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Design and Analysis of Rectenna at 2.42 GHz for Wi-Fi Energy Harvesting

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Abstract—This work proposes a design of rectenna for Wi-Fi energy harvesting application at 2.42 GHz. The proposed antenna includes a modified rectangular patch and two circular radiating elements with partial ground, and adopts a total area of $80 \times 80\,\text{mm}^2$. With the partial ground structure, the proposed antenna shows a better reflection coefficient (S_{11}) at 2.42 GHz. The proposed antenna is a modified conventional patch antenna that shows its improved suitability for Wi-Fi energy harvesting at the targeted band. For rectenna, an impedance matching circuit based on microstrip transmission lines, radial stubs, and enhanced Greinacher voltage doubler rectifier circuits are designed. The rectifier circuit occupies a total area of $25 \times 25\,\text{mm}^2$. The antenna part of the rectenna exhibits quite good $S_{11} < -10\,\text{dB}$ and 3.94 dB peak gain. To validate the design experimentally, a prototype of the proposed rectenna is also fabricated. The measured result indicates that at the resonant frequency the rectenna achieves the peak efficiency of 78.53%, and the output voltage is 4.7 V at 0 dBm input power.

1. INTRODUCTION

Nowadays, radio frequency energy harvesting is a favorable technology to power up wireless IoT devices. These IoT devices require low power to operate the electronic appliance. Radio frequency energy harvesting is the concept to capture the RF signals from the available RF sources in an environment [1]. Energy harvester harvests the RF power and converts it into DC power by using a rectifier circuit which is completely known as "Rectenna". A rectenna consists of a receiving antenna with the rectifier configuration to harvest the DC power. The concept of RF energy harvester is the potential to lower the cost of the system by reducing/replacing the need of batteries [2], and it has the unique feature to harvest the RF power from the environment which is freely and easily available. The RF sources are independent of the nature pattern such as weather conditions and building structures. The number of RF sources is increasing day by day and easily connected with IoT devices [3] and RFEH is capable to energize these IoT devices.

A receiving antenna receives the signal from the available RF sources and completes the process of rectenna with the help of rectifier topology. Different types of receiving antennas have been designed and analyzed by the existing researchers such as dipole [4, 5], circularly polarized [6–8], and dual-band antennas [9–14]. The selection of the targeted frequency band is also an important concern in RF energy harvesting. To avoid bulky devices and complex installation, the ISM band consideration is the best choice relating to antenna size, performance, and targeted bands. Apart from the ISM band rectenna, multiband and wideband rectenna is also an option, but it has bulky devices and lossy performance [15–21]. Different antennas have been designed at 2.45 GHz in [22–28]. In the existing literature [29–34], the ISM band is considered for RF energy harvesting. The performance of the rectenna is quite good in terms of gain, output DC power, and power conversion efficiency (PCE). In [32], the authors have presented a rectenna which has a negative gain, but the PCE is improved at 2 dBm input power, and

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in [33] the gain is very low, and PCE is reported 20% at −20 dBm input power. Rectennas are designed in [34, 35] at 2.45 GHz, and the gains are 5.6 dBi, 4.4 dBi, and PCEs are reported 68% at 5 dBm input power and 50% at −20 dBm input power, respectively.

In this work, a 2.42 GHz rectenna is designed and analyzed. The rectenna performance is improved in two parts. First, a high gain antenna is designed in which the antenna efficiently receives the RF signal from the source. Second, a rectifier circuit is designed for the rectenna, and transmission lines are used here to match the impedance between the antenna and rectifier. The performance of the rectenna is optimized at low input power. Hence, the rectenna shows the novel structure and sufficiently harvests the RF power at low input power. The primary objective of the work is reported accordingly:

- A distinctive, reliable, and energy-efficient energy harvester is designed (shown in Figure 1), investigated, and validated.

