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# High-Efficiency Multiband Rectifier for RF Energy Harvesting Applications

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*Abstract* – **The main objective of the work is to energize the wireless sensor network by using Radio Frequency energy harvesting. It has the potential to harvest the RF energy available in the surroundings. However, the available RF bands in the atmosphere are unpredictable. Therefore, a multiband harvester's design adds more power from the vast number of sub-operating bands. In this work, a multiband rectifier is designed to harvest energy from 1.28 GHz, 1.8 GHz, 2.44 GHz, 3.5 GHz, and 5 GHz frequency bands simultaneously. An enhanced impedance matching network is designed and validated. The purpose of this is to improve the performance of the rectifier. Multiband rectifier achieves higher conversion efficiency than the traditional single-band approach. The highest power conversion efficiency is measured at 89.08% at 0 dBm input power at 1.8 GHz operating band and 4.8 V DC power is received. This paper introduces a novel design structure as well as a simple circuit structure of a multiband rectifier. The proposed rectifier provides sufficient energy to power the sensors used in wireless sensor networks and many other low-power electronic devices in a series of potential applications. It also demonstrates the higher conversion efficiency with existing designs.**

*Keywords* – **Ambient RF Sources, DC Pass Filter, Energy Harvesting, Greinacher Voltage Doubler, Impedance Matching Network, Multi-Band Rectifier, Power Conversion Efficiency, Transmission Line**

## I. INTRODUCTION

Energy harvesting is a unique approach to harvesting electromagnetic energy from ambient RF sources and is easily available to develop self-sustainable standalone electronic devices. It consists receiving antenna to receive the RF power and a rectifier circuit to harvest the DC voltage from the Rectenna. The rectifying circuitry is an important part of the rectenna and it is associated with an impedance matching network (IMN), a high-frequency diode, and a DC pass filter with the load resistor [1]. It has many advantages over other existing energy harvesting techniques. It provides a continuous supply, flexible to move, and apart from that it is independent of nature's activity such as weather conditions, humidity, rain, and many more [2,3]. It can energize low-power electronic devices such as RFID tags, wireless sensors, real-time applications, etc. In [4], the maximum power required for low-power devices is discussed. In recent years, RF energy harvesting has been the active research area for mobile devices [5], wireless sensor-based IoT devices [6], and medical implantation applications [7]. How much power is received from the rectenna depends on the targeted band applications. The various output parameters are required to analyze the behavior of the rectifier and one of them is power conversion efficiency (PCE) which converts RF power to DC [8]. Several rectifier topologies have been introduced by the researchers to analyze the higher conversion efficiency. Most of them are very basic such as single series diode topology [9], single shunt diode [10,11], voltage doubler, tripler, quadruple [12,13], and bridge rectifier type [14]. As per the application and operating frequency based, rectifiers are also categorized into three parts, single frequency based [15,16,17], multiband [18,19], and broadband [12,20]. Usually, a single-band rectifier achieves higher conversion efficiency, but it has a limited DC power collection due to a single targeted band [1,21,22,23]. Single-band energy harvesters could be ineffective due to the independent features linked with several IoT devices and sensor nodes [22,23]. Owing to the impulsive nature of the received radio frequency signal, and unpredictable signal distortion at the targeted band, energy loss leads to the device or node failure. In that position there are no energy is received by the specified band. This shows the limited applicability of the single-band harvester. Broadband rectifiers harvest RF energy from all the available sources but it sacrifices the quality of the impedance-matching circuitry and conversion efficiency. However, there are some difficulties in designing multiband rectifiers, such as impedance matching, complexity, and efficiency. It is challenging to match impedance across several frequency bands because optimal power transfer requires different matching conditions for each band. It is difficult to achieve high efficiency throughout all intended bands because rectifier performance varies with frequency. Furthermore, incorporating parts that perform well across a broad frequency range adds to the design complexity and frequently calls for cutting-edge materials and creative circuit topologies. Completing the design of efficient multiband rectifiers becomes even more difficult when these elements have to be balanced while keeping it small and affordable. However, balancing these factors while maintaining a compact and cost-effective design further complicates the development of efficient multiband rectifiers.

