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Wireless Energy Harvesting Using Rectenna Integrated with Voltage Multiplier Circuit at 2.4 GHz Operating Frequency

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Abstract

In this paper, we utilized villared rectifier technique to harvest wireless energy to overcome previously used RF-WEH rectenna. Our design focuses mainly on a multiple-stage Villard voltage multiplier model to rectify the output voltage of the rectenna and transferred it to a dc load. As a starting point, optimization and parameter analysis offer a novel and small antenna for the 2.45 GHz ISM band that precisely matched. Moreover, the fabricated prototype has measured and simulated results have confirmed the antenna's accuracy in the reflection coefficient. Second, a highly efficient antenna may effectively harvest the electrical energy by combining with the two-stage voltage multiplier circuit presented at the ISM band. Furthermore, the proposed rectenna has the optimum performance compared to state of art rectennas in terms of efficiency, power range, and impedance bandwidth showing pronounced achievement and increasing the DC output power significantly. The prototype is fabricated and experimentally tested to confirm the concept. Measurement results show that the proposed rectenna can be used for RF energy harvesting applications.

Keywords

Energy Harvesting, Radio Frequency, Rectenna, Industrial, Scientific, Medical(ism) Band, Wireless Power Transfer

1. Introduction

Recently, the interest in wireless energy harvesting has been rapidly increasing. The concept of wireless energy transfer came for the first time with the advent of electromagnetism [1]. During the past few decades, significant research has been carried out to harvest energy by converting various energies-types to electrical power [2]. There are a lot of technological processes already in use, which take power from different sources including thermal, vibration tidal, wind source and solar. The present WEH systems mainly work on wind and solar energy sources such as wind turbines and solar panels [3] [4]. However, the WEH, as mentioned earlier systems work in strict circumstances and therefore, the performance of such systems greatly depends on environmental changes such as time and climate.

However, owing to the fast growth of the wireless power industry, there is a significant research interest in energy harvesting from electromagnetic fields [5]. With the rapid growth and advancement of WiFi-enabled Devices, TV-based entertainment, and mobile cellular networks, the power density.

Electromagnetic fields are increasing dramatically, capable of empowering RF powered applications [6]. Although the RF sources often show very low power density values, which can be applied only to some low power applications [7]. EM-based power densities are stable statistically regardless of variation in environmental conditions. Therefore, RF-based energy harvesting systems can operate well in most cases [8] [9]. Advancement toward new technology waves that will include smart homes and smart cities, particularly for the internet of things, will make the dream true as most of these applications are of low power consumption.

One of the fundamental requirements of a WEH system is to transfer electrical power efficiently. The basic component of an efficient WEH system is an antenna connected to a rectifier collectively known as rectenna [10]. A rectenna has the capability of receiving and detecting microwave power signals (EM energy) and converting them into direct current (DC) voltage at the load [11]. General block diagram for a rectenna with its related circuit for power management is shown in **Figure 1**. Initially, rectennas were developed for microwave power transmission-based high-power applications with long distances between transmitter and receiver. The typical received power of such a system ranges from tens of milliwatts to several kilowatts.

In contrast to these systems, the power density of EM fields is comparably very low, usually less than 10 nW/cm^2. Therefore, for RF-WEH based applications, the traditional rectenna designs will not work efficiently. To enhance the

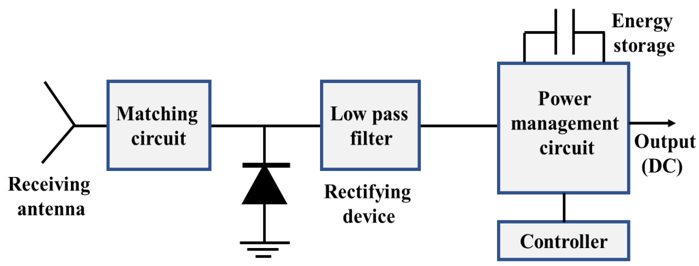


Figure 1. General block diagram for a rectenna with its related circuit for power management.

system's efficiency in such low power density environments, rectenna designs with good power conversion efficiency are required. Significant research work has been carried out on designing rectennas for RF-WEH [12]. However, there are still some limitations with most rectenna designs. First of all, most of the previous rectenna designs are of narrow bandwidth. Secondly, they need high incident power to get high RF to DC conversion efficiency. The third one is that the output is not enough for consumer applications in most rectenna designs.