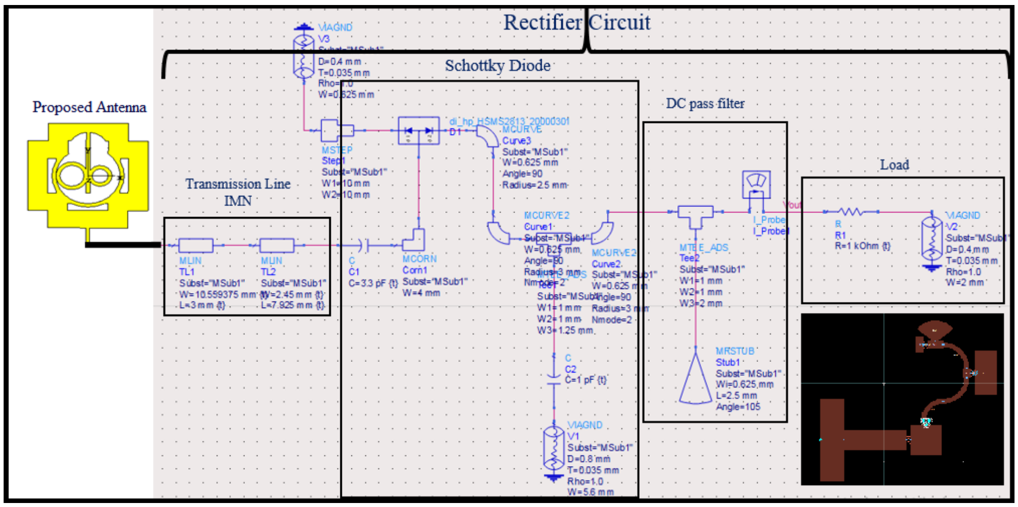


Figure 1. Block diagram of the proposed rectenna.

- The proposed RF energy harvester harvests the RF power from the Wi-Fi at 2.42 GHz band.
- A horizontal T-shape impedance matching network (IMN) is designed and simulated, which consists of a number of transmission lines to design IMN along with a Greinacher voltage doubler topology.
- Using transmission lines in lieu of lumped components reduces system complexity and chances of error during PCB manufacturing.
- The novelty lies in that the work is the unique structure of the antenna and easy implementation of the rectifier circuit. It reduces complexity during PCB fabrication and validation.
- The proposed harvester is compared with the reported literature [29–34], and best to the authors' knowledge it enhanced the rectifier conversion efficiency and also introduced the simple geometry. This is the main objective of the proposed work.
- The proposed work is motivated by existing literature reviews to address the bottleneck in designing new energy harvesters and the implementation of harvesters in the real life application..

The work is structured as follows. Section 2 demonstrates the system architecture, layout, and working principle of the proposed energy harvester. Section 3 discusses the performance analysis of the fabricated rectenna and compares the proposed work with the existing works. Section 4 summarizes the work.

2. PROPOSED RECTENNA DESIGN

In the rectenna design, the purpose of antenna receives the electromagnetic wave, and the rectifier converts the EM waves into DC power to energize the low power sensor applications. To fulfill the requirement of Rectenna at 2.42 GHz, the antenna and rectifier topology have been designed and analyzed by using the CST and ADS tools, respectively. The proposed rectenna circuit is easily integrable with other electronics devices in targeted band applications. Schottky diodes are preferred to use due to their low voltage drop and speedy response. It consumes less amount of power to conduct the response of RF to DC conversion.

2.1. Antenna Structure

To fulfill the requirement of rectenna design, the very first step is to design an antenna. The proposed antenna is simply considered a microstrip patch antenna. It has multiple radiating slots to fulfill the targeted band requirements at 2.42 GHz. Apart from this, the partial ground structure is used with a 50 Ω transmission feed. The reason behind selecting partial ground is to reduce the system cost and complexity. It is a printed antenna using an epoxy FR-4 substrate with a dielectric constant of $4.3 \pm 5\%$. A dual-side printed substrate sheet is used, where the front side represents the radiating patch, and the bottom side represents the ground. The proposed antenna is designed with multiple radiating slots as shown in Figure 2(a). The radiating slots are simply rectangular and circular. The rectangular slot is indexed with two circular radiating patches to obtain the result at the targeted band. The performance parameter of the antenna is shown in Table 1. It shows the optimized parameter used in the design of the proposed rectenna. Each parameter of the rectifier is optimized by the ADS software tune function, and it enhances the performance of the proposed energy harvester.

