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An Improved Conversion Efficiency of 1.975 to 4.744 GHz Rectenna for Wireless Sensor Applications

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Abstract—This article discusses the design analysis of a wideband rectenna (Antenna + Rectifier). It empowers low power devices, battery-less power sensors, and many Internet of Things (IoT) devices. The main focus of this work is divided into two parts. First, to develop the power to operate the wideband frequency of operation without system complexity. To obtain rectifier bandwidth sufficiently, L-section impedance matching with dual Schottky diode HSMS270B is proposed. Second, to improve the rectenna efficiency and output DC power. Wideband rectenna harvests the maximum RF power of 30.590 dBm, 1145.51 mW, 10.703 Volts at 3.2 GHz. The harvested power is easily available to power up the low powered sensor such as gas sensor (500–800 mW), pressure sensor (10–15 mW), and temperature sensor (0.5–5 mW). The peak conversion efficiency of the rectenna is 88.58% at 0 dBm, 34.70% at 10 dBm, and 53.52% at 20 dBm under the load resistance of 100 kΩ. The proposed work shows a 20–25% improvement in conversion efficiency with this approach. For efficient RF energy harvesting applications, the proposed rectenna is capable of covering a wideband application from 1.975 to 4.744 GHz with a single radiation patch. This shows that the novel approach of the considered work and the proposed rectenna has the specialty to capture more energy from a wide area at once.

1. INTRODUCTION

There are many electronic devices in wireless technology that connects us anytime anywhere in day to day life. These wireless devices radiate electromagnetic energy in the air in a very large amount. During the radiation, a lot of energy is wasted. Hence, how to harvest and recycle this wasted ambient RF energy is an important parameter. To harvest this waste energy, the concept of energy harvesting is used. Harvesting this wasted electromagnetic energy is a motivation in itself. We use an energy harvester to harvest the wasted electromagnetic energy which is used to receive the RF energy from the surrounding and transmit it to the receiving antenna. There are a lot of electronic devices and sensors that directly depend on the battery, and it is impossible to change the battery repeatedly. Therefore, rectenna (RF energy harvester) is an appropriate option to replace the battery for energy harvesting applications. Main motivation of the work is to operate self-power driven electronics devices such as wireless sensor networks, wireless power transfer, wireless charging, and Internet of Things (IoT) with the help of rectenna. Recently, with an increasing number of RF energy sources, a lot of attention has been given to ambient RF energy harvesting. This approach provides continuous power to electronic devices without the need for batteries [1, 2]. Usually, the antenna with a rectifier (Rectenna/RF energy harvester) plays an important role in radio frequency energy harvesting (RFEH) applications. Most of the harvesting circuits work on a single frequency band; this shows the improvement in RF to DC conversion efficiency at the high input power [3–8] along with narrowband characteristics, though these narrowband harvesters restrict the RF power scavenging capability at a single frequency band only.

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To harvest the consumable energy at a broader range wideband, miniaturized rectenna is needed. Wideband rectenna efficiently operates self-power electronic devices such as electronic watches, smart gadgets, cellphones charging, and other sensor applications. Consequently, the broadband and multiband antenna is able to operate with broadband or multi-band frequencies at low input power, and it completely fulfills the necessity of antennas with multifunction. A broadband triangular omnidirectional antenna was introduced in [9] for RFEH over the broadband bandwidth. In [10, 11], a dual-band monopole antenna, broadband slot antenna, and flexible substrate antenna in [12] are introduced for RFEH applications. As we know, rectenna is a combination of the antenna with rectifier or voltage doubler, impedance matching network, and nonlinear diodes (high-frequency diode). When recombining the antenna with the rectifier circuit, proper impedance matching should be there. Impedance matching is required for maximum power transfer towards the receiving end of the rectenna, and it improves the conversion efficiency at minimum input power levels [13–15]. Moreover, various rectifier configurations, such as single diode half-wave and full-wave rectifier in [16], voltage doubler topology in [17], and charge Dickson, greinacher rectifier topology in [18], are introduced. In the rectifier topology, the Schottky diode connects with the rectifier circuit. CMOS based and/or Schottky diode-based rectifier circuit is preferable to design RF energy harvester[19]. Due to their lower junction capacitance and low threshold voltage characteristics, Schottky diodes are mostly preferred rather than simple PN junction diodes [20]. Now a complete rectenna circuit is constructed with the help of these parameters. Also, rectennas are considered for integration and adaptability to the environment through an antenna substrate [21]. Broad bandwidth characteristics, moderate gain, and an omnidirectional radiation pattern are preferable characteristics of any compact antenna which efficiently works on RF energy harvesting. Apart from the antenna, a proper impedance matched rectifier circuit is also needed. That can efficiently cover most of the frequency bands such as 1.8–2.2 GHz, 2.3 GHz, 2.4 GHz, 2.5 GHz, 3.2 GHz, 3.4–3.6 GHz, 4.2–4.8 GHz, 5 GHz, 5.1 GHz, and 5.8 GHz. Electromagnetic devices are energized by the received output power that is capable to store sufficient energy for the backup.