Moreover, the proposed 2.4 GHz rectenna is compared in terms of gain, frequency, antenna efficiency impedance bandwidth, antenna dimensions and RF-DC conversion efficiency is shown in **Table 1**. The proposed rectenna showed salient features over these references such as high efficiency with good impedance bandwidth even for such small in size and antenna efficiency. Therefore, our proposed rectenna was found efficient compared to other published results in overall performance.

2. Operation Theory

1) Design and optimization of 2.45 GHz antenna system

The proposed antenna geometry and layout can be seen in **Figure 2**. It is noticeable that the proposed antenna is designed by modifying a basic rectangular patch antenna.

The radiating patch has H shaped with two j-shaped structures on both sides of the patch that significantly contribute to optimum performance. The 50 Ω impedance of the proposed radiating structure is adjusted by the positing of feed, slots in the patch, and ground slot. The overall dimension of the designed antenna is 40 mm × 40 mm × 0.6 mm. The proposed patch antenna is optimized using the parasitic patch in the ground plane and slots in the radiating patch to obtain impedance match resonance better radiation performance, which also help in the miniaturization of the antenna. The optimized parameters of the antenna are displayed in **Table 2**.

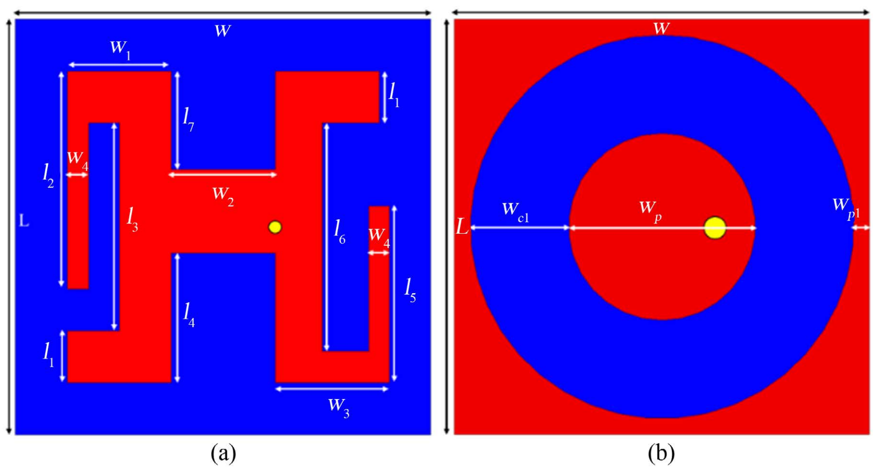


Figure 2. Geometry and layout of the antenna (a) Front view of the patch (b) Back view of the ground.

Table 1. The detailed comparison of the proposed rectenna with state-of-the-art rectenna operating at 2.45 GHz.

Reference	Frequency (MHz)	Dimensions (mm^2)	Gain (dBi)	l-BW (MHz)	Antenna Efficiency (%)	RF_DC Conversion Efficiency (%)
[12]	2400	47 × 47	1.1	400	70	-
[13]	2450	135 × 128	9.8	900	72.5	38
[14]	2450	70 × 70	4.31	700	70	55
[15]	1800	45 × 45	3.9	110	-	61
[16]	2450	48 × 48	3.5	350	95	70
This work	2450	40 × 40	3.39	261	98.9	86

Table 2. Detail parameters of the designed H shaped antenna.

Parameter	Value	Parameter	Value	Parameter	Value
W	40	l_5	17	w_4	2
L	40	l_6	22	w_{c1}	9.5
l_1	5	l_7	9.5	w_p	17.98
l_2	21	w_1	10	w_{p1}	1.5
l_3	20	w_2	10		
l_4	12.5	w_3	11		

The proposed patch antenna was optimized in four steps, as illustrated in **Figure 3**.