Hence, the multiband rectifier [24,18] is a suitable option to harvest the energy from the available ambient sources and trade-off between the output power and higher conversion efficiency. Typically, frequency bands are considered for

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energy harvesting, including GSM 900, GSM 1800, UMTS 2100, Wi-Fi 2.45 and 5GHz, Bluetooth, and LTE 2600, due to the number of devices deployed in the environment. Using the multi-band harvesters provides a notable improvement over the existing single-band and broadband harvesters [25]. Existing works stated in [9, 26] are discussed the narrow bandwidth. Thus, the harvester's performance is prominently affected when changes occur in operating bands. Problems identified during the rectifier design such as low RF power density at a few places, mismatch in impedance, nonlinear behavior of the diode, targeted operating bands, and the value of load resistance, etc. These challenges have to be addressed from a viable point of view. Most researchers have addressed these challenges [13,21,22,24,18,25,9,26,27,28,29,30]. In [2], authors have reported a conversion efficiency of 41%, 40%, and 42% for 0 dBm at 0.7, 0.85, and 0.9 GHz. In [25], reported a triple bands harvester at 1.84, 2.14, and 2.45 GHz among the PCE of 25.3%, 27.9%, and −20 dBm. A triple-band (at 2, 2.5, 3.5 GHz) harvester has presented in [31] with the highest PCE 53%, 31%, and 15.56% at −7 dBm input power. In [19], the author has presented a quad-band harvester with the highest PCE of 47.8%, 33.5%, 49.7%, and 36.2% at 0.89, 1.27, 2.02, and 2.38 GHz for −10 dBm input power. In [32] again quad-band energy harvester was presented by the author. It has the highest PCE of 44.8%, 27.5%, 28%, and 24.2%, at 0.95, 1.83, 2.45, and 2.62 GHz for 10 dBm input power. The author reported in [33] a quad-band energy harvester at 1.3, 1.7, 2.4, and 3.6 GHz, and the highest PCE of 54% is achieved at 1.7 GHz for 10 dBm input power. In [34] demonstrated the performance of quad-band energy harvester at 0.98, 0.88, 1.7, and 2.37 GHz. The authors implemented two different circuits for harvesting the RF signal. Low-frequency harvester (0.88 GHz) observed the highest PCE of 80% for -6 dBm and other triple-band rectifiers analyzed the highest PCE of 77%, 74%, and 54%, respectively, for −6 dBm. The designed rectifier has not achieved the required outcomes due to its narrow bandwidth and bulky size. In this work, a multi-band rectifier is reported for the available bands at 1.28 GHz, 1.8 GHz, 2.44 GHz, 3 GHz, and 5 GHz. In wireless communication and RF energy harvesting, the working bands of 1.28 GHz, 1.8 GHz, 2.44 GHz, 3 GHz, and 5 GHz each have specific functions. Due to its dependable range, the 1.28 GHz band is utilized in specialized applications such as military and satellite communications, despite being less popular. Because it provides a balance between capacity and coverage, the 1.8 GHz band is essential to GSM mobile networks. For short-range, high-data-rate connectivity, such as Wi-Fi, Bluetooth, and Zigbee, the 2.44 GHz band is essential. Newer wireless communication systems frequently employ the 3 GHz spectrum because it offers quicker data rates and higher capacity. With its larger bandwidth and reduced interference, the 5 GHz band is well-suited for high-speed data transport. It is widely used in contemporary Wi-Fi (IEEE 802.11a/n/ac/ax) and certain sophisticated communication systems.

