

Design of an efficient energy harvesting rectifier circuit for powering Wireless Sensor Nodes

Wisam A. Younis, and Shamil H. Hussein

Abstract—With the recent development in wireless communication systems and wireless sensors, Wireless Sensor Network (WSNs) have drawn worldwide attention to control and monitor the physical environment away from places that could be dangerous or challenging to access. The sensor nodes have no power supply. Therefore, the energy harvesting technique is a key solution that has shown good potential instead of their battery dependency. This paper presents a design and simulation of an efficient RF energy harvesting rectifier circuit for powering WSNs nodes. The single and multi-stages of the voltage doubler rectifier (VDR) circuit based on HSMS 2860 Schottky barrier diode (SBDs) has been simulated using layout and investigated at the operating frequency of 5.8GHz using ADS software. The simulated results achieve a good performance at the optimum load (R_L) of 2.2k. The conversion efficiency and DC output voltage of single stage VDR are about 74% and 3.85V respectively at the RF input power of 20dBm. Finally, the simulation results of the proposed circuit have been obtained using layout EM Co-Simulation, lumped element LC, and Microstrip transmission line MTL are better matched.

Keywords—Wireless Sensor Networks (WSNs); Rectifier circuits; Schottky diodes and RF Energy harvesting system

I. INTRODUCTION

IN recent years, the integration of information and communications technologies (ICT) into the urban environment has often been called smart city integration. Thus, technologies that make people's lives easier include wireless sensor networks (WSNs), public wireless hotspots (Wi-Fi), smart metering and smartphone application [1]. Specifically, WSNs are increasingly used in different fields, such as vehicle tracking, structure tracking, habitats, and health [2]. The main limited of the growth in the low power devices such as WSNs and IoTs are cost, size, and maintenance or replace problem of the batteries. In particular, on the physical environment away from places that could be dangerous or challenging to access. Therefore, the energy harvesting techniques are offered as a battery atonement method to powering of low-power WSNs.

The nodes of WSNs are harvested energy from different ambient environment sources such as solar energy harvesting using photovoltaic, mechanical vibration using piezoelectric sensor, thermoelectric, and radio frequency energy harvesting (RFEH) [3]. The WSNs based RFEH system consists of an energy-receiving antenna, impedance matching network (IMN) to achieve maximum transfer of power and voltage to load, rectifier circuits for RF-to-DC conversion, and the DC load

with DC filter circuit at the output terminal as shown in Fig. 1. The Rectenna (Rectifying and Antenna) is made up of set components of this system. The received single or multi band antenna is used for capturing RF energy from ambient surrounds and designed at the frequency to be used [4].

The power gain and radiation efficiency are investigated in [5]. The matched circuit is used for compatible the impedances between antenna and load circuit with DC filter, thus maximum power and voltage can be transferred for powering of low power devices such as WSNs and IoTs. The rectifier circuit is the most important element in the rectenna system for RF to electrical DC current conversion. The rectifier circuit operates based on nonlinear tunnel diodes namely Schottky barrier diodes (SBDs) which made from different companies such as HSMS 28xx and SMS-7630 family due to have several features likes low threshold voltage (V_{th}), low turn on voltage (V_{on}), low series resistance (R_s), low junction capacitance (C_j), and large breakdown voltage (V_{br}) [6]. Different high frequency Schottky-barrier diodes families that have been investigated in the literature review by Table I for RF energy harvesting applications.

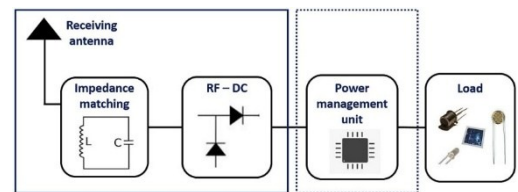


Fig.1. Block diagram of typical RF energy harvesting system [13]

TABLE I
THE CHARACTERISTIC PARAMETERS OF SBDs FAMILY [6]

