Wireless Technologies in Human Healthcare

Wireless Technologies in Human Healthcare:

An Evolution

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Ram Krishan and Manpreet Kaur

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CHAPTER 1

DIELECTRIC RESONATOR RECTENNA FOR RF ENERGY HARVESTING BASED ON FRACTAL TECHNIQUE

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Abstract: With the rapid growth of wireless communication technology, RF energy harvesting has become an area of great interest. It provides a promising alternative to traditional batteries, allowing IoT devices and wireless sensor networks to function independently. However, due to the low and inconsistent RF energy in the surrounding environment, a high-gain rectenna (combining an antenna and a rectifier) is required to efficiently capture and convert the available energy. This chapter presents a single-band cylindrical dielectric resonator antenna (DRA) designed to effectively harness low-power RF signals in the 2.4 GHz Wi-Fi band for energy harvesting applications. To improve the antenna's radiation characteristics and gain, a cylindrical dielectric resonator made of Al_2O_3 with a dielectric constant of 9.8 is selected. The proposed antenna is excited using an aperture coupling technique, where a Hilbert fractal-shaped strip is incorporated into the circular aperture to achieve the desired resonance. At 2.4 GHz, the designed antenna (120 × 120 × 1.6 mm^3) attains a gain of 6.5 dBi. The rectifier circuit employs a single-diode shunt rectifier configuration to convert the received RF signal into DC power efficiently. The antenna and rectifier's performance was validated through simulations and experimental measurements, with the results showing strong agreement. At 2.4 GHz, the rectifier achieves a maximum power conversion efficiency of 66% at an input power of 5 dBm. Under the same input conditions, the rectenna attains a peak output voltage of 1.34 V and a highest power conversion efficiency of 64.4%. The findings of this study indicate that the proposed rectenna is well-suited for various low-power portable biomedical devices, sensors, electronic watches, and energy storage devices like supercapacitors and rechargeable batteries.

Keywords: Dielectric resonator antenna (DRA); Hilbert fractal curve; RF energy harvesting; HSMS2860 diode; Power conversion efficiency (PCE).

1. Introduction

Since RF power is abundantly available from various reliable electromagnetic sources, RF energy harvesting has attracted significant attention recently. This technology enables the collection and utilization of ambient RF energy to power various battery-free electronic devices, such as wearable medical sensors, Wi-Fi-based systems, and remote industrial control sensors. Consequently, RF energy harvesting (RFEH) presents a promising solution for providing a sustainable power source or to improve the battery life of low-power electronic medical devices, including smart watches, mobile phones, calculator displays, and RFID systems [1-2]. In the RF energy harvesting (RFEH) technique, a specialized device known as a rectifying antenna, or rectenna, captures ambient electromagnetic (EM) energy and converts it into DC power. A rectenna system primarily consists of two components: an antenna for energy reception and a rectifier circuit for AC-to-DC conversion. The antenna's efficiency influences the overall performance of the rectenna in capturing RF signals and the rectifier’s power conversion efficiency (PCE) [3]. The dielectric resonator antenna (DRA) is an alternative to microstrip antennas that eliminates surface wave propagation and does not rely on conductive materials. Additionally, DRAs offer higher power-handling capability and greater design flexibility in three-dimensional configurations. The concept of microwave resonators was first introduced by Richtmyer in 1939 and later utilized as electromagnetic (EM) radiators once low-loss ceramic materials became available. While dielectric resonators can be designed in various shapes, the most commonly used geometries include rectangular, hemispherical, and cylindrical forms. Previous studies have explored dielectric resonator-based rectennas; for instance, [6] investigated using a patch-loaded cylindrical DRA to achieve compact dimensions while maintaining adequate gain performance. However, despite its large size, the antenna exhibits relatively low gain. In [7], a microstrip-fed Triangular Dielectric Resonator Antenna (TDRA) designed for the ISM band demonstrated a radiated power of 0.9033 W but suffered from poor gain. The rectification and filtering of the AC signal in this system produce a

DC output current ranging from 1.5 mA to 2.5 mA, depending on the available input power. In [8], a cylindrical dielectric resonator antenna (DRA) was proposed for RF energy harvesting (RFEH) applications in the 2.45 GHz Wi-Fi band. This antenna utilizes Rogers TMM10i™ material with a dielectric constant of 9.8 to improve radiation efficiency. However, this material's cost is higher. However, the cost of this material is relatively high. The authors created a hemispherical dielectric resonator antenna (DRA) composed of clear glass [9] to capture solar and radio frequency energy from the surroundings. However, its RF-to-DC conversion efficiency is relatively low, only about 35.1%. Another study [10] presents a compact patch antenna integrated with a rectifier, achieving 54% efficiency at 2.45 GHz, with a return loss of −52 dB and a bandwidth of 150 MHz. Despite these advantages, the antenna gain remains very low, at just 3.48 dBi.

Fractal geometries can be employed to get the appropriate operating bandwidth in large antennas. Fractal antennas with different geometries, such as the Koch snowflake, Minkowski, Hilbert, and Sierpinski triangle, are used in rectenna designs to increase effective electrical length. In [11], the authors presented a small rectenna for effective Wi-Fi energy harvesting. They used fractal geometry to reduce the antenna size and improve energy harvesting because of its space-filling and self-similarity features. Nevertheless, the antenna has a relatively low gain.

A single-band cylindrical DR-rectenna for RF energy harvesting in the 2.4 GHz Wi-Fi spectrum is shown in this chapter. A Hilbert fractal curve is integrated into the antenna’s ground plane to achieve the desired resonance. The proposed design also features a single-diode rectifier with an impedance-matching network to maximize RF-to-DC power conversion. The following subsections provide a concise explanation of the antenna and rectifier configurations. The geometric description of the antenna is provided in Section 2, followed by discussions and simulated results in Section 3. Section 4 presents the measured results, while Section 5 details the rectifier configuration of the rectenna. Finally, Section 6 includes the concluding remarks and references. This study introduces an innovative approach to enhancing DRA efficiency in the 2.4 GHz Wi-Fi band by integrating a cylindrical dielectric resonator with a Hilbert fractal-shaped ground plane. With the addition of a rectifier for RF energy harvesting, the proposed rectenna is well-suited for low-power electronics applications.