The proposed rectifier is properly matched with the 50Ω feed line at the input of the impedance-matching network. A unique matching network is introduced with the Greinacher voltage doubler topology. The proposed work contributes noteworthy improvements such as multiple operational bands, power sweep, ease of design and implementation, and highest power conversion efficiency with the existing reported literature [21,24,22,18,25,9,26,27,28,29,30,31,32,33]. The primary contribution of the work includes:

- A unique, reliable, and energy-efficient multiband rectifier is designed, analyzed, and validated.
- The rectifier extracts each operational band related to cell phones/mobile devices such as GSM 1800, Wi-Fi, and Bluetooth.
- The microstrip transmission lines are used to design a matching network and a Greinacher voltage doubler topology is initialized to complete the rectifier circuit.
- By using transmission lines in lieu of lumped components reduces system complexity and chances of error during PCB manufacturing.
- The main motivation of the work is the proposed geometry of the rectifier, this is easy to design, implement, and validate.
- The Proposed rectifier is compared with the reported literature [14,18,23,30,35], and to the author's knowledge it enhanced the rectifier conversion efficiency and improved geometry specification. This is the main purpose of the proposed work.
- The work is motivated by the RF spectrum reviews carried out in the existing literature and compensates for the bottleneck of the implementation of the energy harvester.

The work is structured as follows. Section 2 demonstrated the system architecture, layout, and working principle of the proposed multiband rectifier. Section 3 discussed the performance analysis of the fabricated multiband rectifier and their received response. Section 4 summarizes the work.

## II. Introduction to Multiband Rectifier Design

The main aim of the energy harvester is to convert the received RF signal into an operational DC with nominal losses [2,3,9]. The minimal losses occur during the random shifting in operational bands and it degrades the performance of the rectifier. Few existing works are reported in the literature related to system degradation [1,2,18,29,30,31,19,32,33,34]. In this work, a multiband rectifier is designed, it consists impedance matching network, a doubler topology, and a DC pass filter as shown in Fig. 1. Microstrip transmission lines instead of lumped components are used to design the matching network. A 50 Ω feed line is used at the input of the matching network to initialize the power in the rectifier circuit. The number of connected transmission lines is related to operational bands.

The proposed multiband rectifier is simulated on the ADS tools. Table 1 displays the improved dimensions of the proposed rectifier. Here, TL1 and TL2 are connected in series and generate the three operating bands 1.28, 1.8, and 2.44 GHz and other added TL3 and TL4 are responsible for the 3.5 GHz and 5 GHz bands respectively as shown in Fig. 2. Moreover, a Greinacher voltage doubler topology is used due to the voltage multiplication feature and it is a good candidate. It efficiently generated higher electrical output power rather than a half-wave rectifier. High-frequency Schottky diode HSMS 2813 (SPICE Model) is introduced. It has the advantage of small junction capacitance and lower forward bias voltage.

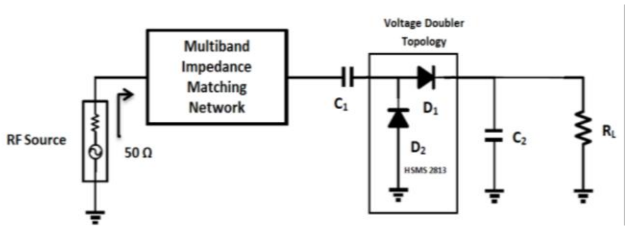



Fig. 1. Simplified Model of Proposed Rectifier

TABLE 1:
PROPOSED DIMENSION OF THE ENERGY HARVESTER

| **Parameter** | **Width** (mm) | **Length** (mm) | **Parameter** | **Value** |
|---|---|---|---|---|
| TL1 | 31.11 | 7.43 | $C_1$ | 150 pF |
| TL2 | 19.80 | 20.79 | $C_2$ | 100 pF |
| TL3 | 11.74 | 12.46 | $R_L$ | 75 KΩ |
| TL4 | 6.77 | 6.78 | SMA Connector | 50 Ω |
| Radial Stub | 4.90 | 2.21 | Diode | HSMS 2813 |