The outer rectangle slot is responsible for the lower band at 1.2 GHz and the inner slot at 2.42 GHz. Though the aim here is to design an antenna at 2.42 GHz, the outer slot is included in the proposed

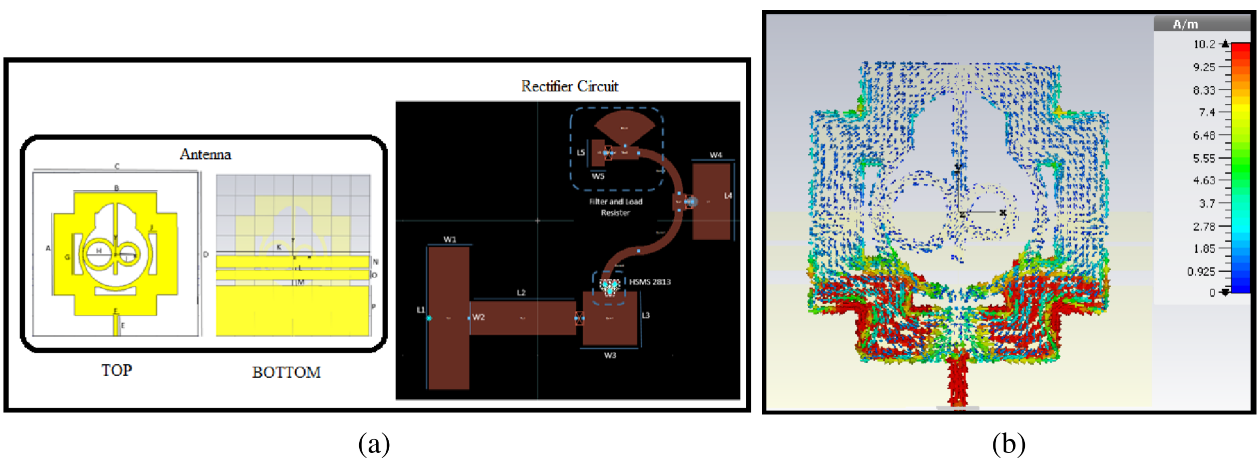


Figure 2. (a) Proposed rectenna geometry. (b) Current distribution at 2.42 GHz.

Table 1. Optimized parameter of the proposed rectenna.

Antenna Parameter (mm)				**Rectifier Parameter (mm)**			
A	40	I	12	$L1$	10.55	$L5$	2
B	40	J	8	$W1$	3	$W5$	1
C	80	K	80	$L2$	2.45	$C1$	3.3 pF
D	80	L	1	$W2$	7.93	$C2$	1 pF
E	10	M	3	$L3$	4	D	HSMS 2813
F	2	N	6	$W3$	4	RL	1 kΩ
G	20	O	5	$L4$	5	Stub Angle	105°
H	4	P	25	$W4$	3		

design. It increases the gain of the proposed antenna and improves the matching with the desired frequency band. Two circular slots on the radiating patch are added after the initialization of rectangle slots. To demonstrate the behavior of the antenna at 2.42 GHz, the surface current on the antenna is demonstrated in Figure 2(b). The surface current is concentrated mostly on the edge of radiating patch and ground layer. The surface current distribution indicates the performance of the proposed antenna. The proposed radiating patch is responsible for the antenna operating at the targeted band application. The obtained gain and reflection coefficient at this band are 3.94 dBi and $S_{11} < -10$ dB, respectively. However, the work aims to design an antenna that operates efficiently at 2.42 GHz. The proposed antenna suitably works with the proposed Impedance Matching Network (IMN) circuit by using a single voltage doubler topology. It satisfactorily harvests the RF power at the targeted band and is easily integrable with the proposed rectifier topology.