2.Geometrical description of the proposed antenna

The proposed antenna is a single-band rectenna designed for RF energy harvesting. Figures 1(a) and 1(b) illustrate its schematic layout, showing the top view without the cylindrical DRA and the isometric view. The design includes a cylindrical dielectric resonator (DR) made of alumina (Al_2O_3) with a dielectric constant of $\varepsilon r = 9.8$ and a loss tangent of $\tan \delta = 0.002$, positioned above the ground plane to achieve optimal performance. The selected DR is mounted on an FR4 substrate with dimensions of $120 \times 120 \times 1.6$ mm^3 and a dielectric constant of 4.4. The DR material has a diameter of 76 mm and a height of 28 mm. To fine-tune the antenna at 2.4 GHz, a Hilbert-shaped fractal strip is integrated into the circular aperture. The antenna is excited using an I-shaped microstrip line coupled to the circular aperture and excites the cylindrical dielectric resonator (DR). The dimensions of various antenna parameters are as follows: W_G=120 mm, L_G=20 mm, L_F=70 mm, W_F=3 mm, D=76 mm, H=28 mm, H_s=1.6mm, L_1=24 mm, L_2=16mm, L_3=9 mm, L_4=8.1 mm andL_5=10mm.The antenna's resonance frequency is adjusted to 2.4 GHz by employing a Hilbert strip fractal with an effective length (Leff), as defined in Equation 1. The effective length is determined by summing the individual segment lengths of the Hilbert curve.

$$L_{eff}=L_1+L_2+L_3+L_4+L_5 \qquad (1)$$

The antenna is tuned to a resonant frequency of 2.4 GHz with the aid of the Hilbert strip, and this frequency is determined using the formula given in Equation 2:

$$f_r=\frac{c}{2\times L_{eff}} \qquad (2)$$

where, $c=3\times10^8$ m/sec is the speed of light.

To match the desired resonant frequency, a correction factor k is introduced.

$$\text{So, } f_r= k\,\frac{c}{2\times L_{eff}} \qquad (3)$$

where k is the ratio of the desired resonant frequency to the calculated frequency (i.e. from Equation 2).

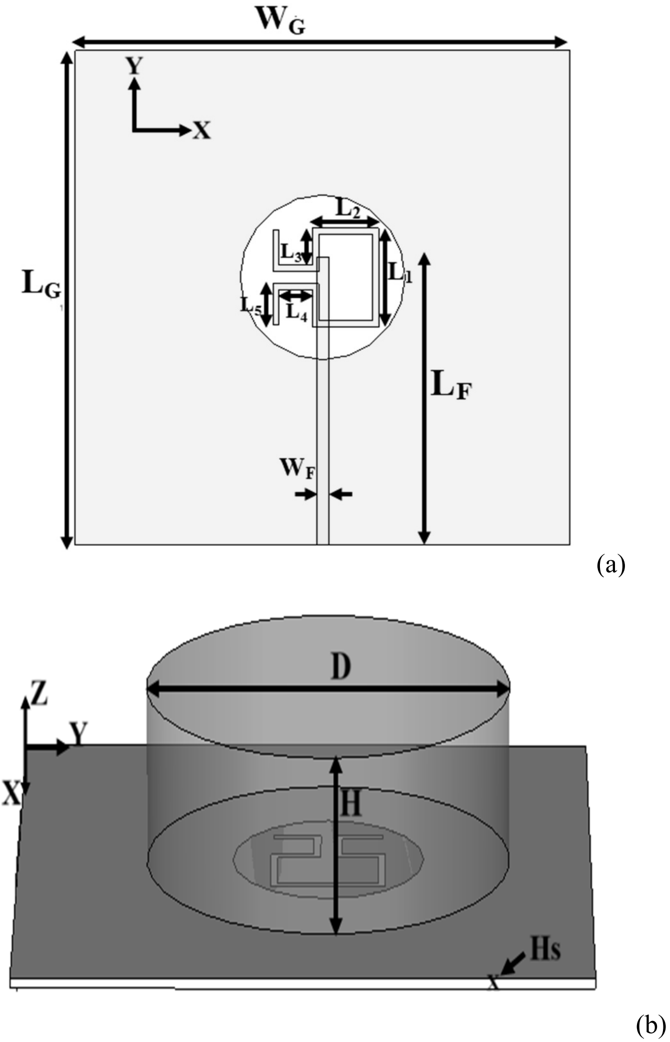


Figure 1. Schematic diagram of the proposed antenna (a) Top view without cDRA (b) Isometric view

A step-by-step process is illustrated in Figure 2 to simplify the design of the proposed antenna. Initially, as shown in Antenna 1, an I-shaped microstrip line on the backside of the substrate feeds a circular aperture, which excites the cylindrical dielectric resonator antenna (DRA). To achieve the desired operating frequency of 2.4 GHz, as defined by Equations (1) to (3), a first-iteration Hilbert fractal strip is introduced inside the circular aperture, as shown in Antenna 2. The final design, incorporating this fractal structure, is illustrated in Antenna 3. Figure 3 illustrates the simulated $\mathbf{S_{11}}$ performance across different design stages, from Antenna 1 to Antenna 3. The analysis reveals that Antenna 1 initially resonates at multiple frequencies, specifically 2 GHz and 2.5 GHz, but with a relatively low return loss. Antenna 2 achieves three resonance frequencies at 2 GHz, 2.5 GHz, and 3.3 GHz by introducing a first-iteration Hilbert fractal strip. Finally, with the addition of a second-iteration Hilbert fractal strip, Antenna 3 is finely tuned to 2.4 GHz—the desired resonance frequency for energy harvesting applications.