Equation 1 represents the input signal towards the IMN and IMN connected with the voltage doubler as shown in Figure 1. The applied input voltage in the circuit is represented as

$$V_{in} = a \sin w_t. \tag{1}$$

Here a represents the amplitude of the sinusoidal waveform. In the voltage doubler topology, the value of the load resistance $RL$ is greatly affected by the diode input impedance of the diode and it must be selected carefully. Figure 1 represents the working model of the proposed rectifier where $D1$ and $D2$ are operated accordingly. When $D1$ is operated in the forward bias $D2$ is off and energy is stored in the source capacitor $C2$ (150 pF). When $D2$ is operated $D1$ is off and energy is stored in the source capacitor $C1$ (100 pF). A DC pass filter as a radial stub (angle 100°) is used to block the harmonics at other operational bands. From [36], the diode current is expressed as

$$I_D \;=\; I_s\left[exp\left(\frac{a \sin w_t - 0.5V_{DC}}{mV_t}\right)\right], \tag{2}$$

where $V_{\mathrm{DC}}$ represents the DC output voltage, the output voltage, $V_T$ the thermal voltage, and $m$ is the ideality factor of the proposed design

$$V_{DC} \;=\; I_{DC}\, XR_L, \tag{3}$$

where $R_L$ is the load resistor and $I_{\mathrm{DC}}$ is the DC current at the output.

To justify the proposed rectifier design, a prototype is fabricated and tested. As shown in Fig. 3, a rectifier model is fabricated on the FR4 substrate ($\epsilon r$ = 4.3, $t$ = 1.6 mm), with the transmission lines and capacitors. The value of load resistance $R_L$ is chosen 75 KΩ because it is able to power more sensor devices.

The load resistor value must be chosen very carefully because it shifts the resonant by the non-linear performance of the diode. The overall size of the proposed rectifier is 60 × 35 mm$^2$. The impedance matching network ensures the maximum power conversion efficiency and maximum sensitivity is achieved at $Z_a$ = 50 Ω at the operating frequency bands and avoids the radiation of higher order harmonics generated through the rectifying element. DC pass filter ensures that only DC passes from the rectifying load. In general, in this work, the complete system performance is evaluated by the power conversion efficiency versus RF Input power ($P_{\mathrm{in}}$). The RF input power is considered between −10 to 20 dBm in certain cases.

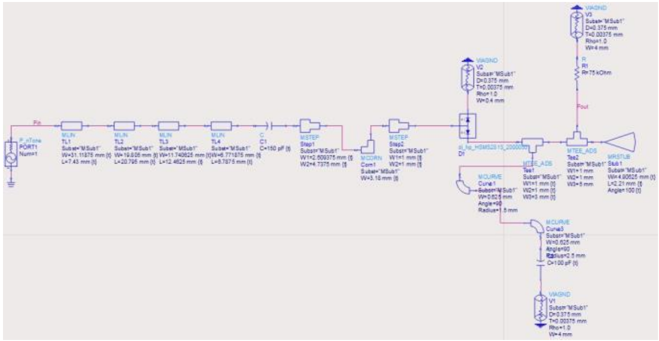


Fig. 2. Schematic of the Proposed Rectifier

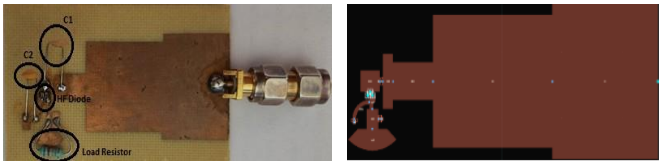



Fig. 3. Model of Proposed Rectifier

A guideline for the proposed rectifier is summarized below, incorporating the above design and analysis.

- As per the requirement of the device, determining the operating bands and selecting the high-frequency Schottky diode accordingly.
- Designed the impedance-matching network using a transmission line instead of lumped components.
- Determined the optimum value of input power (Pin), transmission lines, and capacitors $C1$, $C2$ by the rectifier simulation.
- By using the harmonic balance simulation analysis, determined the optimum load resistance value $R_L$
- Slightly tune the parameters with the ADS Tune function for an optimized performance of the rectifier.
- Finally, designed the multiband rectifier circuit shown in Fig. 3.