2.2. Rectifier Topology

A rectifier is a device used to convert RF to DC at the receiving end of the system. Figure 2(a) shows the rectifier circuit configuration to harvest the RF power and convert it to back DC power. The rectifier circuit consists of a single-stage voltage multiplier. The reason behind selecting the topology is its easy implementation, complexity reduction, and high efficiency with efficient DC output voltage. The rectifying circuit was optimized using the Keysight Advanced Design System (ADS) software. The rectifier comprises a voltage doubler, a source capacitor C_1 3.3 pF, capacitor C_2 1 pF, and load resistance R_L is 4.7 kΩ. Load resister is used to extract the DC power at the receiving end of the device. The load resistance is chosen as a representation of a pressure sensor [33] which is the target application to have in mind for the proposed rectenna. For better compatibility and maximum power transfer between the antenna and rectifier, an impedance matching network is necessary. A simple series microstrip transmission line is used in place of lumped components to reduce the mismatches during fabrication and measurements. An impedance matching network (IMN) is designed in the rectifier circuit, and it follows the voltage doubler circuit. The maximum received power (P_r) is calculated according to Equation (1) [36].

$$P_r = S \cdot A_{\mathit{eff}} \tag{1}$$

where S represents the power density with an effective aperture area A_{eff} of an antenna, and effective aperture area is defined in terms of wavelength by Equation (2).

$$A_{\mathit{eff}} = \frac{\lambda^2}{4\pi} \tag{2}$$

Thus, the gain is directly related to received RF power. If the gain is maximum, then maximum RF power is received from the antenna. However, the antenna gain is always controlled by the antenna size. In the next to IMN, single-stage Greinacher voltage doubler topology is introduced where Spice model of a nonlinear diode (HSMS-2813) is used during the rectenna designing. To remove the fundamental frequency signal and harmonics generated by the nonlinear behavior of diodes, a DC pass filter is preferred to use. A radial stub is used as a DC pass filter in the rectifier configuration, and it prevents the reflection of microwave power. A load resistor is placed at the end of the device to extract the DC power from the rectenna. To obtain the best performance over the power range from -10 dBm to 20 dBm, the simulation and optimization process of the complete rectifier circuit have been analyzed in ADS, and the conversion efficiency response of the harvester is observed.

3. RESULT AND DISCUSSION

To validate the performance of the proposed rectenna setup, experimental results are discussed in this section. The performances of the rectenna in terms of the reflection coefficient, radiation pattern, gain, DC output voltage, and power conversion efficiency are demonstrated here. The proposed antenna is simulated in the CST software, and the reflection coefficient S_{11}, 2-D radiation pattern, and gain of the targeted band are observed. Figure 3 presents the return loss characteristics. Simulated and measured return losses are quite matched at 2.42 GHz. The measured result of S_{11} indicates a slight improvement at the targeted band. This shows better compatibility with the experimental approach. Figures 4

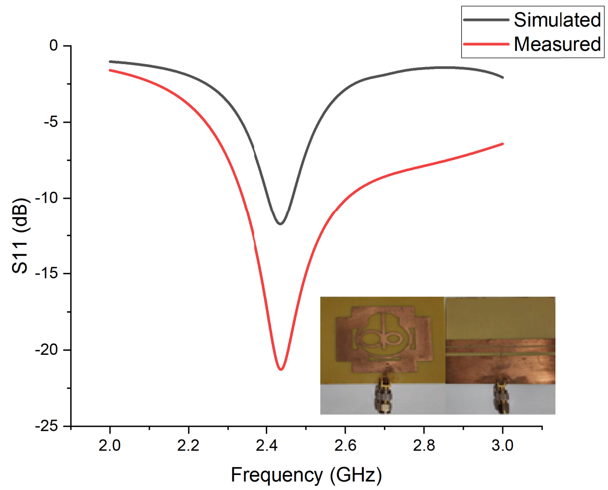


Figure 3. Reflection coefficient of the proposed antenna.