Different slots in the radiating structure and parasitic element in the ground plane to modified a basic rectangular patch. The optimum performance and optimization of the antenna are obtained by parasitic elements in the ground and different slits in the radiating patch. **Figure 4** shows a comparison of the reflection coefficient involves in the designing steps of the proposed antenna. The designed antenna's reflection coefficient is significantly improved step by step. In the first step, the proposed antenna operated in two weak resonance moods at 2.9 and 2.97 GHz with S11 < −4. Furthermore, by adding symmetric slots in the radiating patch, that patch becomes H-shape, a single weak resonance mood is obtained at 2.3 GHz with S11 < −1.1. In the third step, two symmetric strips are added to the radiating patch and one parasitic slot element is added in the ground. First resonance mood is shifted from lower to higher frequency while the other is shifted from higher to lower and two moods are obtained at 2.1 and 2.55 GHz. By increasing the diameter in the ground slots and adding symmetric strips in the radiator, the suggested antenna was successfully operated at the desired ISM band.

Moreover, the designed antenna is perfectly matched with 50 Ω impedance and operated at a single frequency with a reflection coefficient of −20 dB. The

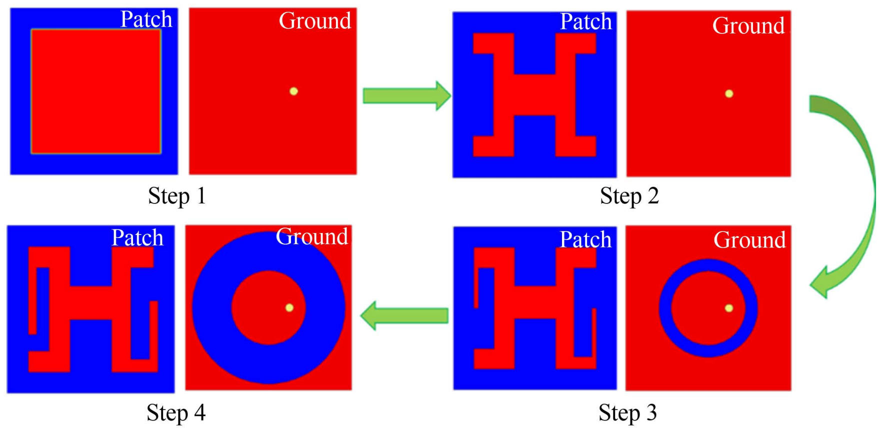


Figure 3. Miniaturization and designing steps of the proposed antenna.

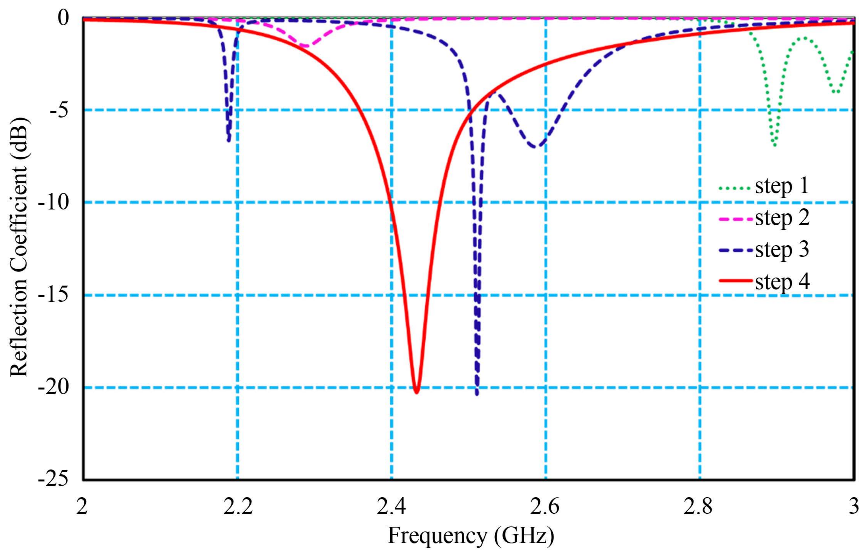


Figure 4. Reflection coefficient comparison for the proposed antenna designing steps.

designed antenna offers an optimum bandwidth of 9% at 2.43 GHz. It is worth mentioning that it is perfectly simulated in the ISM band, as shown in Figure 5.

