts captured AC signals to usable DC power. Although multiband and broadband rectennas have been explored in previous research, single-band designs maintain significant advantages in terms of rectifier efficiency and matching network simplicity, particularly for targeted applications. Numerous studies have reported the rectennas for RF energy harvesting at different frequency bands [4]. In [5], a rectenna is introduced using a planar wide-angle antenna with a Taconic substrate that provides 3.34 dBi gain, and a dual diode rectifier with a matching network achieves 51.8 % PCE at 10 dBm. In [6], a compact, tacked eight-sector rectenna array design for wide-angle coverage using FR4 is proposed to operate at 5.84 GHz to provide almost equal coverage in all directions for WPT in IoT applications. The Schottky diode and hybrid combining method with impedance matching is introduced to enhance power conversion efficiency and output voltage. In [7], a 2x2 rectenna array using a high-gain fractal geometry antenna with a 2.5 mm thickness substrate and a single-stage voltage multiplier LC MN network is designed for rectenna. A hexagonal shape antenna with a triangular slot on the ground operating at 2.45 GHz with a 6.68 dBi gain is presented in [8]. The triangular slot improves the gain of the antenna. A high-gain pentagonal shape patch 2.45 GHz single band antenna with a rectangular slot on the ground is presented in [9]. In [10], a graphene-based screen-printed antenna for a rectenna is designed using polyester, wax, and FR4 with a circular patch and notch on the ground plane, which provides a 1.9 dBi gain and a rectifier with 43 % conversion efficiency at the 2.42 GHz band. In [11], a metasurface-inspired CP monopole antenna with asymmetrical staircase partial ground operating at 5 GHz is presented for RFEH application. A voltage tripler rectifier circuit using 6 diodes and an L-C matching network is implemented. A compact antenna with a fractal geometry using the Kotch curve have been presented for the 2.45 GHz frequency band [12]. This antenna has a large weight due to the high thickness of the substrate material. A compact loop antenna with a Kotch fractal geometry is considered for RF energy scavenging. Use of an In-loop ground plane for impedance matching in this antenna made the structure complex [13]. In [14], a compact 2.45 GHz circular patch antenna is designed using a reduced ground plane. The rectifier circuit is composed of an HSMS 2852 Schottky diode and an L-shaped IMN.

A dual-band tree shape antenna is presented using Kotch fractal geometry and a two-branch matching network using radial stub for 2.45 and 5 GHz Wi-Fi band [15]. In [16], a Dielectric Resonator Antenna (DRA) is proposed for the 2.6 and 3.5 GHz frequency band. It uses a single diode rectifier and an IMN made of an open, short circuit and radial stub. In [17], a sickle-shaped antenna is presented for 2.4 and 5.8 GHz. A single Schottky diode and an IMN rectifier are proposed for dual-band operation. A circular shape printed monopole antenna is designed using the coplanar waveguide feeding technique for GSM 1800 and UMTS band 1. It uses a Greinacher voltage doubler rectifier and IMN in two branches [18]. In [19], an E-shaped triple band patch antenna is designed using the Moth search algorithm. This antenna works for LoRa, GSM-1800, and UMTS-2100 bands. [20] proposes a rhombus-shaped dual wideband antenna with a rhombus slot and two rectangular strips on the ground plane operating at 3.3 -3.7 and 4 -6.3 GHz. The antenna achieved gains of 3.5, 3.3, 5.2 and 5 dBi. Two-line PI IMN is implemented to improve PCE. The simulated and measured V_{DC} of 1.8 V and 70 mV are obtained. In [21], an ultra-wideband square patch antenna with an inverted L-slot and dual ground plane operating from 1.4 -5.4 GHz is proposed.