Diode model	V_{th} [V]	V_{br} [V]	I_s [μ A]	R_s [Ω]	C_j [pF]
HSMS 2820	0.151	15.1	0.02	6.1	7.1
HSMS 2850	0.150	3.81	3.00	25.00	0.180
HSMS 2852	0.150	3.81	3.00	25.00	0.180
HSMS 2860	0.250	7.00	0.050	6.00	0.75
HSMS 286B	0.70	7.00	0.050	6.00	0.180
HSMS 285C	0.150	3.80	3.00	25.00	0.180
SMS 7630	0.090	2.00	5.00	20.00	0.140

There are different topologies of the rectifier circuit design which used for Rectenna applications as reported at many researches such as Half wave rectifier, Full wave rectifier,

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Voltage doubler rectifier, Villard charge pump, Graetz charge pump, and finally Dickson charge pump [7]. These types are introduced different values output voltage, current, power and conversion efficiency at the particular values of input power and load resistance.

Mohamed M. Mansour, Shota Torigoe and others proposed rectifier circuit using a T-matching network and a single series diode is designed to operate over a frequency range from 0.9 to 2.4 GHz. This system aims to achieve a power conversion efficiency (PCE) of more than 60% across both the lower and higher frequency bands in 2021[8]. Yanhu Huang, Jiajun Liang and others proposed a high-efficiency rectifying circuit for 5.8 GHz RF power transmission. It achieves a conversion efficiency of 59.6% and an output voltage of 2.003 V at a 1-meter distance, peaking at 3.17 V in 2024 [9].

In 2024 [10], Fayrouz, Nabil, and etc. are proposed a new two stage rectifier circuit design operating at the frequency of 2.45 GHz for energy harvesting applications. This design includes a doubler circuit with an output DC voltage of 7.33 V and an amazing power conversion efficiency (PCE) almost of 65%. The design that is being shown enables the output signal produced by VDR and Dickson rectifiers to be increased.

Salhane, Ilham, et al. are proposing a 5.8 GHz Rectenna system for powering battery-less wireless sensor nodes in 2023. The proposed rectifier circuit is designed in the microstrip line technique with a series and parallel topologies for operating at the frequency of 5.8GHz and input power is varying with a range from (-30 to 30 dBm). Both HSMS 2850 and HSMS 2852 Schottky diodes have been used to achieve the best performance at the operating frequency. The simulated results of the optimized circuit present a power conversion efficiency of 43% at the input power of 20 dBm and the feed by 0.2k Ω load resistance with an output voltage is about 2.92 Volt [11].

In 2024 [12], Huang, Yanhu, et al. proposed an efficient rectifier circuit for RF energy harvesting applications. This circuit operated at the frequency of 5.8GHz using multi-section impedance conversion and the harmonic suppressions. In order to compensate for the capacitive impedance of the nonlinear rectifier diode, the short stub is used in the matching circuit design. The simulated and measured maximum output voltage is about 3.18 V that it's linear with the transmission distance. The proposed rectifier achieves high conversion efficiency of about 60% at the operating frequency of 5.8GHz.

This paper presents an analysis and design of the single/multi-stages voltage doubler rectifier circuit for RF energy harvesting applications such as wireless powering for low power wireless sensor devices. The rectifier circuit based HSMS-2860 Schottky diode has been selected due to high efficiency at the operating frequency of 5.8GHz compared to other different Schottky diodes as reported in Table I.

II. VOLTAGE DOUBLER CIRCUIT DESIGN

Most of published research concentrates on single band rectifier operations; multiband harvesting was uncommon and requires more research to determine the best rectifying procedures. Voltage doubler can satisfy high output voltage, which is extremely important for providing low power devices

operation. Therefore, to satisfy the criteria of conversion efficiency and sufficient output voltage, that's why voltage doubler configuration was chosen for the proposed design. In the multistage voltage doubler shown in Fig. 2, the parallel configuration of capacitors in each stage reduces circuit impedance, simplifying the matching task [13]. Different stages are designed using ADS software to determine the highest efficiency within a variable range of input power and optimal range of output DC voltage for low power sensors.