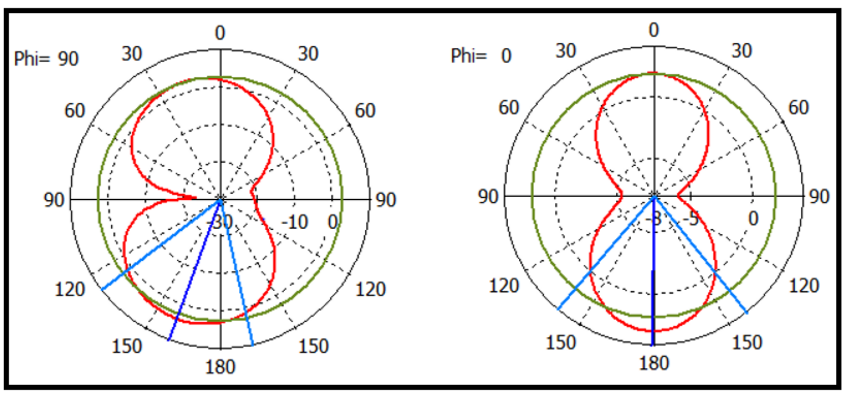


Figure 4. 2D radiation pattern H plane (YZ plane $\Phi = 90°$), E plane (XZ plane $\Phi = 0°$) of an antenna.

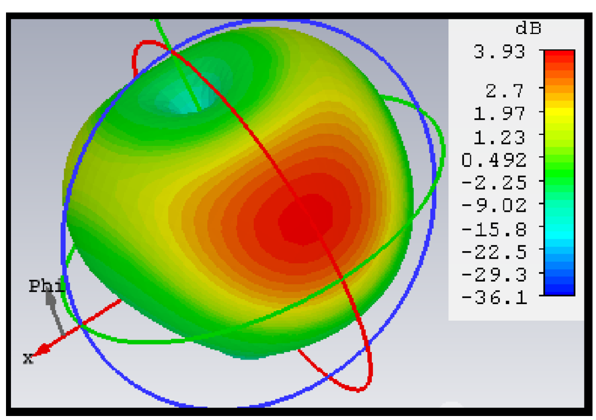


Figure 5. Realized gain of the proposed antenna.

and 5 present the radiation patterns of the E-plane and H-plane, and gain of the proposed antenna is realized. The 3.93 dB gain is observed which is good enough for radiating and receiving RF energy from the available Wi-Fi source.

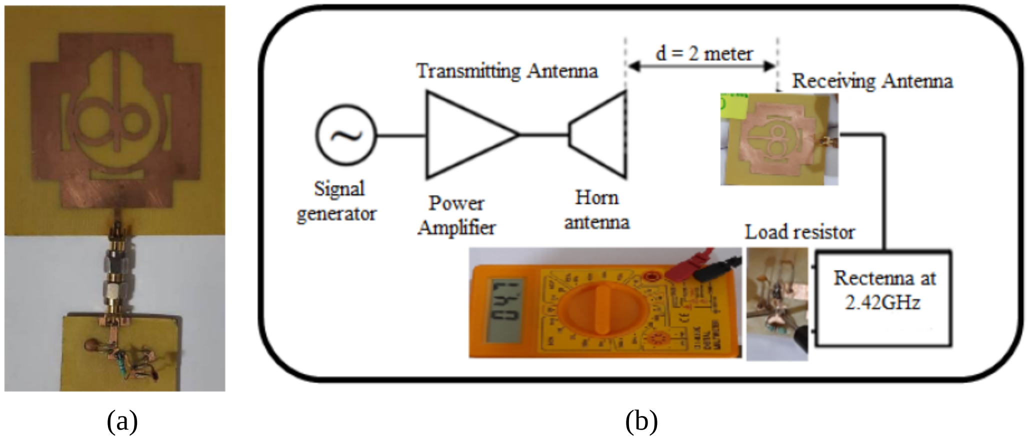


Figure 6. (a) Prototype of complete rectenna. (b) Measurement setup for the proposed rectenna system.