This antenna achieved a gain of 1.8, 2.1, 2.45, 2.8, and 3.6 dBi. The rectifier incorporates three Impedance-Matching (IM) branches and a DC combining technique. The simulated and measured V_{DC} of 1.8 V and 82 mV are recorded, respectively. In [22], a dual diode rectenna composed of four-element antenna arrays at 2.45 GHz is proposed. The gain of this antenna is 7.2 dBi. The highest PCE achieved is 85.7 %. Mohammed M. Hasan et al. [23] introduced a multiband MPA operating at eleven frequency bands using multi-fins and fabricated using FR4 substrate for RFEH application. The antenna provides a gain of 6.349 dBi at 3.95 GHz. The research discussed in the literature often experiences issues with weak gain antennas, oversized and intricate designs, and low power conversion efficiency at minimal input power. To create a rectenna for powering IoT sensors, a high-gain antenna, an efficient rectifier, and a simple matching network are required. This paper introduces a cost-effective, high-gain rectenna designed for the 2.45 GHz band, corresponding to common Wi-Fi frequencies. The approach in this work features a novel heptagonal patch antenna derived from circular geometry and enhanced with four strategically positioned slots to obtain resonance at the target frequency. The design incorporates a reflector to significantly boost antenna gain and a simple, compact, and efficient voltage doubler rectifier circuit utilizing Schottky diodes.

The proposed solution addresses key challenges in IoT deployment by providing a sustainable power source that eliminates battery dependencies while maintaining a compact form factor suitable for integration with IoT devices. Experimental results demonstrate successful energy harvesting from standard Wi-Fi routers, validating the practical applicability of the rectenna design for powering low-energy IoT applications in smart environments. The flowchart of the rectenna component is demonstrated in Figure 1. The elucidation of the antenna structure is given in Section II. Details of rectifier design are summarized in Section III. Section IV narrates results and discussion. Section V provides the conclusion.

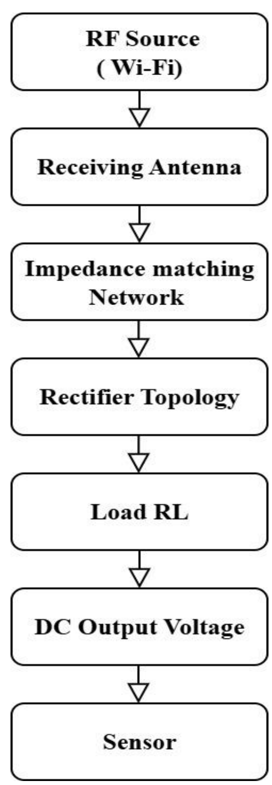


Fig. 1 Flowchart for Rectenna design and without reflector

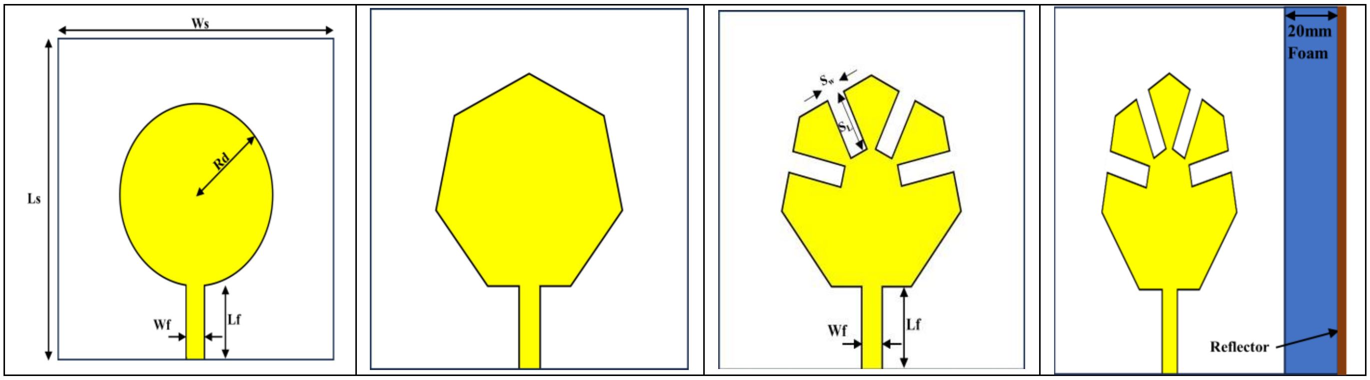


Fig. 2 Structure of antenna (a) Circular patch (Ant 1), (b) Heptagonal patch (Ant 2), (c) Slotted Heptagon (Ant 3), and (d) Antenna with reflector (Ant 4).