## III. RESULT DISCUSSIONS

Greinacher voltage doubler topology for the multiband rectifier design is computed in the Advanced Design System (ADS) software. It analyzes the behavior of the non–linear diode (Schottky Diode) by using the harmonic balance (HB) analysis and S-parameter simulator to simulate the response of

$S_{11}$ of the proposed rectifier. Here, the considered input impedance is 50Ωto match the impedance with the antenna output impedance. The construction size of the input impedance circuit is characterized and optimized by the overall system. To attain the input impedance of the overall system a number of transmission lines are introduced as shown in Fig. 2. Initially, the $S_{11}$ performance of the proposed rectifier circuit is analyzed and tested. The results are shown in Fig. 4, which demonstrates the S11 below −10 dB at all considered bands and shows a quite good impedance matching network. It is measured by the vector network analyzer (VNA) at −10 to 20 dBm RF input power. Measured and simulated response matches efficiently. Next, power conversion efficiency (PCE) at different frequency bands is analyzed. Figure 5 clearly observes the response of the multiband rectifier. It indicates the power conversion efficiency at 1.28 GHz, 1.8 GHz, 2.44 GHz, 3.5 GHz, and 5 GHz. With the analysis of the multiband rectifier, it achieves the higher conversion efficiency of 35.64%, 89.08%, 67.62%, 38.80%, and 25.48% at 1.28 GHz, 1.8 GHz, 2.44 GHz, 3.5 GHz, and 5 GHz respectively. The RF input power is considered here between −10 dBm to 0 dBm. The Power conversion efficiency is calculated accordingly [14].

$$\eta_{PCE} = \frac{P_{DC}}{P_{EF}} = \frac{V_{dc}^2}{P_{RF}R_L} \quad . \qquad (4)$$

The standard equation to figure out the performance of power conversion efficiency (PCE) of the multiband rectifier is expressed as

$$\eta_M = \frac{P_{DC}}{P_{EF}} = \frac{P_{DC}}{P_{RF}^1 + P_{RF}^2 + P_{RF}^3 + \dots + P_{nRF}^1}, \qquad (5)$$

However, the PCE is the ratio of output DC power to the total input power. In Eqs. 5, $\eta_M$ represents the multiband rectifier efficiency and is determined by the received DC power and available RF input power. Figure 5 shows the calculated response of the power conversion efficiency at different input power. The RF input power varies from −10 dBm to 0 dBm and the PCE of 89.08% is higher at 1.8 GHz at 0 dBm input power. Other targeted bands receive the PCE of 35.64%, 67.62%, 38.80%, and 25.48% at 1.28 GHz, 2.44 GHz, 3.5 GHz, and 5 GHz respectively. As observed from Fig. 5, as the RF input power is increased from −4 dBm to 0 dBm the power conversion efficiency is increased accordingly.

Hence, the proposed rectifier receives higher conversion efficiency at low input RF power. The overall power conversion efficiency of the proposed rectifier is also calculated at different frequencies. To generate the radio frequency signal Agilent E8257D signal generator is used to energize the proposed rectifier. Through varying the RF input power and operating bands, the received DC voltage is measured via multi-meter as shown in Fig. 6(a,b) and Fig. 7. The simulated (S) and measured (M) output voltage is received between −10 dBm to 20 dBm. Which is 4.7 V (S), 4.8 V (M) at 1.8 GHz, 1.26 V (S), and 2.3 V (M) at 2.44 GHz respectively.

Figure 6(b) displays the output power response of the proposed multiband rectifier at −10 dBm to 0 dBm input RF power. It illustrates the highest output power. The power of a multiband rectifier is expressed as

$$P_m = \sum_{i=1}^{n} P_{fi}, \qquad (6)$$

where $P_m$ represents the input RF power towards the multiband rectifier, $n$ tends to show the number of operating bands and $P_{fi}$ represents the power of each targeted band.