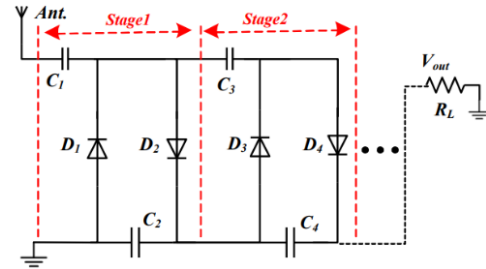


Fig. 2. N-stage circuit of voltage doubler rectifier

The input impedance of the rectifier circuit showed in Fig. 3 must be determined, to design the matching circuit, which aims to transfer the maximum possible power to the load circuit, the ADS software was utilized, as illustrated in Fig. 4. It is observed that the input impedance (Z_{in}) of the rectifier circuit based on HSMS 2860 SBD diode is about $1.2-j*23.16$ Ohms at the frequency of 5.8GHz.

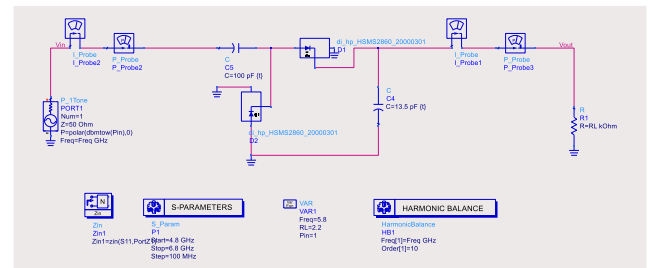


Fig. 3. A single-stage voltage doubler rectifier circuit has been adopted

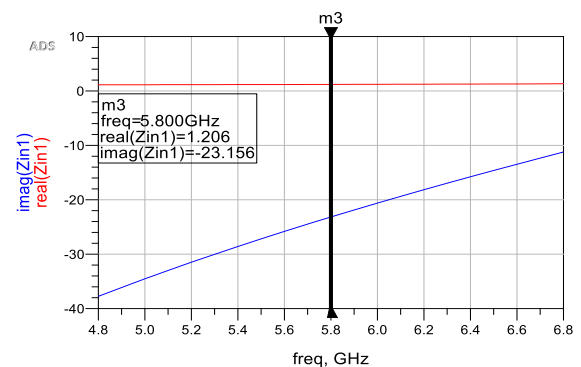


Fig. 4. Evaluating the rectifier circuit's input impedance using ADS software

The theoretical calculations of the input impedance (Z_{in}) are provided by the following equations. Theoretical value of Z_{in} approved at Equ. (1), which mentioned in [14], Where Z_1, Z_2 are Z_{in} of SBD diodes ($D_1, \dots, D_N$), w is the angular frequency in rad/sec as $w = 2\pi f$, the capacitor C_2 represents as a short circuit at the resonant frequency of 5.8GHz. As a result, the term

$\left(\frac{1}{j\omega C_2} \parallel R_L\right)$ has a negligible effect on the impedance of VDR circuit, and Equ. (1) can be rewriting and expressed by Equ. (2).

$$Z_{in(VDR)} = \frac{1}{j\omega C_1} + [Z_1] \parallel \left[Z_2 + \left(\frac{1}{j\omega C_2} \parallel R_L \right) \right] \quad \dots \dots \dots (1)$$

$$Z_{in(VDR)} = \frac{1}{j\omega C_1} + [Z_1] \parallel [Z_2] \quad \dots \dots \dots (2)$$

The configuration Schottky barrier diode (SBD) consists of intrinsic and extrinsic parameters such as nonlinear junction resistance (R_j), junction capacitance (C_j), and series resistance (R_s) as shown in Fig. 5.

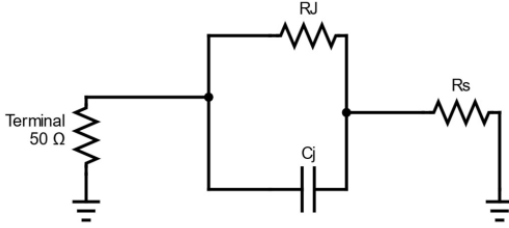


Fig. 5. Equivalent Circuit Model of SBD diodes.