2. Antenna Design

A novel heptagonal shape is considered for an antenna design due to its simple geometrical shape, which helps achieve better coverage, good impedance matching, resonance, bandwidth, and radiation pattern required for energy harvesting applications. The structure is also useful for designing compact single-band, wideband and multiband rectennas.

The slotted antenna design followed a systematic evolutionary approach through four distinct configurations: The Initial Circular Patch (Ant1) consists of a simple circle with a radius of 21 mm, which served as the baseline design. Heptagonal modification (Ant2) is the transformation of the circular patch into a heptagonal (7-sided) geometry.

The effective area of the modified structure is the same as the original circular design. Slotted heptagonal design (Ant3) is the enhanced heptagonal patch with four strategically positioned slots. The slot dimensions are length S_L=12.3 mm and width S_W =4 mm. These slots are positioned to modify the current distribution and optimized impedance matching. The RL (S11) of antenna 3 observed is -16.54 dB.

In Reflector-Enhanced Configuration (Ant4), a metallic reflector is added, positioned 20 mm behind the antenna. The foam material is used as a dielectric spacer between the antenna and reflector. The development of Ant 1 to Ant 4 is represented in Figure 2. The antenna design involves the use of EM simulation software CST, and simulated performance is observed using RL(S11), gain, and radiation characteristics.

The antenna is fabricated on a low-cost flame-retardant 4 substrate ($\varepsilon_{r\,=}$ 4.4 and h=1.6 mm). The FR4 material is flame-retardant, cost-effective, exhibiting low moisture absorption and good mechanical strength. The overall optimized antenna dimension is 70 x 70 mm, and the antenna parameters are as follows: Lg = Wg = Ls = Ws 70 mm, Lf = 16.5 mm, Wf = 3 mm, S_L = 12.3 mm, S_W = 4 mm. Table 1 represents antenna dimension parameters.

Table 1. Antenna structure dimensions

Parameter	Description	Value (mm)
Lg	Length of ground	70
Wg	Width of ground	70
Ls	Substrate length	70
Ws	Substrate width	70
Lf	Feedline length	16.5
Wf	Feedline width	3
S_L	Slot length	12.3
S_W	Slot width	4
Rd	Circle radius	21

The simulated RL(S11) of Ant 1 to Ant 4 is analyzed and displayed in Figure 3. The four slots on Ant 3 show improvement in impedance and return loss(S11) at 2.45 GHz compared to Ant 1 and Ant 2 structures. In addition to the slots, a metal plate as a reflector improves the impedance of Ant 4 and enhances the gain characteristics. The simulated and measured RL(S11) of optimized Ant 4 is illustrated in Figure 4. The simulated gain of the antenna with and without a reflector, and the measured gain with a reflector, is displayed in Figure 5. The return loss (S11) is measured using an Agilent-made 9 GHz microwave VNA. The reflector-based slotted Ant 4 gain is measured in the Anechoic chamber in Figure 6. The antenna radiation characteristic E-plane (phi=900) and H-plane (phi=00) is presented in Figure 7. The design equation of the circular antenna is represented in Equations (1) and (2).

$$f_r = \frac{X_{mn} \cdot c}{2\pi a_e \sqrt{\varepsilon_r}} \quad (1)$$

$$a_e = a\left\{1 - \frac{2h}{\pi a \varepsilon_r}\left(1n\,\frac{\pi a}{2h} + 1.7726\right)\right\}^{1/2} \quad (2)$$

Equation (1) represents the antenna resonant frequency, Xmn is 1.8411for the dominant mode TM_{11}, Ɛr is the substrate relative permittivity, and c is the free-space light velocity. Equation (2) represents the effective radius of the circular patch. a_e. Where h is the substrate thickness, and a represents the actual radius of the circular patch [24].