3. Simulated performance of the proposed antenna

The simulated E-field vector distribution within the cylindrical dielectric resonator antenna (DRA) at 2.4 GHz at various planes is displayed in Figures 4(a) and (b). The field orientation is characterized using the TE_{mnp} mode notation**,** where m, n, and p represent the half-cycle sinusoidal variations along the axial (z), radial (r), and azimuthal **(**Φ**)** axes, respectively. The field variation, denoted by δ, ranges between 0 and 1 [12]. The results show that the $TE_{02\delta}$ mode is generated at the resonating frequency. The movement of the E-field vectors (arrows) further confirms the antenna's operation in the $TE_{02\delta}$ mode at 2.4 GHz**.**

The surface current distributions of the second iteration Hilbert curve at 1.9 GHz and 2.4 GHz are displayed in Figures 5(a) and 5(b). At 1.9 GHz**,** the activation of higher-order resonances causes the current to become more localized, with increased concentrations in specific regions. As the frequency increases to2.4 GHz**,** the current becomes more concentrated along the fractal strips, benefiting from the increased structural complexity. This process enhances impedance matching and improves energy coupling into the resonant structure. The extended current path also effectively increases the electrical length, facilitating optimal operation at 2.4 GHz**.** The observed current distribution confirms that the proposed antenna efficiently operates in the single-frequency band at 2.4 GHz**.**

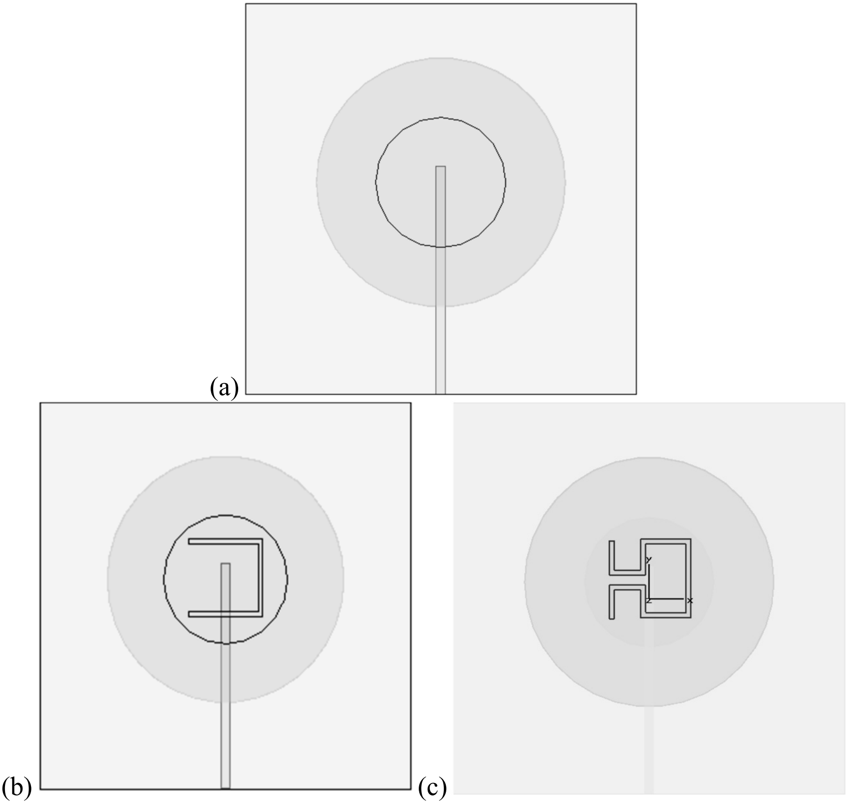


Figure 2. (a) Antenna 1, (b) Antenna 2, (c) Antenna 3. Step-by-step design process of the proposed antenna through various iterations of the Hilbert fractal. (a) Antenna 1 (b) Antenna 2 (zeroth iteration) (c) Antenna 3 (First iteration)