The simulation results show that the antenna is radiated in the omnidirectional patterns and the H and E planes are shown in Figure 6. The proposed antenna performed a gain of 4 dB at a frequency of 2.43 GHz, as depicted in Figure 6.

As shown in Figure 7, the most current flow is in the one direction from the left side to the right of the patch and follows a monopole mode. Due to the strong coupling effect of the ground plane with a parasitic plane, the current also flows on the parasitic plane's edge and follows the same monopole modes.

2) Design and optimization of the proposed rectifier topology

The main crucial part of the rectenna is the rectifying circuit, which can decide how good the conversion efficiency (RF-to-DC) will be for operating the battery-free devices or charging the batteries [17]. We choose the HSMS 2850 from Skyworks for the proposed rectifier circuit based on the efficient performance.

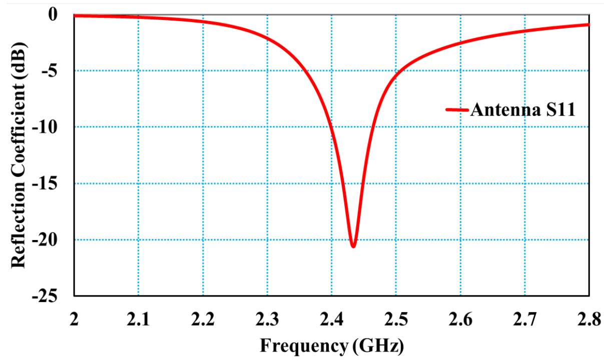


Figure 5. Reflection coefficient of the designed antenna.

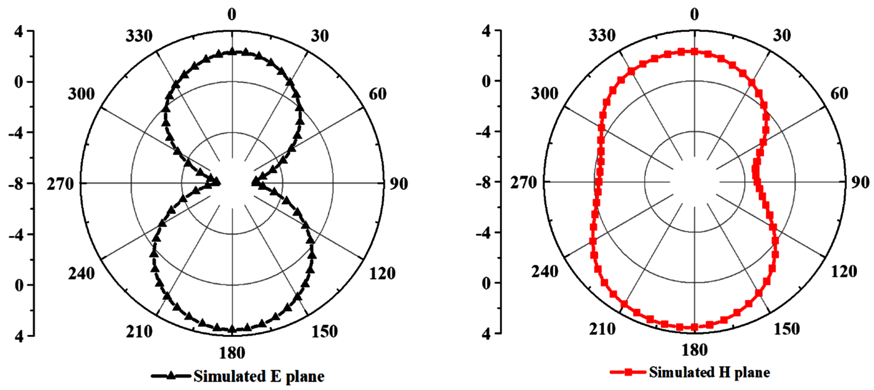
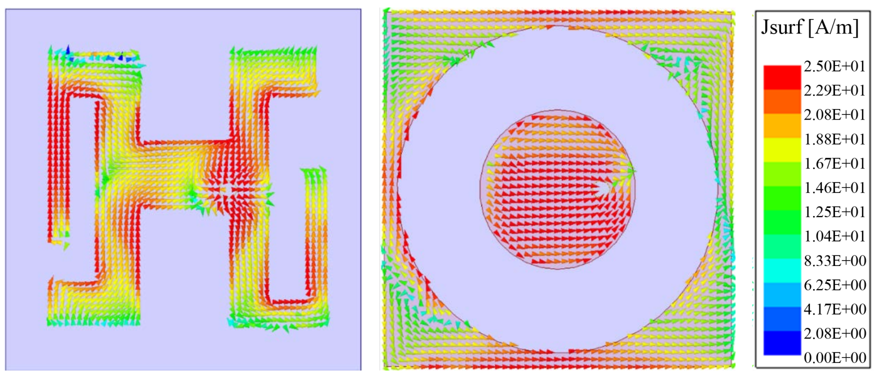


Figure 6. Polar plot of the designed antenna at 2.4 GHz.



(a) (b)

Figure 7. Surface current distribution of the proposed antenna.