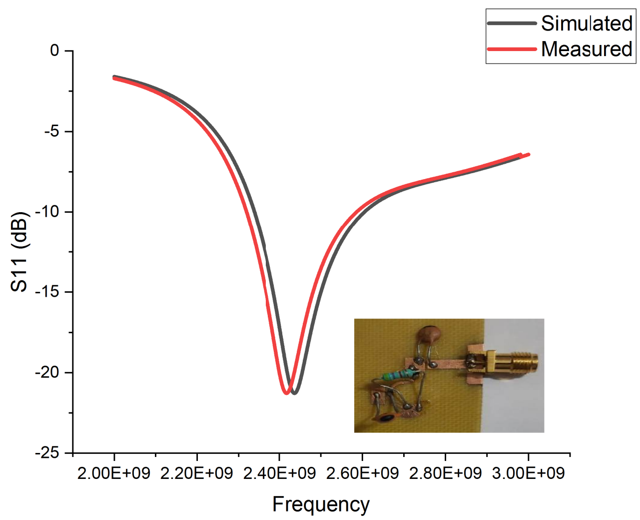


Figure 7. S_{11} of the proposed rectifier.

An RF energy harvesting circuit is designed and tested by connecting the proposed antenna and rectifier circuit through a connector (SMA-Adapter, TY-TMJS-9PCO, and B08V8Z85P3) as shown in Figure 6(a). The proposed rectenna performance is evaluated by the measurement setup as shown in Figure 6(b). Two antennas are used: one for transmission of RF signal (Horn Antenna) and the second one for receiving the RF to DC power with the integration of the rectifier circuit. This setup converts and harvests the RF power comfortably with the targeted band. The Agilent vector network analyzer is used as a power source. Step by step process is shown in the following manner:

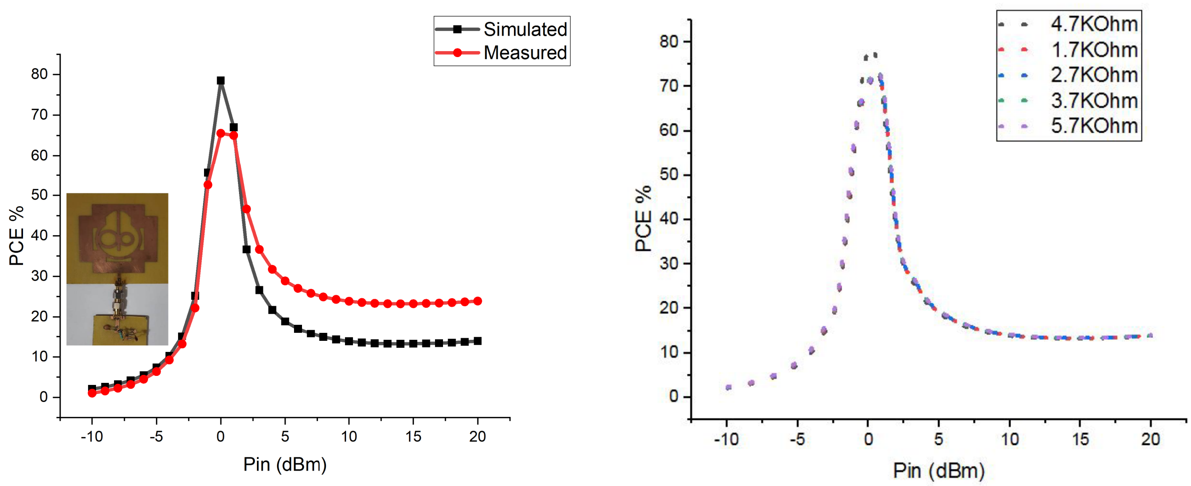
- During the first step, the received power is measured at a far-field distance of $d = 2$ meters by connecting the proposed antenna to the spectrum analyzer.
- In the second step, the spectrum analyzer is removed, the rectenna placed at the location of the antenna, and then DC voltage is measured. The DC voltage and efficiency measured across $4.7\,\text{k}\Omega$ are shown in Figure 6(b).
- Through varying the RF input power and fixed operating frequency, the DC voltage is measured via voltage meter as shown in Figure 6(b). The simulated (S) and measured (M) output voltages are received between -10 dBm and 20 dBm, which are 4.7 V(S) and 4.7 V(M) at 2.42 GHz.