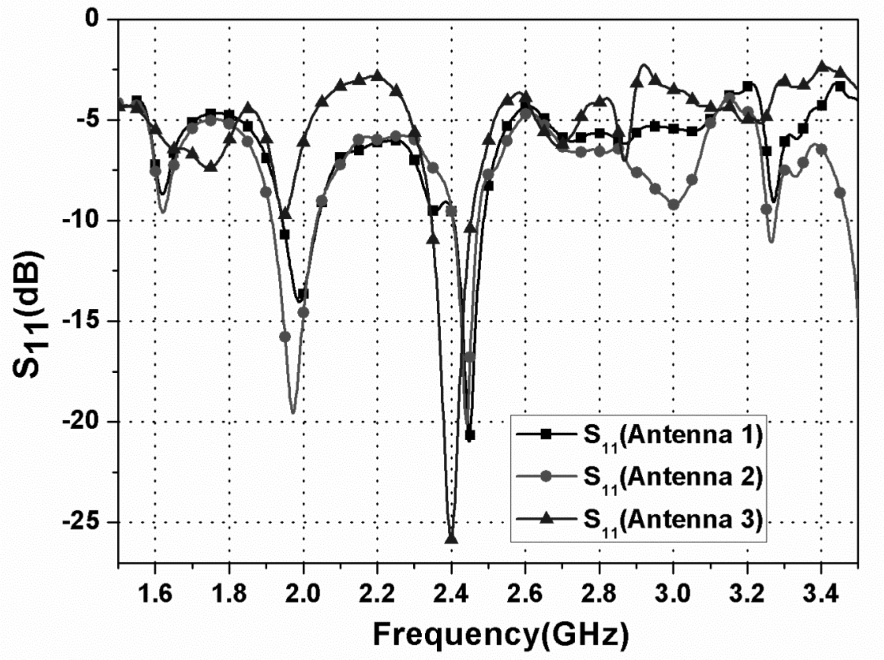


Figure 3.S_{11} (dB) parameters of different antenna configurations

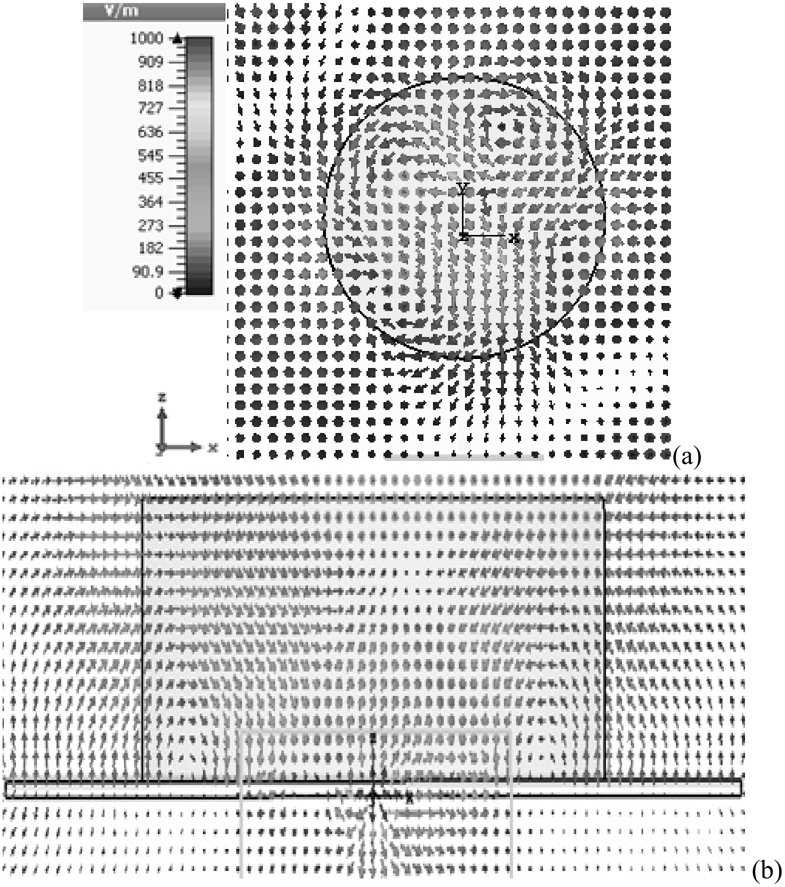


Figure 4. E-field vector distribution at 2.4 GHz (a) top view (b) cross-sectional view

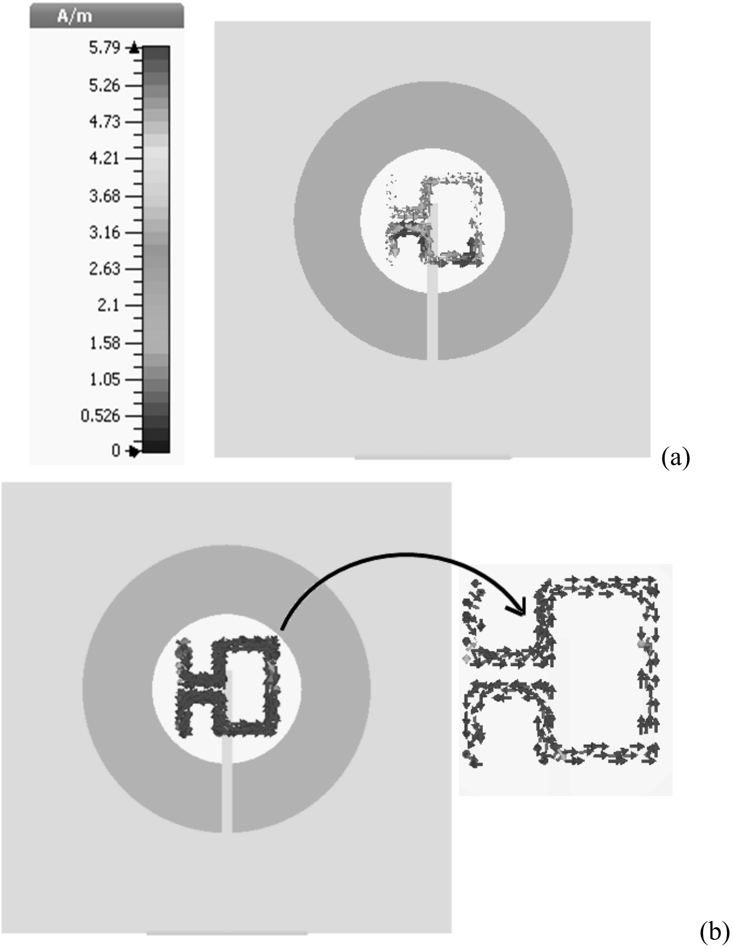
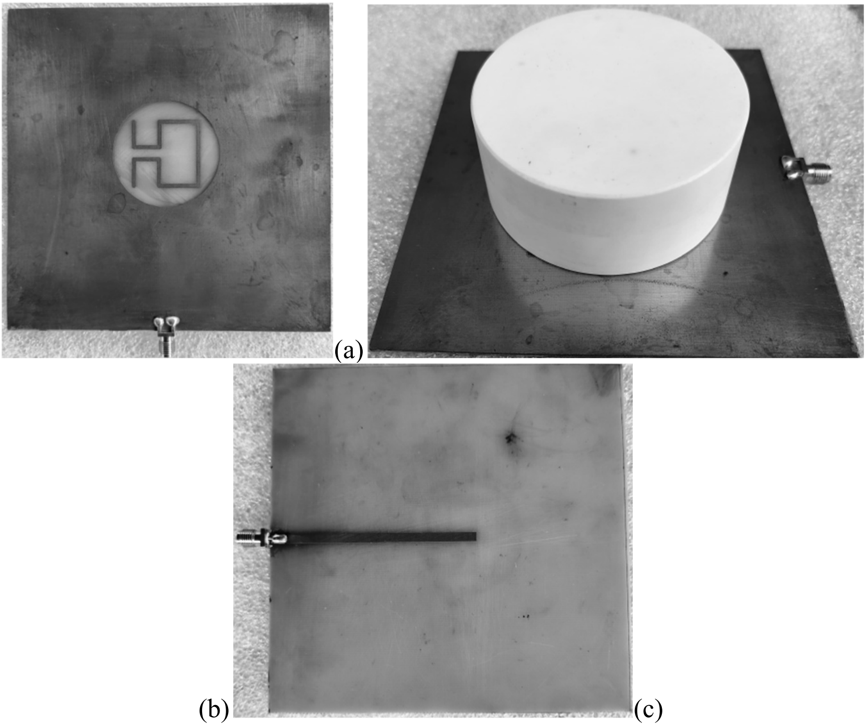