The primary objectives of the research are: The first objective fulfills the requirement of the broadband antenna structure; the second demonstrates the behavior of rectenna in terms of received RF power; and the third examines the RF to DC power conversion efficiency of the proposed rectenna.

- To design a broadband rectenna, an octagonal microstrip patch (three notches) antenna integrated with an L impedance matching network and dual diode topology to reduce the complexity of the broadband harvester.
- To investigate the RF power of a broadband rectenna (1.975–4.744 GHz) using ADS simulation, the broadband rectenna harvests the maximum RF power of 30.590 dBm, 1145.51 mW, 10.703 Volts at 3.2 GHz, and the received power shows the uniqueness of the work with the comparison of literature in [15, 18, 22–25]. It is easily applicable to power up the low power sensor devices [26].
- Analyze the performance of the rectenna in terms of power conversion efficiency. It includes a compact antenna with wideband characteristics. A simple geometry structure is used with efficient rectifier circuits to improve rectenna parameter performance. Peak conversion efficiencies of the rectenna are 88.58% at 0 dBm, 34.70% at 10 dBm, 53.52% at 20 dBm, and a load resistance of 100 kΩ [15, 18, 22–25].

In this paper, a compact octagonal broadband rectenna is analyzed. A simple octagonal patch with three rectangular notches on the top is introduced. Additionally, a defected ground structure (DGS) is applied in the ground plane [27]. It shows the broadband bandwidth during the simulation. For maximum power transfer and improved RF to DC conversion efficiency, voltage doubler topology with a simple L impedance matching circuit is designed. Peak conversion efficiencies of the rectenna are 88.58% at 0 dBm, 34.70% at 10 dBm, and 53.52% at 20 dBm. The proposed work shows the 20–25% improvement in conversion efficiencies at 0 dBm, 10 dBm, and 20 dBm from the existing literature [15, 18, 22–25]. The benefits of the proposed rectenna are cost-efficient, no complexity, compact structure, improved performance parameters. Moreover, it is the most important that it covers broadband applications as compared to existing literature [3–8].

The rest of the paper is arranged as follows. Section 2 discusses the antenna structure and a rectifier circuit integrated as a rectenna. Section 3 shows the result analysis of the proposed rectenna. Section 4 concludes the paper.

2. DEFECTED GROUND STRUCTURED RECTENNA CONFIGURATION

The word rectenna is a combined arrangement of an antenna and a rectifier circuit, which reproduce the waste RF energy in terms of DC power, and that DC power is easily available to power up low power devices/appliances/sensors, etc. The received RF power will be in dBm, and available DC power will be in milliwatts and/or microwatts. This concept enhances the productivity towards green energy. In general, in a rectenna, the antenna mainly plays an important role when we require to harvest/store wasted RF power. In this work, a simple structure of the microstrip patch antenna with an octagonal patch of three rectangle notches is introduced. The proposed antenna [28] is considered to fabricate on a cost-efficient FR4 substrate, where the relative permittivity (ϵ_r) is 4.4, loss tangent of the substrate 0.02, and thickness (h) of the substrate 1.6 mm. The total size of the antenna substrate is ($W \times L$) $40 \times 45\,\text{mm}^2$, which is $0.26\lambda_0 \times 0.29\lambda_0$ at 1.975 GHz, $0.32\lambda_0 \times 0.36\lambda_0$ at 2.4 GHz, $0.42\lambda_0 \times 0.48\lambda_0$ at 3.2 GHz, $0.56\lambda_0 \times 0.63\lambda_0$ at 4.2 GHz. As a feed line, a microstrip transmission line is used to energize the antenna. Figure 1 demonstrates the basic antenna structure at the initial stage and after the parametric analysis of notches in the patch. To improve the impedance bandwidth, three rectangular notches at the top of the antenna patch are designed to cover different frequency bands. To increase the overall performance of the antenna in terms of broad-bandwidth and reflection coefficients, notches are created step by step in the antenna patch. Finally, the broadband characteristics of the proposed antenna are obtained over the parametric analysis of notches in the antenna patch.