We have performed various rectifier simulations, such as a basic half-wave rectifying circuit with a series diode, a voltage doubler, and the proposed Villard multiplier shown in Figure 8. The objective of this optimization was to compare the performance of these rectifiers with regards to an output voltage and RF-to-DC conversion efficiency. The subsequent equations were applied for the RF-to-DC conversion efficiency calculation.

$$Power_{DC}\frac{v_{DC}^{2}}{R_{L}} \tag{1}$$

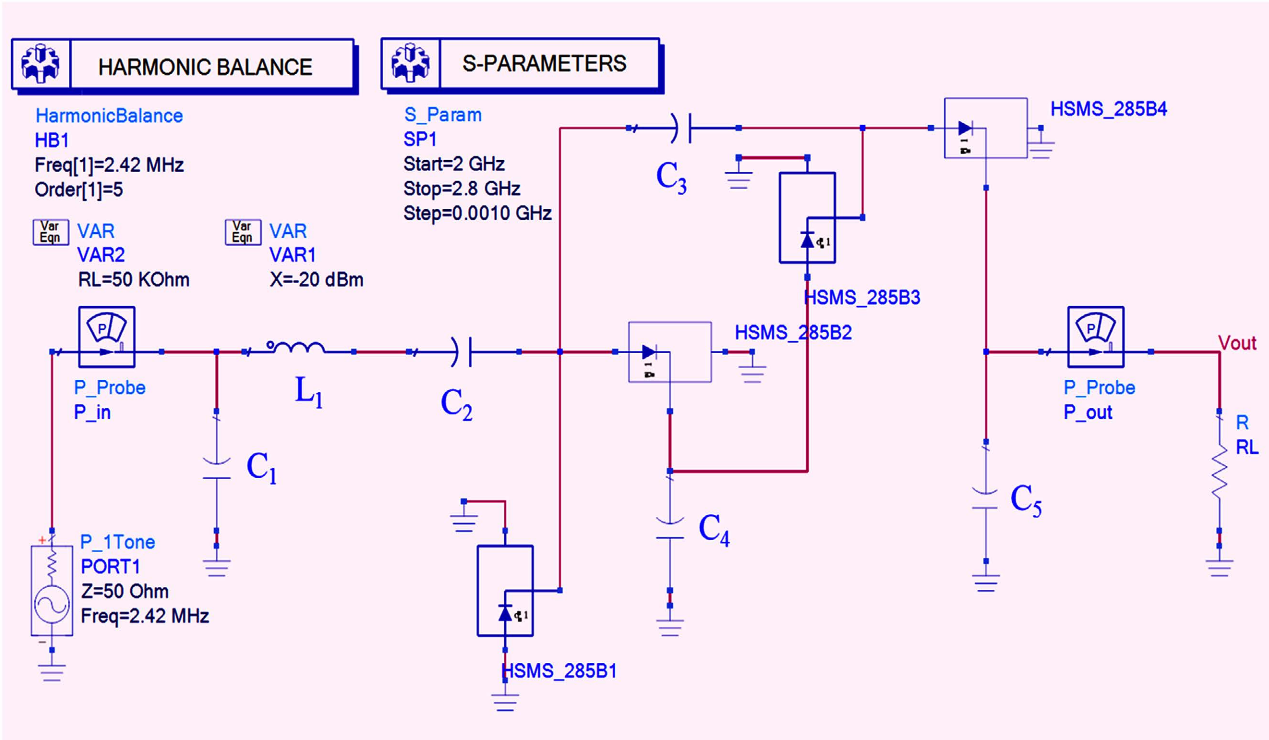


Figure 8. Proposed Villard multiplier circuit for the RF-to-DC conversion.

$$\eta_{RF\text{-}DC} = \frac{Power_{DC}}{P_{RF}} \times 100 \qquad (2)$$

R_L shows the load resistance of the rectifier at the output end, while the P_{RF} shows the available power of the rectifier at the input end [18]. Another purpose of the optimization was to enhance the conversion efficiency (η). Thus, to achieve this, we kept rectifier capacitors, load resistance, and impedance matching networks as the optimization variables in the harmonic balance optimization.