Figure 5. Surface current distribution of second iteration hilbert curve (a) 1.9 GHz (b) 2.4 GHz

4. Validation of the proposed antenna

A prototype was fabricated to validate the performance of the proposed antenna, as shown in Figures 6(a)–6(c). The antenna design was simulated using the commercial electromagnetic simulation software CST Microwave Studio™. The fabricated prototype's S_{11} and gain performance were measured using an Agilent PNA-L N5230A Network Analyzer and compared with the simulated results, as depicted in Figures 6(d) and 6(e). The prototype achieved a maximum gain of 6.5 dBi in the broadside direction. Furthermore, the antenna demonstrated high radiation efficiency, reaching a peak of 89.2%**,** indicating that it effectively radiates (or receives) most of the input power.


(a)
(b)
(c)

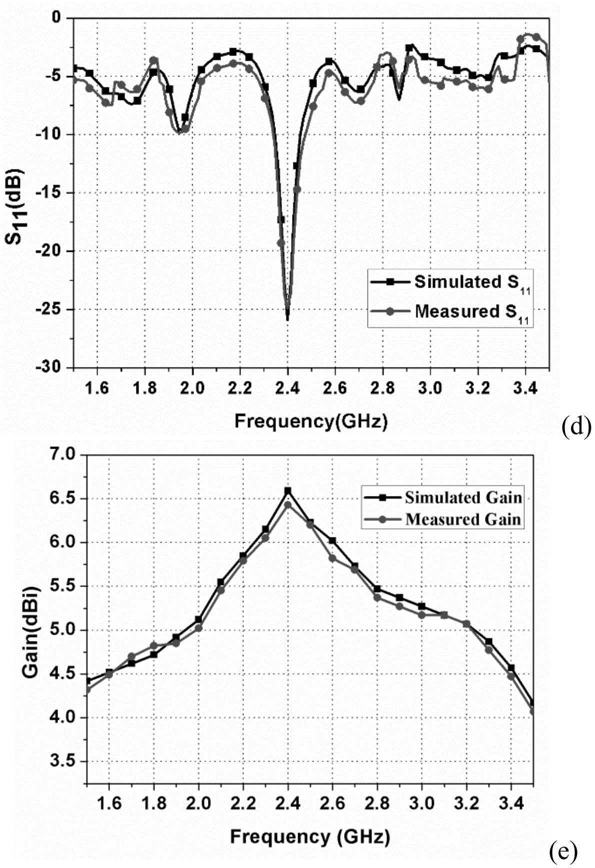
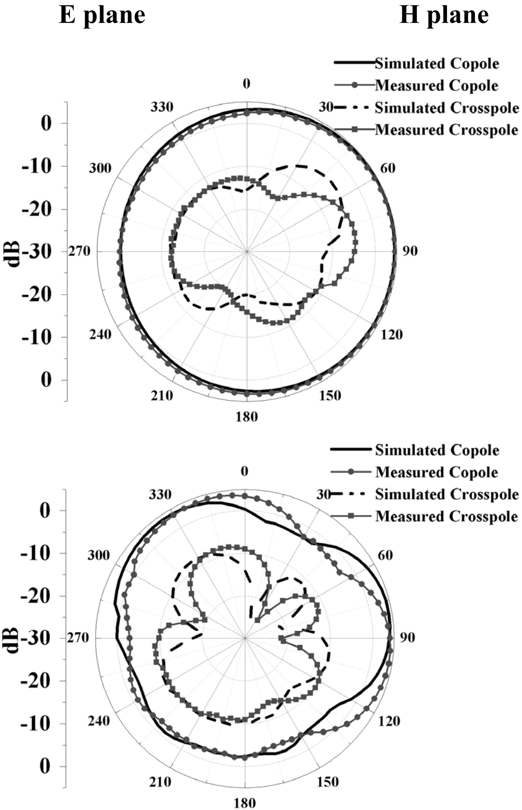


Figure 6. Fabricated antenna and simulated and measured characteristics performance comparison (a) top view (b) side view (c) back view (d) S_{11}characteristics (e) Gain performance

The 2D radiation pattern in the antenna's E and H planes at the desired operating frequency is shown in Figures 7(a) and (b). The antenna exhibits near-omnidirectional radiation characteristics, making it ideal for ambient RF energy harvesting applications that require efficient RF collection from various angles. Additionally, both co-polarization and cross-polarization performances remain relatively stable with minimal variation. The slight discrepancies between the simulated and measured results may be attributed to soldering imperfections in the SMA connector or minor fabrication inconsistencies. According to the experimental results, the proposed antenna for ambient RF energy collecting works well and efficiently at 2.4 GHz.



(a)

(b)

Figure 7. Simulated and measured copole and crosspole radiation pattern at 2.4 GHz (a) E plane (b) H plane

Table 1 compares the designed DRA with existing designs from the literature to evaluate its performance. Several studies have explored antenna designs operating in the 2.4–2.45 GHz frequency range, varying in substrate permittivity (εr), dimensions, bandwidth (BW), and gain. The proposed DRA operates at 2.4 GHz with a dielectric constant of 9.8, whereas other designs either do not specify their dielectric constants or likely use lower values. Unlike these designs, the proposed antenna achieves high gain (6.5 dBi) while maintaining a relatively simple structure, whereas others suffer from lower gain or greater design complexity. This highlights the antenna’s effectiveness in delivering high gain with reasonable bandwidth, making it a promising candidate for RF energy harvesting and wireless power transfer applications.