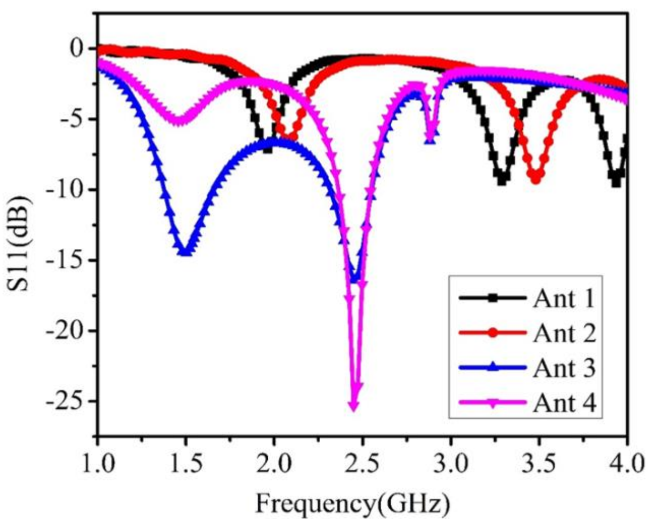


Fig. 3 Simulated RL of Ant1 to Ant4 and without reflector

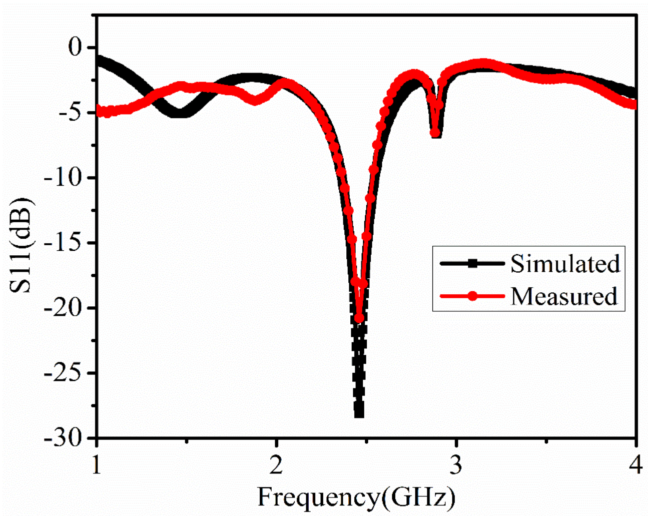


Fig. 4 Simulated and measured RL of Ant4

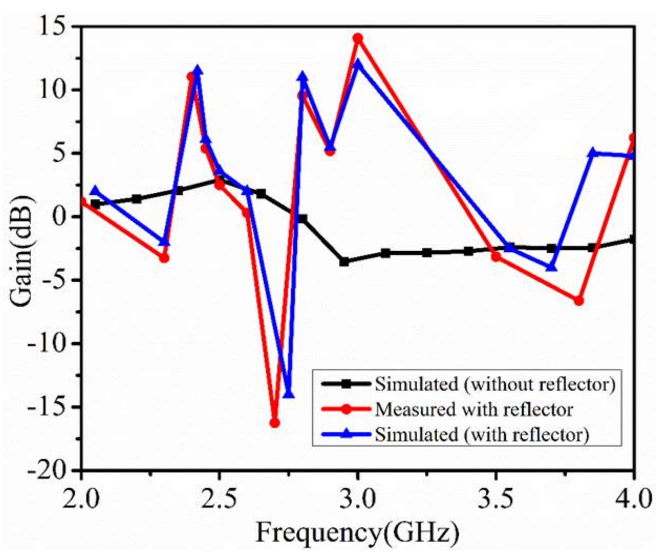


Fig. 5 Simulated and measured gain of antenna

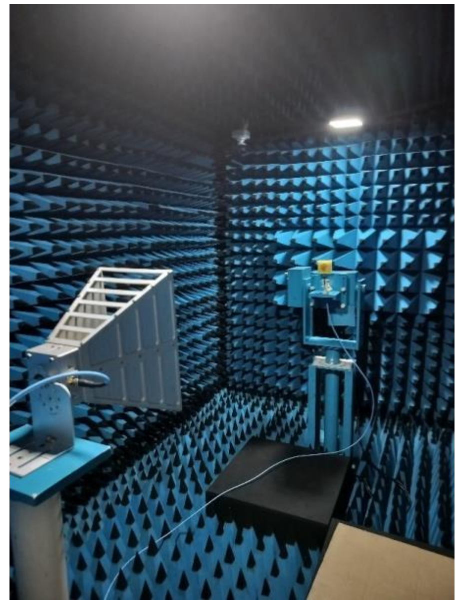
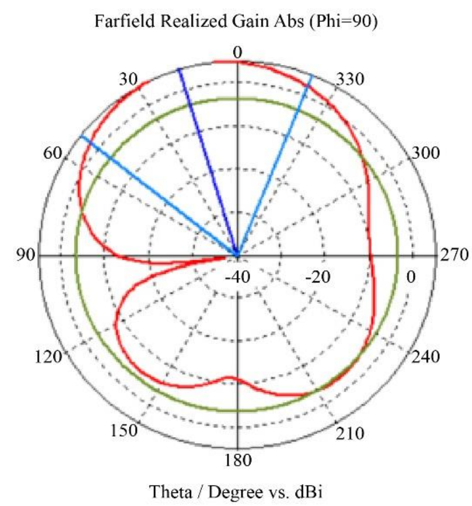
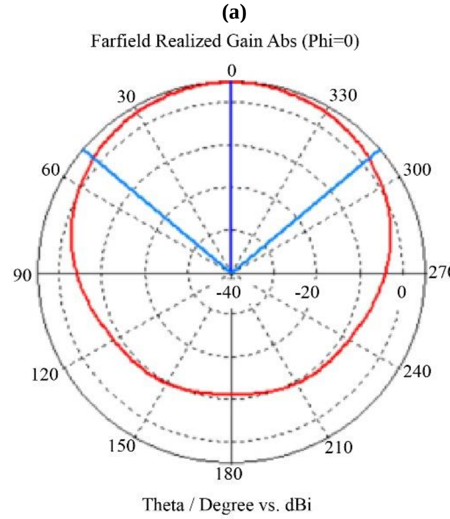


Fig. 6 Antenna gain measurement set up in Anechoic chamber



(a)



(b)

Fig. 7 Simulated RP at 2.45 GHz (a) E-plane, and (b) H-plane.

3. Rectifier Design

The rectifier topology (VDR) comprises two Schottky diodes, input and output capacitors of 100 pf for filtering and the nearest optimized value of commercially available load resistor RL=4.7 K for testing. The SMS7630-079LF Schottky diode is selected due to minimal forward voltage drop, low junction capacitance, fast switching speed appropriate for 2.45 GHz, and an SMD package for compact implementation [25]. The matching network utilized microstrip transmission line TL2 (L=12.7mm, W=3.5mm) and open circuit stub TL3 (L=10.8mm, W=3.5mm) for impedance transformation.

The TL1 is used to connect the SMA connector. The circuit simulations are performed to optimized matching network dimensions. The Smith chart analysis is used to refine impedance matching using ADS simulation software. The circuit arrangement of the rectifier with a matching network is given in Figure 8.