After optimizing the proposed circuit, the S-parameters were extracted in Figure 9, and the components values for proposed villard multiplier circuit are presented in Table 3. As it can be observed that the proposed rectifier is well matched at the ISM band with S11 less than −37 dB. The simulated −6 dB impedance bandwidth is 180 MHz (2.34 - 2.52 GHz), while a −10 dB impedance bandwidth is 100 MHz (2.38 - 2.48 GHz). Figure 9(b) shows the RF-to-DC conversion efficiency and output voltage against the input power range of −20 dBm to 20 dBm. The efficiency increases from −20 to 10 dBm of input power with a RL load of 90 kΩ. However, the output voltage was increased from 0.5 to 6.5 volts in the given range of input power. By comparing these results with the single-stage doubler's results, the proposed voltage multiplier efficiency and output voltage were increased 35% and 2.7 volts, respectively.

It is interesting to show the optimum load for the proposed design because the state of the art rectifiers have a strong dependency on the load values owing to

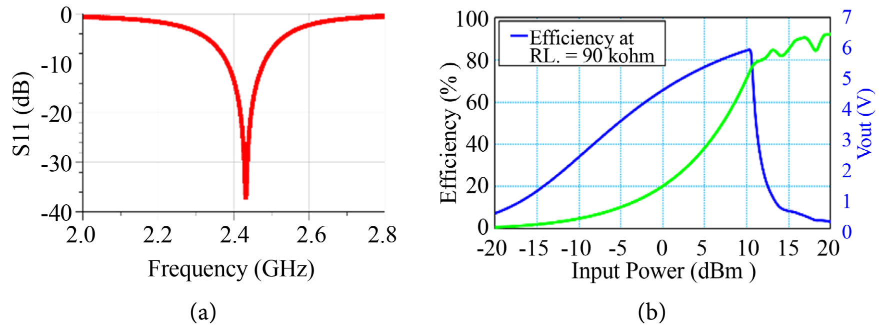


Figure 9. Performance comparison of the proposed optimized Villard multiplier circuit. (a) The reflection coefficient of the Villard multiplier circuit. (b) The Villard multiplier circuit's conversion efficiency and output power at 90 kΩ loads.

Table 3. Values for the components employed in the proposed voltage multiplying circuit of Figure 8.

Parameter	value	Parameter	value	Parameter	value
C_1	4.2 pF	C_2	150 pF	C_3	20 pF
C_4	90 pF	C_5	15 pF	L_1	4.5 nH
R_L	10 - 90 kΩ				

the variation in the input impedance, thus degrading the efficiency of the rectifier [19] [20]. Therefore, we simulated the variable load sweep from 10 kΩ to 100 kΩ against the input power range of −20 dBm - 20 dBm. Figure 10 shows the conversion efficiency with the variable load. It can be observed that the highest efficiency was observed from 10 kΩ to 100 kΩ loads. At 10 kΩ, the efficiency was 75%, while at 20 kΩ, it was 80%. However, from 30 kΩ to 100 kΩ, the efficiency was found greater than 85%, which is the important behaviour of our proposed voltage multiplier against the state of the art rectifiers operating at 2.4 GHz band [20] [21].

The layout of the proposed circuit with its dimensions with front view and isometric view is shown in Figure 11(a) and Figure 11(b). The layout was based on the Rogers RT duroid 6010 with a standard available thickness of 0.635 mm and a dielectric constant (εr) of 10.2 and a tangent loss ($\tan\delta$) of 0.0035. The dimension of this layout is 20 mm × 21.5 mm, which is very small compared to other paper works; thus, it can easily be integrated with the antenna without changing its performance.