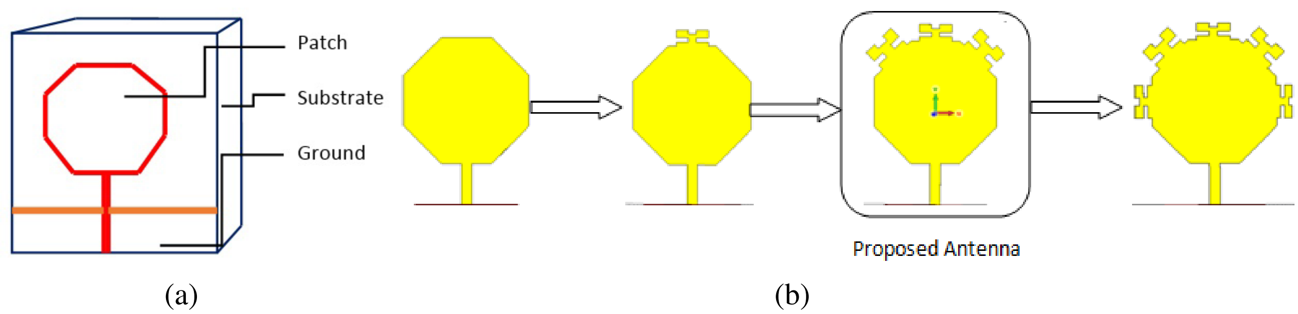

Figure 1. (a) Basic antenna structure. (b) Proposed design evolutions.

Figures 2(a), (b), and (c) contain the proposed antenna geometry along with a complete rectenna circuit. The proposed rectenna circuit first embeds the RF source with an antenna as an input. In terms of simulation, an advanced design system (ADS) is considered where antenna impedance can be easily connected to the rectifier circuit with the help of an SNP file. The SNP file is connected with IMN, voltage doubler topology, and DC load. In the complete rectenna circuit, to operate the load and convert received RF power into DC power, the rectifying circuit is shown in Figure 3. It consists of an L impedance matching circuit, voltage doubler topology, and the load with 100 kΩ. The reason behind the selection of a particular load resister is the compatibility of the wideband frequencies and the effect of the load resistance across the diode. A series capacitor ($C_1 = 150\,\text{pF}$) and shunt inductor ($L = 5\,\text{nH}$) are taken in the proposed matching circuit to properly match the antenna and rectifier impedance. For these two Schottky diodes D_1 and D_2 (HSMS 270B) with capacitors ($C_2 = 180\,\text{pF}$, $C_3 = 0.2\,\text{pF}$) are added in the voltage doubler circuit.

It is clearly understood from Figure 3 that the proposed rectenna receives RF signals from the transmitting antenna and converts them to DC by using the full-wave voltage doubler. Moreover, the input impedance of the rectifier is frequency-dependent, input power-dependent, and also dependent on the available DC load. The values of the inductor and capacitor are optimized through an ADS tuning program, which is used in impedance matching. High-frequency Schottky diodes are used where D_1 (HSMS 270B) is energized on the opposite (-ve) cycle, and capacitor C_2 stores the received energy. However, on a positive cycle, diode D_2 is in use while D_1 is closed during the positive cycle and stores energy in capacitor C_3. The reason behind selecting HSMS 270B diode is that it has a low junction capacitance of 6.7 pF and a forward voltage of 0.55 V with high switching speeds at multiple frequencies, and it is best suited for wireless wideband applications.