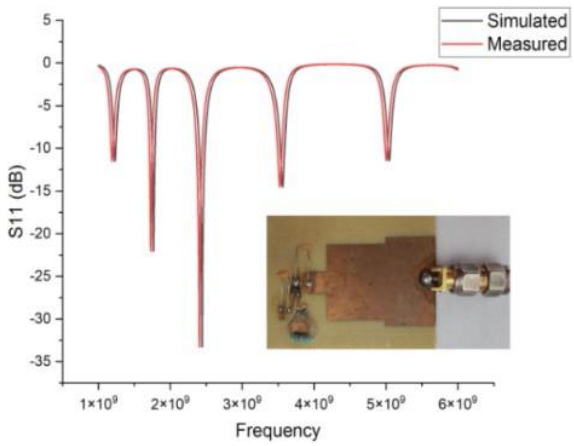



Fig. 4. Simulated and Measured $S_{11}$ of Rectifier

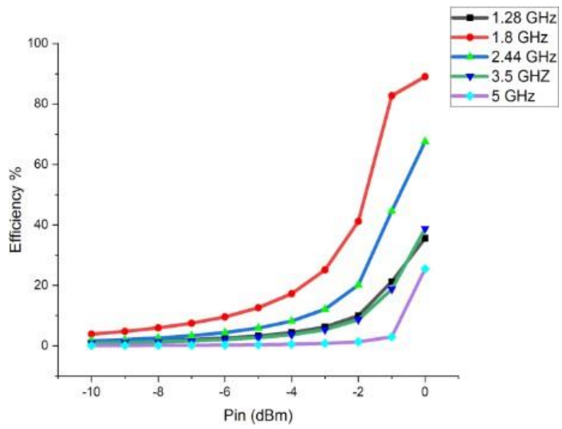



Fig. 5. Calculated Power Conversion Efficiency

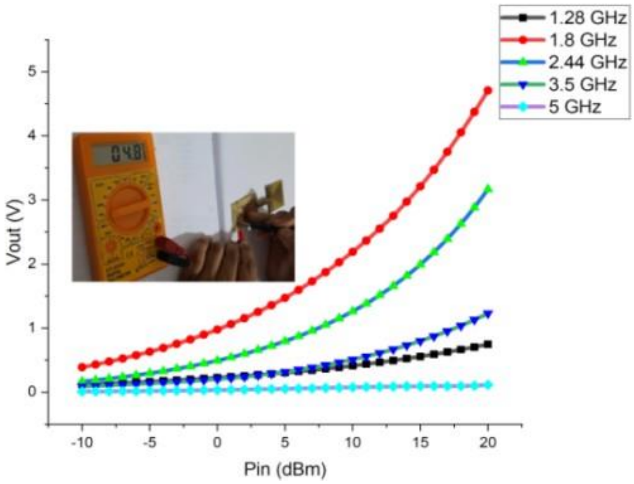
Correspondingly, the power conversion efficiency of the proposed rectifier is calculated from

$$\eta_m = \frac{P_m - P_{Loss}}{P_M}. \qquad (7)$$

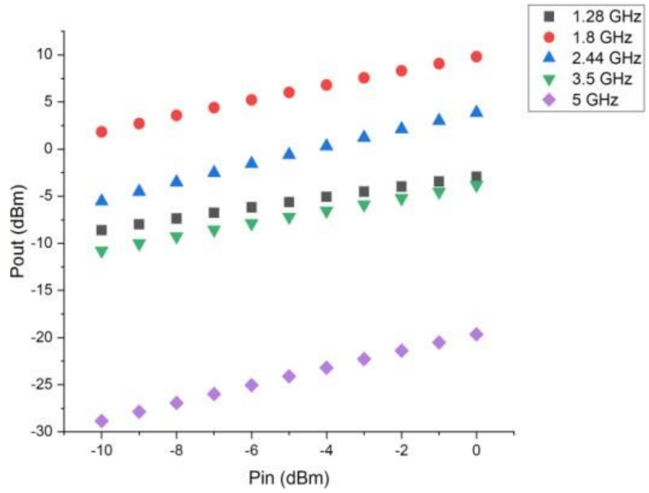
Here $P_{Loss}$ is the power loss due to the non-linear characteristics of the diode.