As shown in Figure 7, the reflection coefficient of the rectifier configuration shows a quality match with the antenna reflection coefficient as in Figure 3. The observed response at 2.42 GHz, the DC output voltage, and conversion efficiency are 4.7 V, 78.53% at 0 dBm input power with 4.7 kΩ load resistance. The RF input power is considered here between −10 dBm and 20 dBm. The power conversion efficiency is calculated accordingly

$$\eta_{\text{PCE}} = \frac{P_{\text{dc}}}{P_{\text{EF}}} = \frac{V_{\text{dc}}^2}{P_{\text{RF}} R_L} \tag{3}$$

However, the power conversion efficiency (PCE) is the ratio of output dc power to the total input power. It represents the harvester's reliability and durability. Figure 8(a) shows the calculated response of the power conversion efficiency at different input powers. The RF input power varies from −10 dBm to 20 dBm, and the PCE of 78.53% is achieved at 0 dBm input power. As observed from Figure 8(a), the RF input power is increased from −5 dBm to 5 dBm, and the rest of the power conversion efficiency is slightly decreased accordingly. Hence, the proposed rectifier receives higher conversion efficiency at low input RF power. Figure 8(b) shows the power conversion efficiency plot concerning the load resistor variation to select the efficient value of the load resistor. The observed response demonstrates the variation of load resistor from 1.7 kΩ to 5.7 kΩ, and the value of load resistor of 4.7 kΩ is chosen for efficient energy harvester which exhibits a higher response of PCE.

Table 2 illustrates the comparative result analysis of the proposed work against the existing work. It shows significant improvement among the existing designs, and it is one of the notable circuits that



(a) (b)

Figure 8. (a) RF to DC efficiency plot. (b) Load resister variation plot.

Table 2. Comparative analysis of proposed rectenna with other existing rectenna.

Ref.	**Frequency (GHz)**	**Gain**	**Load Resistor**	**Output Power (DC)**	**PCE**
[29]	2.4	2.3 dBi	4.7 kΩ	NS	NS
[30]	2.45	NS	3.8 kΩ	1.3 V	20% @ 0 dBm
[31]	2.45	3 dBi	2 kΩ	NS	72% @ 0 dBm
[32]	2.45	−0.19 dBi	3.3 kΩ	1.811 V	≈ 62% @ 2 dBm
[33]	2.45	0.8 dBi	4.7 kΩ	97 mV	20% @ −20 dBm
[34]	2.45	5.6 dBi	5 kΩ	3.24 V	68% @ 0 dBm
Proposed Work	2.42	3.94 dBi	4.7 kΩ	4.7 V	78.53% @ 0 dBm

*NS — Not Specified, PCE — Power Conversion Efficiency exhibit relatively higher conversion efficiency at the 0 dBm input power level. The proposed energy harvester demonstrates quite satisfactory performance to receive higher conversion efficiency by the energy harvester at a low input RF power level. The resistive load is considered 4.7 kΩ which is sufficient to work with different low-power electronic appliances. Hence, the complete rectifier circuit is easily applicable to harvest the DC power at very low input power.

4. CONCLUSIONS

The major contribution in this work includes a novel antenna design implementation with notable gain, and the design of the rectifying circuit is quite simple with high power conversion efficiency. The obtained DC voltage from the rectenna is suitable to energize the low power applications. Experimental results are in a reasonable agreement with the simulated ones. At the 0 dBm RF input power, the measured maximum RF to DC efficiency and DC output voltage are 78.53% and 4.7 V, respectively, with a load resistance of 4.7 kΩ. In addition to its good performance along with the notable gain, higher power conversion efficiency, and novel structure, the proposed rectenna offers several mechanical advantages, such as simple geometry, light weight, easy fabrication, and implementation, which make the rectenna a promising candidate for future RF energy harvesting in low-power electronic devices. Extended research in the future will be considered on different substrate materials for antenna design and compact antenna size also for other operating bands.

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