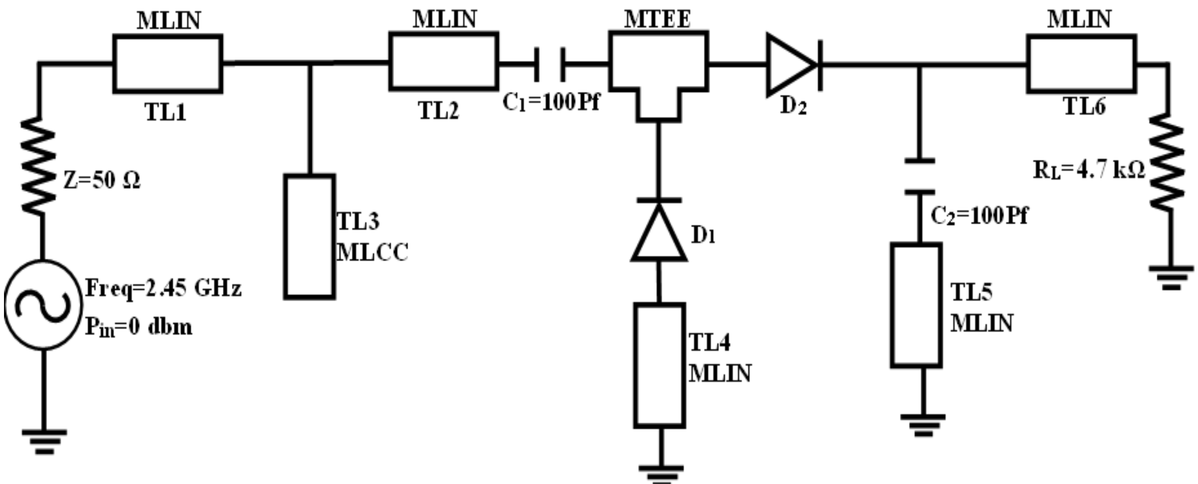


Fig. 8 Schematic of VDR rectifier with matching network

The FR4 substrate material, which ensured cost-effectiveness and manufacturing simplicity, is employed for fabrication. The simulated and measured RL(S11) of the rectifier integrated with IMN is displayed in Figure 9. The simulated rectified DC output voltage (V_{DC}) for different values of load resistor RL from 1K to 6K is displayed in Figure 10. The V_{DC} voltage increases with the increase in the value of the load resistor RL. The maximum V_{DC} of 1.7 V is observed at 2.45 GHz for 0 dBm signal power. The RF-DC PCE of the rectifier is observed for RL = 1K to 6K, as shown in Figure 11. The peak PCE of 67% is observed for RL = 4K. The practical value of RL is chosen as 4.7K, which is the nearest optimized value of the resistor. The PCB is fabricated using Gerber files from the final optimized design. The SMD components are mounted using the reflow soldering technique, and the rectifier circuit is assembled carefully to minimize the parasitic effects. The fabricated rectenna device is shown in Figure 12 the rectenna test environment composed of a TP-Link Wi-Fi router as an RF source operating at 2.45 GHz. The rectenna device is positioned at 45 cm from the RF source. The harvested DC voltage is recorded using a high-precision DMM. The rectenna measurement setup is displayed in Figure 13.

4. Results and Discussions

4.1. Performance Analysis and Interpretation

The implemented rectenna demonstrates a promising outcome for RF energy harvesting applications. The evolution from a circular patch to a heptagonal design with strategically placed slots significantly improved the antenna's resonance characteristics at 2.45 GHz.

The simulated RL (S11) is improved from -16.54 dB in the basic design to -28 dB with the reflector integration, representing superior impedance matching and efficiency. Power transfer. The measured value of RL(S11) observed is -21 dB.