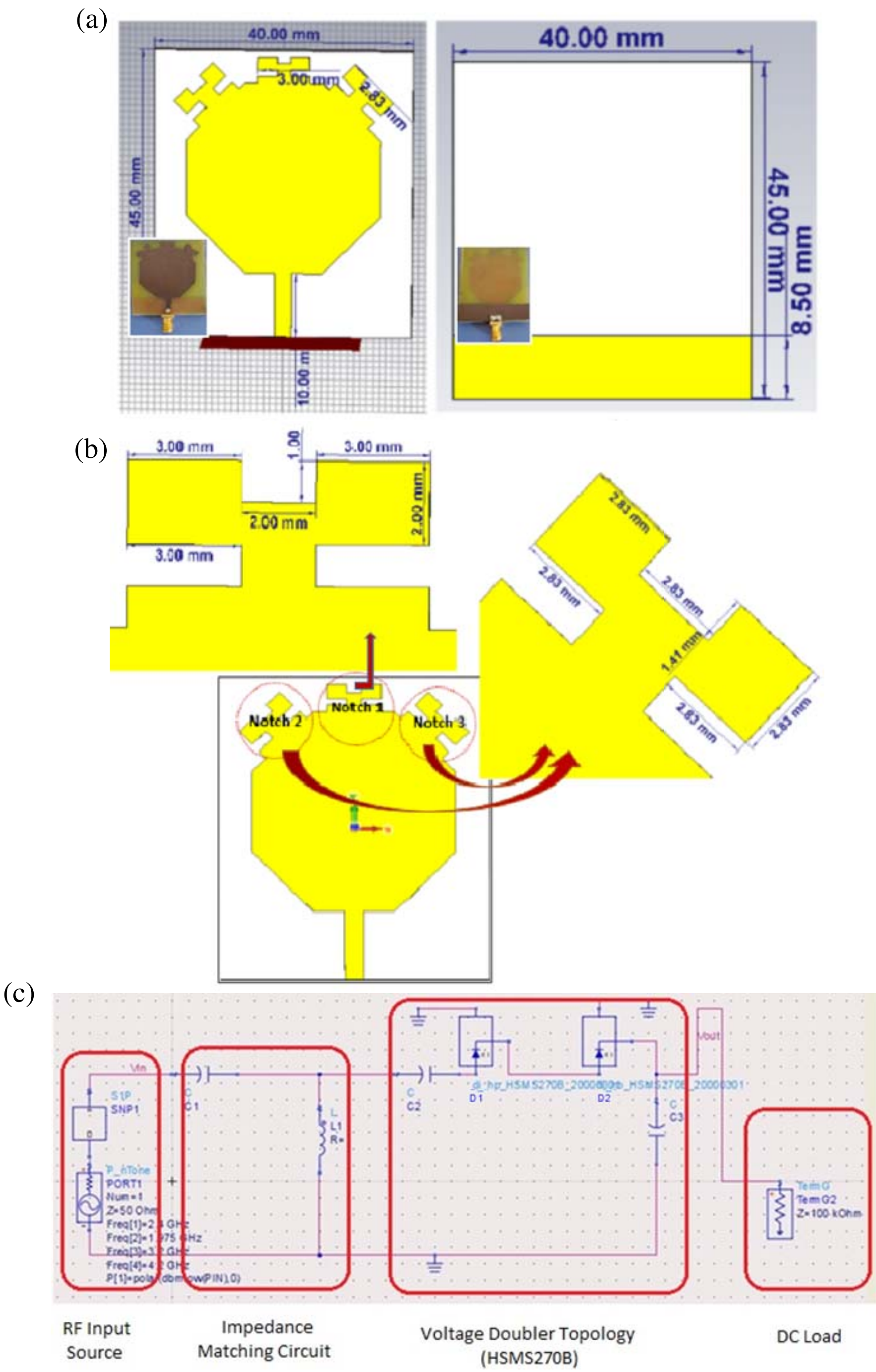

Figure 2. (a) The geometry of proposed antenna. (b) Complete geometry of proposed antenna. (c) The element of energy harvester circuit.