Table 2 enlists the comparative result analysis of the proposed work against the existing work centered on multiband rectifier design. It shows significant improvement among the existing design and is considered as a notable circuit that exhibits higher conversion efficiency at the 0 dBm input power level.

The proposed multiband rectifier demonstrates quite satisfactory performance to achieve higher PCE at a low RF input power level. The resistive load is considered 75 KΩ which is easily working with different low-power electronic appliances. Hence, the complete rectifier circuit is easily applicable to harvest the dc power at very low input power.




(a)




(b)

Fig. 6. Received response of the proposed rectifier: (a) Received DC Voltage, (b) Received output power

TABLE 2:
COMPARISON OF THE PROPOSED RECTIFIERS WITH EXISTING WORK

| Ref. | Frequency | Rectifier Topology | PCE % | Load Resistor | Rectifying Diode |
|---|---|---|---|---|---|
| 14 | 1.8–2.5 | Voltage Doubler | 70 | 14.7 KΩ | SMS 7630 |
| 23 | 1.8, 2.1, 2.4 | Single Series | 43.4, 46.5, 38.4 | 2.5 KΩ | HSMS 2850 |
| 30 | 0.55,0.75, 0.9, 1.85,2.15,2.45 | Voltage Doubler | 80 | 10–75 KΩ | SMS 7630 |
| 18 | 0.9,1.8,2.1,2.4 | Voltage Doubler | 15 @ −20 dBm | 11 KΩ | MSS20-141 |
| 35 | 1.8,2.1,2.6 | Single Series | 35 @ −20 dBm | 5.6K Ω | HSMS 2850 |
| Proposed Work | 1.28,1.8,2.44, 3.5,5 | Greinacher Voltage Doubler | 89.08 @ 0 dBm | 75 KΩ | HSMS 2813 |

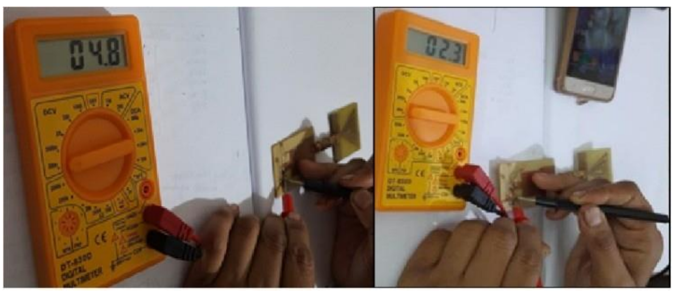



Fig. 7. Rectifier Measurement at 1.8 GHz and 2.44 GHz

## IV. CONCLUSION

In this work, a multiband rectifier for radio frequency energy harvesting is outlined, analyzed, and validated. It consists of a 50Ω input impedance, an RF to DC rectifying circuit to convert RF signal into DC voltage, a DC pass filter (in form of radial stub), and a resistive load. A series of microstrip transmission lines is initially applied to design the impedance-matching circuitry. The transmission lines (TLs) are optimized through the ADS tune function. The optimized TLs are used with Greinacher voltage doubler topology and perform satisfactorily in the targeted bands of 1.28 GHz, 1.8 GHz, 2.44 GHz, 3.5 GHz, and 5 GHz wireless networks. The analytical results of the proposed rectifier demonstrated a multiband frequency operation (−11.368 dB at 1.28 GHz, −22.045 dB at 1.8 GHz, −33.26 dB at 2.44 GHz, −14.53 dB at 3.5 GHz, and −11.423 dB at 5 GHz) and power conversion efficiency achieved up to 89.08% at the 0 dBm input power level. The received output DC voltage at 1.8 GHz is 4.8 V. The presented results of the proposed rectifier demonstrate the system's stability, compatibility, and durability in the operating bands of interest. The novelty lies in the work is it uses a fewer number of rectifying elements that lead to better RF to DC power conversion efficiency. Enhancing the PCE at other operating bands and designing a more compact rectifier for RF energy harvesting is our future expectation.

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