Table1. Performance comparison of the DRA with existing literature

References	**Frequency (GHz)**	**ε_r**	**Dimension (mm^3)**	**BW (%)**	**Gain (dBi)**
[6]	2.4	-	120×100×0.3	2.09	5.14
[7]	2.45	9.8	63×53×1.51	4.90	5.38
[8]	2.45	9.8	60×50×1.6	12.24%	5.15
[9]	2.45	-	45×45×3.2	16.33%	-
[10]	2.45	-	40×47.5×1.6	-	3.48
[11]	2.45	-	38×38×1.6	4.48	2.12
[This work]	2.4	9.8	120×120×1.6	4.17	6.5

5. Proposed rectifier circuit configuration

The essential component of the rectenna system that transforms ambient radio frequency energy into usable DC electrical power is a rectifier [13]. The rectifier circuit consists of a load resistor, a diode, a DC pass filter, and an impedance matching network (IMN). The IMN ensures proper impedance matching between the receiving antenna and the conversion circuit at the target operating frequency, maximizing power transfer efficiency. A key element of the rectifier, the diode, plays a significant role in determining its overall performance. Therefore, selecting the right diode is essential for achieving an optimal rectifier design. A diode with a low turn-on voltage is ideal for rectification, as ambient RF energy typically has a very low power density. Conventional diodes, with their relatively high turn-on voltages, are unsuitable for operation at RF power levels. Schottky diodes are well-suited for RF rectifier design due to their high switching speed and low turn-on voltage. Several Schottky diodes, including the MA4E1317, SMS7630, and HSMS28xx series, are commonly used in energy harvesting applications. For the proposed rectifier design, the HSMS2860 Schottky diode has been selected due to its suitability for low-power energy harvesting, particularly at an input power level of approximately 0 dBm. Additionally, selecting the proper rectifier configuration is essential. Various rectifier arrangements have been studied recently for DC voltage generation, including the voltage doubler configuration [15]–[17] and the single-diode configuration [10, 14]. Figure 8(a) shows the proposed single-band rectifier circuit layout diagram with an impedance matching network (IMN: W_1, L_1, W_2, L_2, W_3, L_3), HSMS Diode, DC pass filter (C) and a load resistor (R_L). Figure 8(b) displays the fabricated prototype of the proposed rectifier circuit. Surface-mount devices (SMDs) enhance the circuit's performance by minimizing parasitic effects and improving compactness. The rectifier circuit is printed on a 1.6 mm FR4 substrate, with optimal dimensions (in mm) designed for efficient operations: W_1=16 mm, L_1= 4.6 mm, W_2= 0.5 mm, L_2=16.2 mm, W_3= 1.2 mm and L_3 = 2.5 mm, C=15 pF and R_L=1.0 kΩ. The rectifier circuit is designed using the Keysight Advanced Design System (ADS) software.

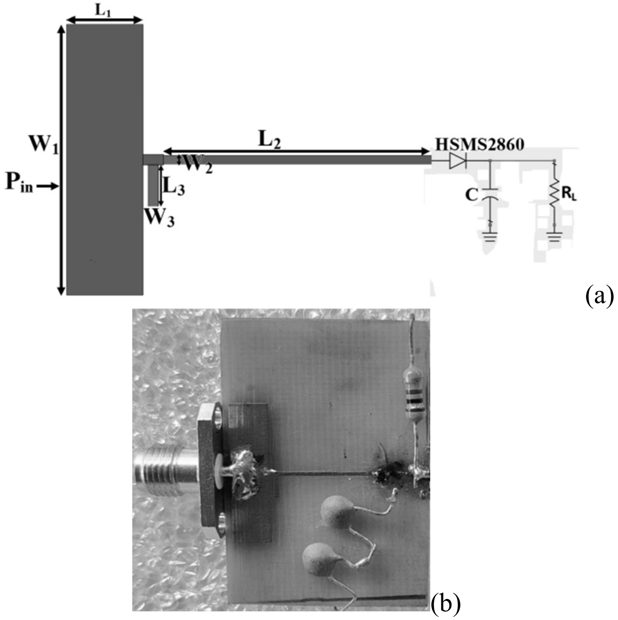


Figure 8. (a) Schematic layout of the proposed rectifier circuit (b) Fabricated prototype of the rectifier circuit

The power conversion efficiency (PCE) and output voltage (Vout) of the rectifier circuit have been optimized through parametric analysis, and the resulting performance metrics have been presented. Figure 9 illustrates the S_{11} performance and frequency response for varying input power levels with a 1 kΩ load resistance. The proposed rectifier operates efficiently across a wide input power range from -5 dBm to 5 dBm at both resonant frequencies. Moreover, the rectifier improves impedance matching across different input power levels within each frequency band, ensuring stable and efficient performance.

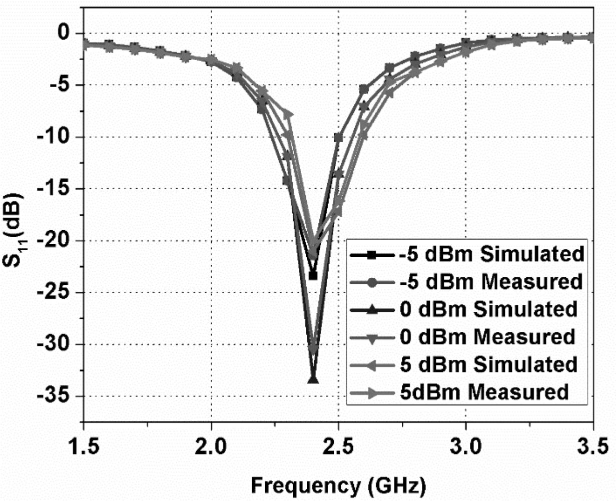
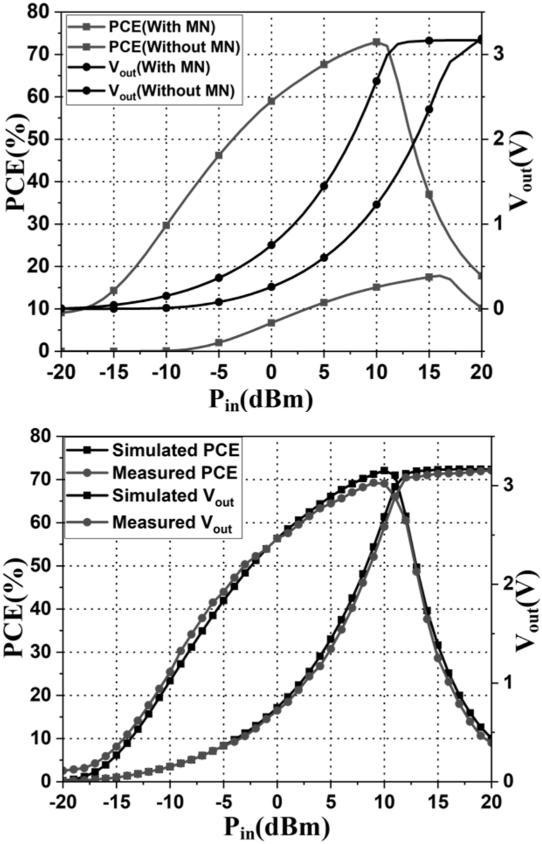