3. RESULT AND DISCUSSION

The major focus of the work is to disseminate a new concept of a compact antenna structure for RF energy harvesting applications rather than the general antenna. The proposed antenna with the defected ground (DGS) [27] is beneficial for capturing a better response in any energy harvester circuit as shown in Figure 3. Therefore, we have seen that this wideband antenna is the best contender for the reception of wideband applications with a single radiation patch. Return loss below -10 dB for the wideband is

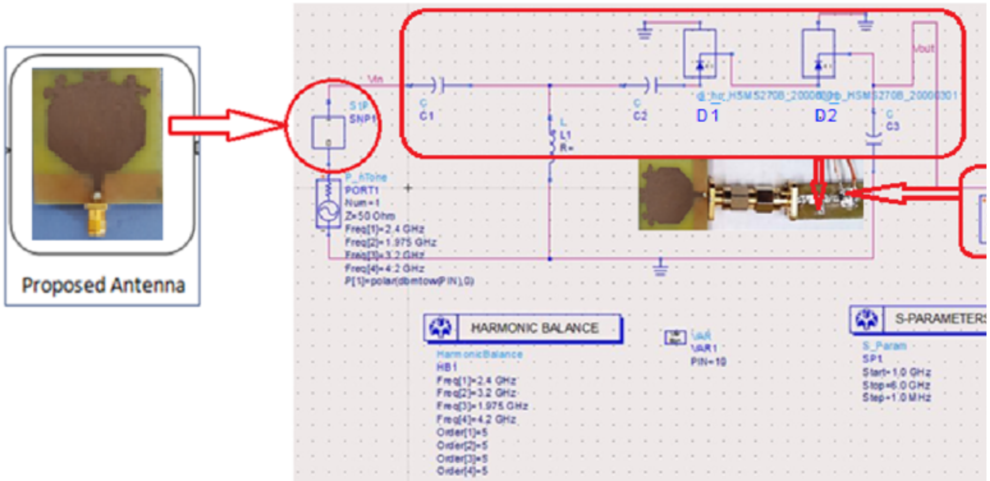

Figure 3. Proposed rectenna circuit.

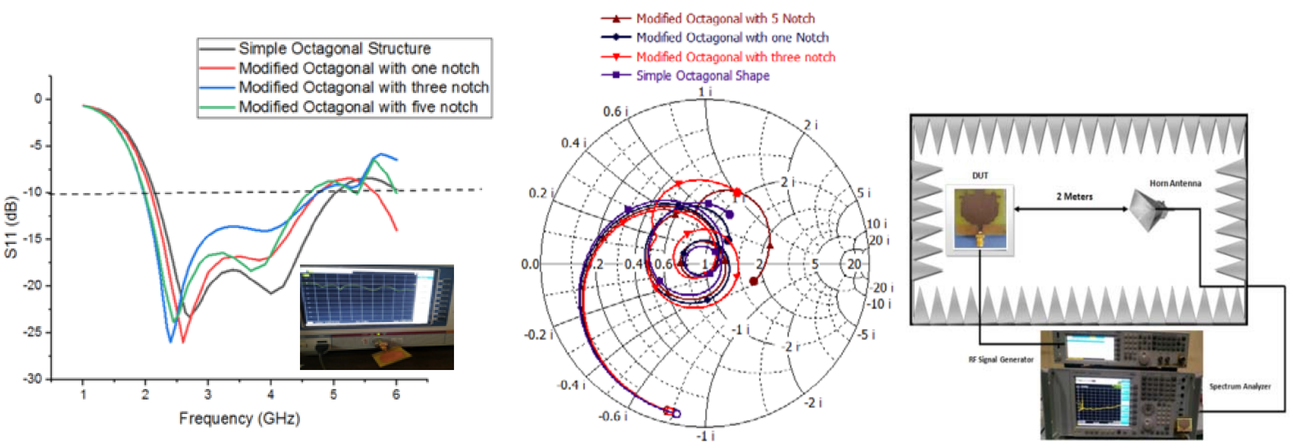

Figure 4. (a) Reflection coefficients of proposed antenna. (b) Smith Chart. (c) Measurement setup.

seen in Figures 4(a) and 4(b) which show the Smith chart calculation. The simulated result shows the good performance of the proposed antenna over the considered frequency range.