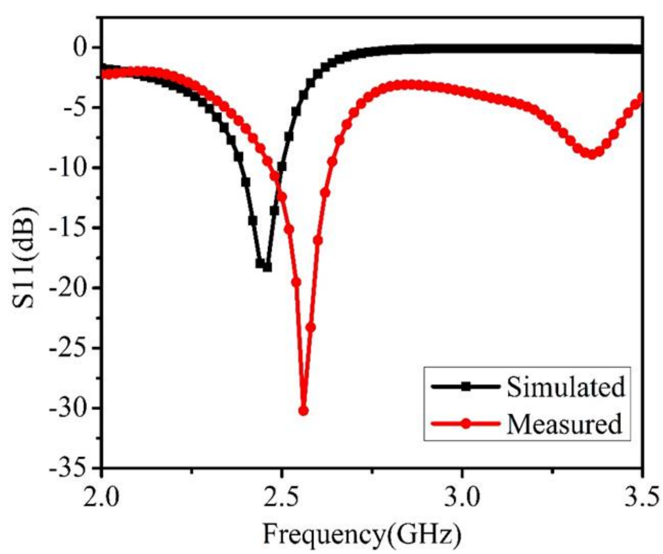


Fig. 9 Simulated and measured S11 for Rectifier circuit

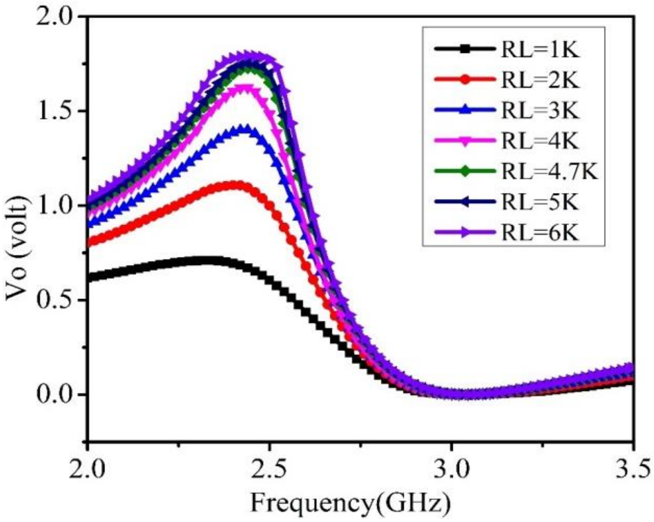


Fig. 10 DC output voltage of rectenna Vs Frequency

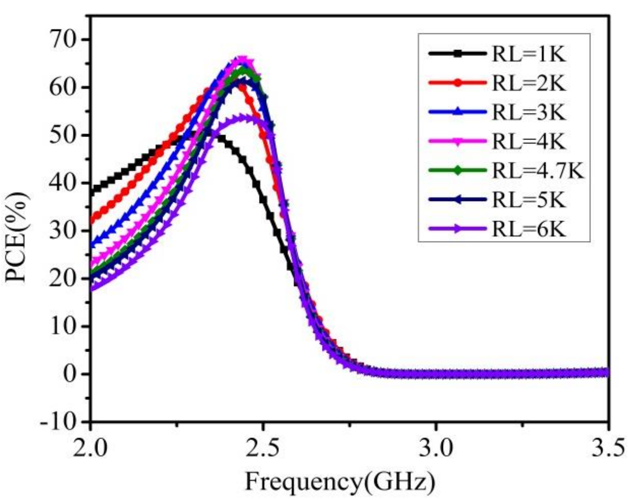


Fig. 11 PCE vs Frequency

A particularly noteworthy achievement is the substantial gain improvement from 2.63 dBi to 6.1 dBi at 2.45 GHz, with a peak gain of 11.5 dBi observed at 2.42 GHz. This significantly enhances conventional patch antennas and contributes directly to increased energy harvesting capability. The gain improvement can be attributed to the combined.

Fig. 12 Rectenna measurement Setup

The effect of the slotted heptagonal geometry and the reflector creates favorable conditions for constructive wave interference and directional radiation. The minor discrepancies observed between simulated and measured S11 values warrant discussion. These variations likely stem from fabrication tolerances, soldering inconsistencies, and the limitations of the FR4 substrate at microwave frequencies.

Fig. 13 Single band rectenna device

Despite these variations, the measured performance remains well within acceptable parameters for practical applications. The rectifier circuit, employing a voltage doubler topology with SMS7630-079LF Schottky diodes, demonstrated effective AC-to-DC conversion. The generated output voltage of 180.8 mV from a Wi-Fi router at 45 cm distance represents a practical achievement, especially considering the relatively low power density of Wi-Fi signals compared to dedicated RF power sources.

This voltage level, while modest, is sufficient for powering ultra-low-power microcontrollers or sensor nodes when integrated with appropriate power management circuits. Table 2 outlines the comparative evaluation of the proposed system and related research. The proposed rectenna exhibits compact size, simple structure, and high gain compared to the related work. This study demonstrates an improved measured DC output voltage with respect to the work presented in [20, 21]. The rectifier exhibits improved PCE at 0 dBm in comparison to relevant studies.