Figure 9. Simulated and measuredS_{11}vs. frequency performances of the proposed rectifier.

Figure 10 illustrates the impact of the impedance matching network (IMN) on the rectifier PCE (power conversion efficiency) and DC output voltage (V_{out}). A matching network (MN) significantly enhances rectifier performance by improving power conversion efficiency (PCE) and output voltage (V_{out}). The rectifier achieves higher efficiency with an MN, whereas PCE remains lower without it. Similarly, the output voltage is higher with an MN than without, as shown in Figure 10(a). At lower input power levels, the rectifier without an MN struggles to convert power efficiently, limiting its effectiveness. The MN makes the rectifier more suitable for energy harvesting and rectification applications by enabling optimal performance at lower power thresholds. Figure 10(b) shows the simulated and measured power conversion efficiency and output voltage (V_{out}) at 1 kΩ load resistance.



(a)

(b)

Figure 10. Performance variation of the proposed rectifier for PCE and V_{out} (a) with and without Matching Network (MN) (b) Simulated and measured results.

At an input power of 5 dBm, the proposed rectifier circuit achieves a maximum power conversion efficiency (PCE) of 66%. Figure 11 illustrates the PCE and output voltage (V_{out}) as functions of input power (P_{in}). At 0 dBm input power, the rectifier achieves a PCE of 56%, while at 5 dBm, the maximum PCE of 66% is reached. Correspondingly, the output voltage (V_{out}) is 0.78 V at 0 dBm and increases to 1.44 V at 5 dBm. The rectenna's minimal component design reduces losses associated with individual elements, enhancing overall efficiency. The output voltage of the rectenna system is primarily determined by the power harvested by the antenna and the rectifier's conversion efficiency, both of which contribute to improved performance.

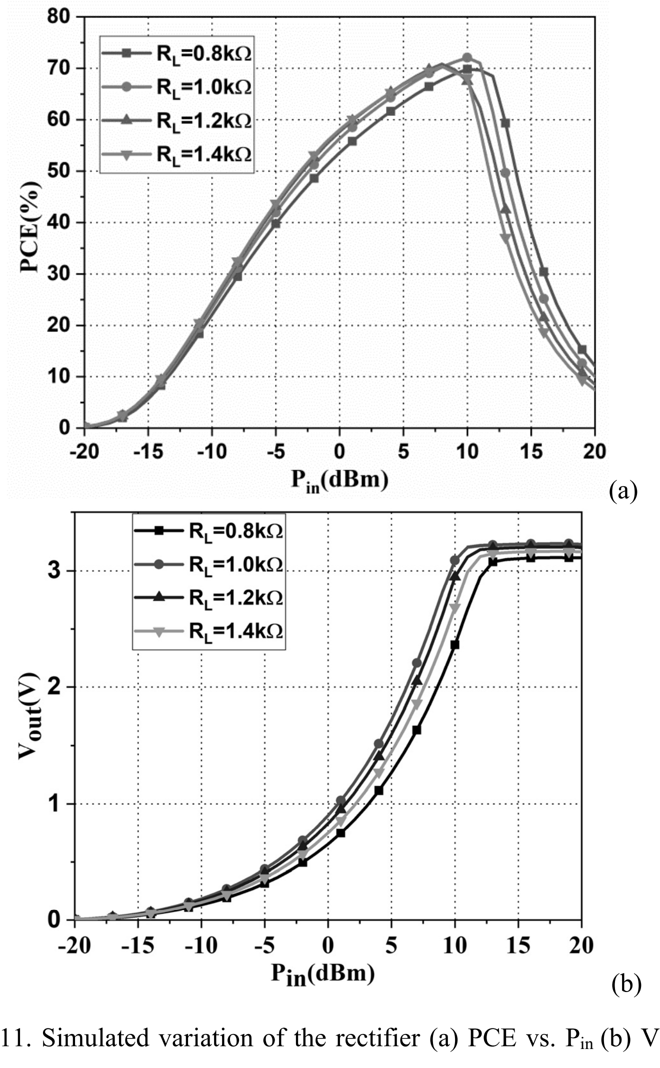


Figure 11. Simulated variation of the rectifier (a) PCE vs. P_{in} (b) V_{out} vs. P_{in}.

A comparison has been made with the existing literature to find the novelty of the proposed rectenna and the results of this comparison are presented in Table 2. Among the studied designs, the proposed rectifier with the HSMS2860 diode is the most efficient, achieving a power conversion efficiency (PCE) of 66% at 5 dBm input power. For comparison, the HSMS2850 diode achieves a PCE of 54% at 0 dBm input power [10], while the SMS7630 diode attains a PCE of 55% at a slightly higher input power level of 3 dBm [14, 17]. In comparison, the HSMS-2820 diode and other voltage doubler rectifier (VDR)-based systems exhibit lower power conversion efficiencies (PCEs). For instance, the HSMS-2820 achieves only 45% PCE and that too at a significantly higher input power of 20 dBm [15]. Similarly, the rectenna in [16] demonstrates poor power conversion efficiency. Overall, the proposed rectifier design outperforms existing references regarding efficiency and performance, making it a more effective solution for RF energy harvesting applications.