Figure 4(c) shows the rectenna measurement system. A standard horn antenna with an RF signal generator is used for transmitting the RF input power. Receiving antenna (DUT) is placed at a 2-meter distance from the transmitting device in an anechoic chamber. Specific distance has been selected to perform complete work with all selected frequency bands. At the time of measurement in an anechoic chamber, the RF input power (P_{in}) is sent through the signal generator. The value of RF input power is varied from -10 to 20 dBm. Some losses that occurred during the measurement are also evaluated here. A digital multimeter is used to measure the received DC voltage (V_{dc}) across the 100 kΩ load resistor (R_L). The power conversion efficiency of the rectenna is calculated in Equation (1) according to the corresponding input power.

$$\text{Efficiency}(\%) = \frac{V_{\text{dc}}^2/R_L}{P_{\text{in}}} \tag{1}$$

The conversion efficiency of the rectenna shows the received DC power with available input RF power. This is directly related to the radiation and reception properties of the rectenna. The corresponding power conversion efficiency is shown in Figure 5. It can be seen that at different input powers (P_{in}) peak efficiencies of the rectenna are 88.58% at 0 dBm, 34.70% at 10 dBm, 53.52% at 20 dBm, at the frequency

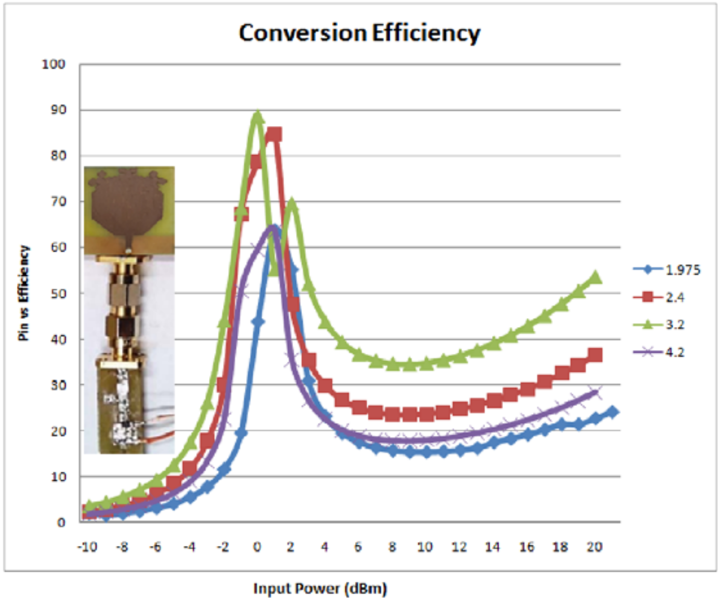

Figure 5. Power conversion efficiency of proposed rectenna.

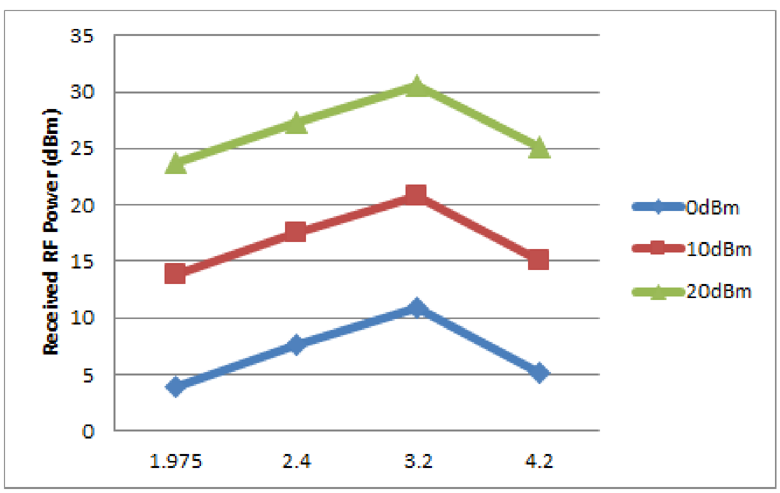

Figure 6. Received RF power in dBm.

3.2 GHz, 78.58% at 0 dBm, 23.69% at 10 dBm, 36.45% at 20 dBm, at 2.4 GHz, 59.63% at 0 dBm, 17.91% at 10 dBm, 28.37% at 20 dBm, at 4.2 GHz, and 43.77% at 0 dBm, 15.33% at 10 dBm, 22.66% at 20 dBm, at 1.975 GHz.