Table 2. Comparative study of the proposed work with similar work

Ref	Frequency Band (GHz)	Substrate	Size of antenna (mm)	Gain(dBi)	DC output voltage Vo	Rectifier Efficiency (%)
5	5.8	Taconic (2.5)	60 x 60 x 5	3.34	1.95 V (Simulated)	51.8 % @ 10 dBm
10	2.45	Polyester, Wax, FR4	96 x 96	2.3,2.2,1.9	--------	43
11	5	FR4(1.6)	100 x 75	6.82	4.86@ 12 dBm (Simulated)	67.8
20	3.3-3.7 & 4-6.3	FR4(1.6)	60 x 60	3.5& 3.3 and 5.2 &5	70 mV (Measured) 1.8 V (Simulated)	81.5 @3 dBm 66.3 @8 dBm
21	1.4-5.4	FR4(1.6)	60 x 60	1.8, 2.1, 2.5, 2.8, 3.6	82 mV (Measured) 1.8 V (Simulated)	78 @8 dBm
22	2.45	FR4(1.6)	-----	7.2	2.7 V@16dBm	85.7 @ 16 dBm
23	0.776, 1.41, 1.5 1.84, 2.45,2.87, 3.19, 4.06, 5.2, 5.7, 6.95	FR4(1.6)	171.70 x 90.90	6.349 @ 3.95	-------	-------
Proposed work	2.45	FR4(1.6)	70 x 70	6.1 @ 2.45 & 11.5@ 2.42	180 mV (Measured) 1.7 V@0 dBm (Simulated)	67 @ 0 dBm

4.2. Limitations and Considerations

Despite the promising results, several limitations should be acknowledged. The directional nature of the enhanced antenna with a reflector necessitates proper orientation toward RF sources for optimal performance. While beneficial for maximizing harvested energy from known RF sources, this directivity may limit effectiveness in scenarios with unpredictable or mobile RF sources. Additionally, while promising, the demonstrated output voltage of 180.8 mV requires voltage boosting and power management circuitry for practical application in most IoT devices.

The efficiency of the rectenna system is also frequency-dependent, optimized specifically for 2.45 GHz, which limits versatility in environments where other frequency bands predominate. The performance in real-world conditions may vary significantly from simulated measurements due to multipath effects, interference, and fluctuating RF. Power levels. Further testing in diverse deployment scenarios would provide more comprehensive insights into practical performance boundaries.

4.3. Ethical Implications and Environmental Impact

The RFEH system replaces the use of conventional chemical batteries, which ultimately reduces environmental pollution, hazardous e-waste, and chemical leakage to achieve sustainable development goals in engineering. To minimize the environmental burden, material selection, eco-friendly PCB design, and recyclability of materials need to be considered. To avoid electromagnetic exposure, ambient RF sources and low-power transmitters are recommended for rectenna design, which may affect the rectifier efficiency. Implementing these ethical implications helps achieve a sustainable battery-less IoT ecosystem.

5. Conclusion

This study has successfully demonstrated the design, fabrication, and testing of an efficient rectenna system for RFEH in IoT environments. The novel heptagonal slotted antenna design with reflector integration represents a significant advancement over conventional patch antennas, achieving a highest gain of 11.5 dBi at 2.42 GHz with a compact form factor of 70 mm × 70 mm.

The compact integrated rectifier circuit, employing SMS7630-079LF Schottky diodes in a voltage doubler configuration, successfully converted ambient RF energy from a standard Wi-Fi router into usable DC power. The measured output voltage of 180.8 mV demonstrates practical viability for powering low-energy IoT devices, particularly when combined with appropriate power management circuitry.

5.1. Practical Implications and Future Directions

The rectennas operating at a single frequency band, like Wi-Fi, Bluetooth, and Cellular frequency bands, are easy to design with fewer components, a simple matching network and are suitable for IoT, WSN and RFID applications. Single-band rectennas face challenges when it comes to capturing energy from various RF sources, especially when the RF environment is subject to dynamic changes. The future study may consider utilizing CMOS and MOSFET-based rectifiers along with ultra-low threshold devices to boost the efficiency of the rectenna. The tunable MN with a varactor diode and

MEMS devices will be helpful in improving the efficiency of the device. Antennas incorporating metamaterials and RT/duroid substrates can be advantageous for creating compact, high-gain antennas, enhancing the functionality of rectennas for a broad range of IoT applications. The multiband and wideband rectennas can be designed to overcome the limitations of a single-band antenna.

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