Table 2. Performance comparison of the rectenna with existing literature

References	**Frequency (GHz)**	**Type of diode**	**Rectifier Topology**	**P_{in}(dBm)**	**PCE (%)**
[10]	2.45	HSMS2850	Single diode	0	54
[14]	2.45	SMS7630	Single series diode	0	54
[15]	2.45	HSMS-2820	VDR	20	45
[16]	2.45	HSMS-2862	VDR	0	51
[17]	2.4	SMS7630	VDR	3	55
Proposed rectifier	2.4	HSMS2860	Single Diode	5	66

6. Experimental validation of the rectenna system

A wireless power transfer system utilizing microwave technology is shown in Figure 12. It consists of a transmitting unit, which includes an RF generator and a horn antenna to transmit RF signals at 2.4 GHz, and a receiving unit, which comprises a receiving antenna and a rectenna circuit that converts RF energy into DC power. A multimeter measures the converted power, demonstrating the system's ability to wirelessly transfer and harvest energy. An SMA connector is used to link the prototype antenna and rectifier components. The primary purpose of the rectenna system is to harvest ambient radiofrequency energy from the surrounding environment and convert it into usable DC power. However, an experimental measuring setup was developed to test the rectenna due to specific infrastructure limitations, as shown in Figure 12(a). The fabricated prototype of the rectenna is presented in Figure 12(b). The maximum distance between the rectenna system and the transmitting antenna is 200 cm, where the energy density is approximately 0 dBm. At an input power (Pin) of 5.5 dBm, the rectenna achieves a peak Power Conversion Efficiency (PCE) of 64.4%. The rectenna's output voltage (V_{out}), measured using a voltmeter, is 0.7 V at a P_{in} of 0 dBm and 1.34 V at a P_{in} of 5.5 dBm.

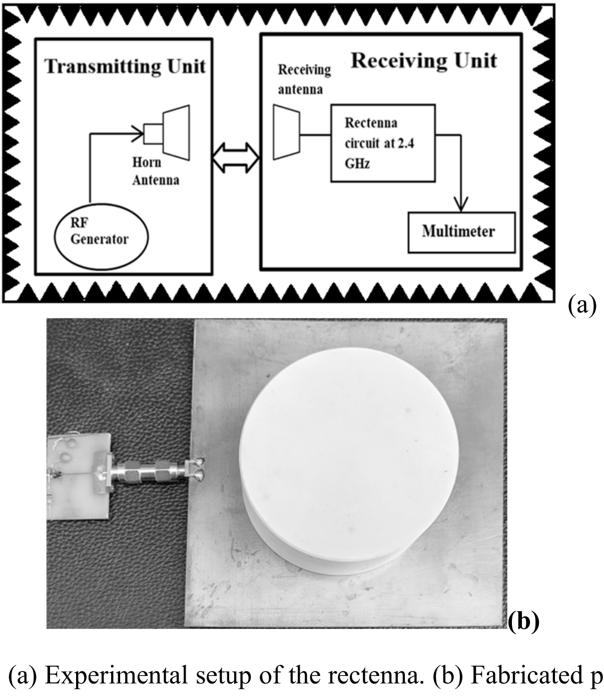


Figure 12. (a) Experimental setup of the rectenna. (b) Fabricated prototype of DR-Rectenna.

7. Conclusion

This chapter introduces a single-band dielectric resonator rectenna (DR-rectenna) designed for radio frequency energy harvesting (RFEH) applications**.** A cylindrical dielectric resonator (DR)is selected for the antenna design, and a Hilbert fractal shape is incorporated into the circular aperture to achieve resonance at the2.4 GHz Wi-Fi band**.** The performance of the antenna with different iteration orders is studied and compared with the measured results. With a simulation tool, the proposed antenna achieves a maximum gain and radiation efficiency of 6.5 dBi and 89.2% at 2.4 GHz frequency. Using an HSMS2860 Schottky diode, a single shunt diode rectifier configuration is implemented for rectification. The proposed rectifier offers power conversion efficiency (PCE) of 66 % and output voltage of 1.44 V at 5 dBm RF input power. Thus, the proposed rectenna can be used to power wireless sensor networks (WSNs), which are an integral part of applications in smart cities, environmental monitoring, and industrial automation. Additionally, the proposed rectenna can energize low-power devices such as medical implants and wearable electronics, providing a sustainable battery-free power source due to its high performance. The design and analysis of this rectenna for harvesting ambient RF energy, optimized for powering low-power devices such as 5G, IoT, LPWAN (Low Power Wide Area Network), RF-powered RFID tags in logistics, asset tracking as well as retail can benefit from continuous power supply, enhancing efficiency and reliability which can contribute to future advancements in this field.

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CHAPTER 2

APPLICATIONS OF IOT IN HUMAN LIFE AND HEALTHCARE

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Abstract: The Internet of Things (IoT) has significantly transformed human life and healthcare by enabling smart connectivity, real-time data exchange, and automation across various domains. In everyday life, IoT applications span smart homes, intelligent transportation, and smart cities, enhancing convenience, efficiency, and sustainability. Smartwearables and smart home systems make things easier daily, and IoT-based smart infrastructures improve the way we consume energy and organize our cities. IoT has changed the way patient care is administered in healthcare by remote monitoring, AI-assisted diagnostics, telemedicine, and personalized treatment plans, resulting in better medical outcomes and greater access to healthcare services. Is it safe to say that the Internet of Things is facing a massive future with a lot of future challenges ahead? With changing times and new developments like 5G, edge computing, artificial intelligence and blockchain can be incorporated to avoid risk. This review presents a wide-ranging analysis of IoT on human life and healthcare through its many life-changing benefits, while showing concerns that need to be dealt with in order to reach sustainable, secure, and ethical IoT.

Keywords: Internet of Things (IoT), Sensors, Cloud computing, Healthcare, Blockchain, Smart cities, Artificial intelligence (AI).