The RF power received from different frequencies is shown in Figure 6. It shows proper impedance matching of rectifying circuits under different input powers of 0 dBm, 10 dBm, and 20 dBm. It is seen that the outstanding impedance matching is accomplished at 3.2 GHz.

The obtained values of output power related to frequencies are depicted in Table 1.

The designed rectenna is sufficiently matched for 1.975 GHz to 4.2 GHz frequencies. Beyond these frequency ranges, it is not suitable for targeted applications. The overall calculated parameters of the proposed rectenna are properly matched to the simulated results. It is concluded that at 100 kΩ, a voltage of 10.703 V is attained, and the conversion efficiencies at this DC load are 88.58% at 0 dBm, 34.70% at 10 dBm, and 53.52% at 20 dBm, at frequency 3.2 GHz.

From the existing literature (as shown in Table 2), it could be easily analyzed that the proposed RF

Table 1. Obtained output power of proposed energy harvester.

Frequency GHz	P_{in} vs P_{out}			V_{out} (mW)	V_{out} (Volts)
	0 dBm	10 dBm	20 dBm		
1.975	3.823	13.791	23.659	232.22	4.819
2.4	7.554	17.49	27.255	531.46	7.294
3.2	10.868	20.808	30.59	1145.51	10.703
4.2	5.059	15.063	25.078	321.96	5.674

Table 2. Comparison analysis of proposed rectenna with existing literature.

Ref.	Frequency (GHz)	Maximum Conversion Efficiency (%)	Optimal DC Load	Received RF Power	Applications	Distance between TX & DUT	Gain
[15]	0.9–1.1, 1.8–2.5	75 at 20 dBm	2000 Ω	NR	WPT & WEH	1 m	NR
[18]	1.8–2.5	70 at 0 dBm	14.7 Ω	250–300 mV	Sensors	1 m	4.1 dBi
[22]	0.89–5.5	62.5 at 0 dBm	5 kΩ	NR	Energy Harvester	0.7 m	4.3 dBi
[23]	1.1–2.7	85 at 12 dBm	700–4500 Ω	NR	WPT & WEH	1 m	7.47–8.66 dBi
[24]	0.8–1	31.8 at 18 dBm	200 Ω	20 mW	NR	NR	NR
[25]	1.65–2.5	62 at −15 dBm	10 kΩ	0.5 V	Energy Harvester	–	–
[29]	5.8 GHz	73.4 at −6 dBm	1 kΩ	540 mV	IoT applications	0.02 m	8.66 dBi
Proposed Work	1.975–4.744	88.58 at 0 dBm	100 kΩ	1145.51 mW, 10.703 V	Sensors	2 m	4.3 dBi

*NR — Not Reported

harvester design exhibits improved conversion efficiency compared to [15, 18, 22–25]. This work shows a significant improvement in the energy harvester circuit. It includes a compact antenna along with wideband characteristics. A simple geometry structure is used with efficient rectifier circuits to improve the rectenna parameter performances. It has high conversion efficiency and improved RF power while covering a better bandwidth range for efficient RF energy harvesting. It can be easily applicable to power up the low powered sensors.

4. CONCLUSION

In the proposed work, a simple, cost-efficient, and new wideband antenna with an efficient rectifying circuit is designed. From the proposed rectenna, the calculated maximum output DC voltage and RF power are 10.703 Volts and 1145.51 mW, respectively. The maximum conversion efficiency of the rectenna is measured by 88.58% at 0 dBm. The result obtained after the simulation ended is 3.86 dB gain and shows the wideband characteristics between the bands 1.975 GHz and 4.744 GHz. All the calculated results show good agreement with the simulated data. Connecting this designed rectenna system into electronic devices will minimize the maximum power requirement for sensor applications and is capable of providing battery-free operation for devices that require the power of 1145.51 mW or less. The harvested power is easily available to power up the low powered sensor such as the gas sensor (500–800 mW), pressure sensor (10–15 mW), and temperature sensor (0.5–5 mW). In the future, a focus on the enhancement of gain and a more compact harvester for wideband rectenna will be proposed.

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