3. Measurements

The antenna and rectifier were analyzed and fabricated with a milling machine technique. The etching method removes unwanted metals from the metallic layer so that the intended patterns for the antenna and rectifier are obtained. The choice of proper dielectric material is a significant part of rectenna design. The proposed rectenna was printed on the Rogers RT/duroid 6010 material

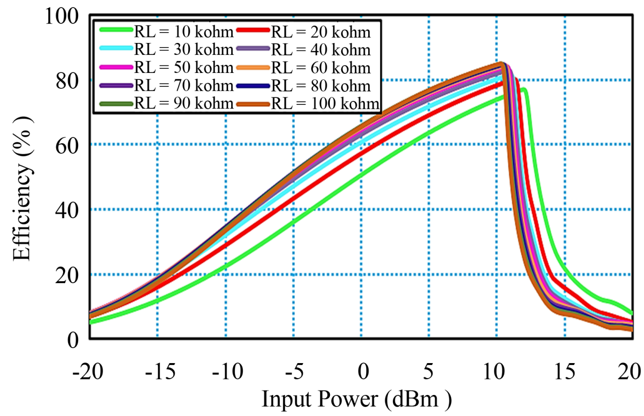
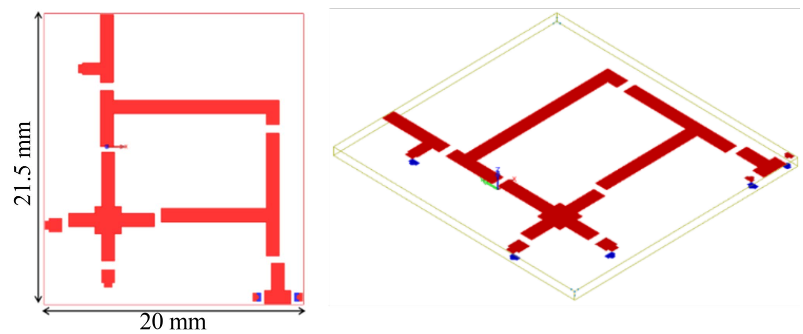


Figure 10. The conversion efficiency of the proposed optimized Villard multiplier circuit with variable load resistance against the low input power values.



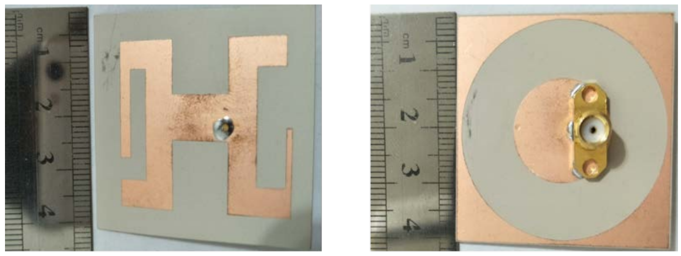
(a) (b)

Figure 11. The layout of the proposed circuit with its dimensions. (a) Front view. (b) Isometric view.

substrate having a dielectric constant of 10.2, a thickness of 0.635 mm, and a tang loss of 0.0035. This material helped us reduce the antenna size due to its high dielectric const. The fabricated antenna's radiating patch and ground plane are shown in Figure 12(a) and Figure 12(b), respectively. The size of the proposed fabricated antenna is 40 mm × 40 mm × 0.635 mm. The fabricated prototype of the proposed voltage multiplier circuit is shown in Figure 13. The size of the fabricated prototype of the proposed voltage multiplier circuit is 25 mm × 25 mm × 0.635 mm. Moreover, a 50 Ω SMA connector was attached to the antenna and a voltage multiplier circuit for measuring their performance, such as the reflection coefficient, the conversion efficiency, and output voltage.

The reflection coefficient of the rectenna was measured using the network analyzer shown in Figure 14(a). The proposed antenna was connected to one of the ports of VNA. The measured results regarding S-parameters from the VNA are extracted and compared with the simulated results in Figure 14(b).

The setup shown in Figure 15 was adopted to measure the output voltage of a rectifier circuit. The comprised of a signal generator, which generates 2.4 GHz signal and connected with the rectifier circuit. The voltage across the 82 kΩ resistance was measured using the oscilloscope.



(a) (b)

Figure 12. Photos of the proposed fabricated antenna on Rogers RT/duroid 6010 substrates.

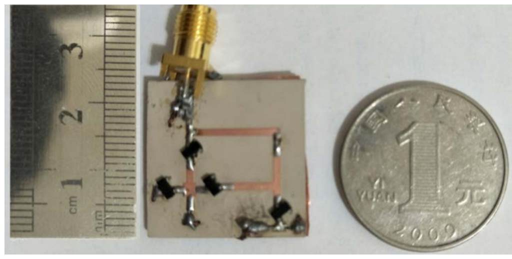
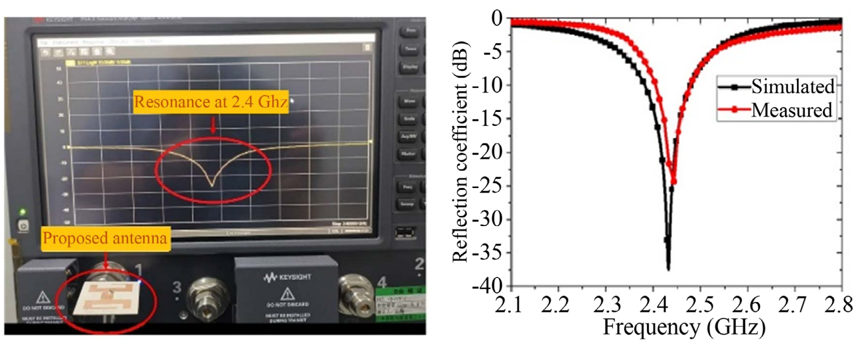


Figure 13. Photos of the proposed fabricated rectifier on Rogers RT/duroid 6010 substrates with components.



(a) (b)

Figure 14. (a) S11 measuring network analyzer with S11 on the screen for the proposed antenna; (b) Comparison of the simulated and measured reflection coefficients.

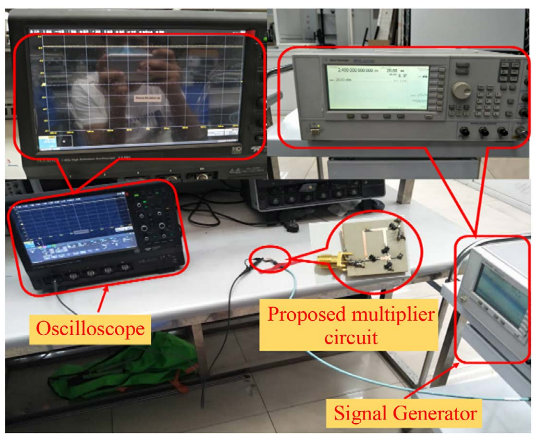


Figure 15. Measurement setup utilized for the measurement of the multiplier performance.

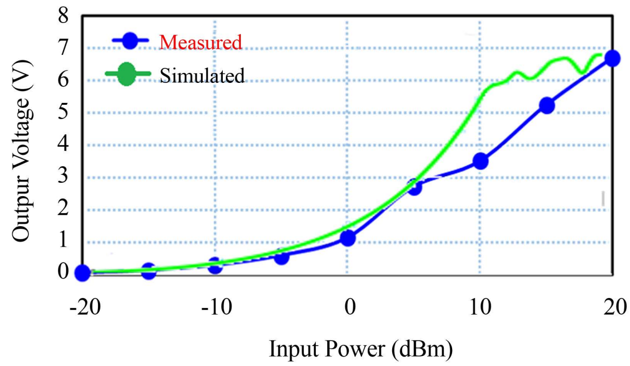


Figure 16. Comparison between measured and simulated output voltage of the proposed multiplier circuit.

The measured and simulated voltage are shown in **Figure 16** against the input power that was varied from −20 to 20 dBm. As can be seen, a voltage of 6.7 V was observed at the input power of 20 dBm. This value is very close to the simulated output voltage. Additionally, an excellent agreement was found at all the input power between the measured and simulated output voltages.

4. Conclusion

We have proposed a novel shape antenna which is optimized and fabricated with the two-stage villard rectifier. Our method relies on the novelty of the model of our antenna and rectifier in which the size of rectifier is 40 × 40 mm and for antenna we choose 20 × 21.5 mm size. Rogers RT duroid 6010 material is being used for both rectifier and antenna fabrication with 0.635 mm thickness. Rectifier impedance matching optimized by using smith chart tools in ADS and HBS analysis has been conducted and shown. Experimental results are quite near to schematic results of antenna and rectifier.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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