The input impedance of two SBD diodes ($Z_{1,2}$) can be calculated by Equ. (3) that depended on the model circuit.

$$Z_{1,2(SBD)} = R_s + \frac{R_j}{1 + j\omega R_j C_j} \quad \dots \dots \dots (3)$$

Where the nonlinear component R_j can be determined by:

$$R_j = 8.33 \cdot 10^{-5} \cdot \frac{nT}{I_b + I_s} \quad \dots \dots \dots (4)$$

Where the T is the temperature (300°K), $n=1.05$ is an ideality factor, $C_j=0.18$ pF, $R_s=6 \Omega$. and I_b, I_s are the base and saturation currents which are equal to $5\mu A$ and $50nA$ respectively. These values above are taken from data sheet of HSMS 2860 SBD diode. The theoretical value of R_j is calculated about $5.19594 \text{ k}\Omega$, whereas, the ($Z_{1,2}$) of SBD diode is $(10.47-j*152.32) \text{ Ohms}$ and the $(1.38-j*37.5)$ for VDR rectifier circuit at the operating frequency. It is observed that the analytical value by Eqs. (1) and (2) and the simulated value via Fig. 4 of the input impedance (Z_{in}) for the rectifier circuit is closely matched.

III. IMPEDANCE MATCHING NETWORKS (IMNS)

Impedance matching between the antenna and the Schottky diode rectifier is crucial due to the diode's nonlinear properties, which cause its input impedance to vary with input power levels and loads. The main goal of the impedance matching network is to maximize power transfer from the receiving antenna to the rectifier circuit and to increase the RF input voltage level for the rectifier. The three main types of matching networks for RF energy harvesting are L-type, π -type, and T-type, as Fig. 6 [15]. Transmission lines are sometimes employed as well [16]. ADS software used, lumped elements LC and microstrip transmission line (MTL) matching circuits designed to optimize efficiency in the proposed design. The quality factor (Q) is a measure of the energy stored in the reactance to that being consumed by the resistance. The L-type IMNs is commonly

used due to having only two components and simpler design. Therefore, the Q factor is not changed and cannot be chosen as it is a fixed factor by the matched factor. The other types of the IMNs are used to eliminate L-type constraints. In this work, a π matched network has been used due to achieving highest conversion efficiency.

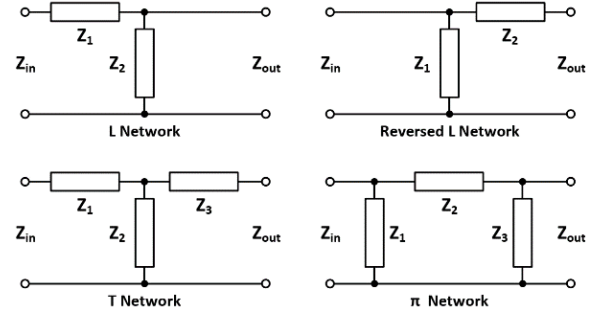


Fig. 6. Different types of the matching networks [36]

IV. SIMULATION RESULTS

This work reported an analysis, simulated, and implemented of the rectifier circuit design for RF energy harvesting applications such as self-powering of wireless sensor nodes using ADS library package tool. In order to design a high-efficient rectifier circuit for this purpose, the Schottky barrier diode (SBDs) should be a suitable choice for giving high RF-to-DC conversion efficiency at the operating frequency of 5.8GHz. There are different SBD diodes used for this purpose as reported in Table 1. In order to choose SBD diodes correctly, the conversion efficiency of different SBD diodes as a function of RF input power have been simulated at the frequency of 5.8GHz as shown in Fig. 7. It is observed that the HSMS 2860 SBD gives best performances and it's available numerous from companies.

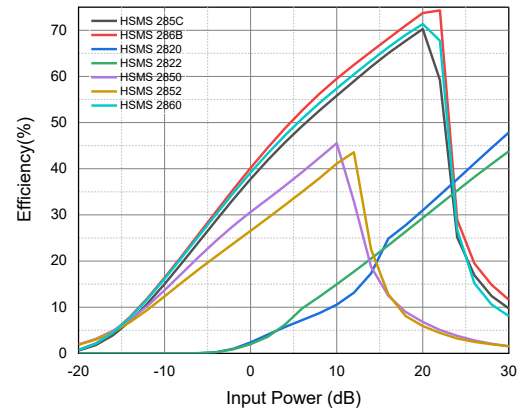


Fig. 7. The simulated efficiency as a function of input power for various types of Schottky diodes at an operating frequency of 5.8 GHz

An Advanced Design System (ADS) software was utilized to compare the different type of Schottky diode, for the chosen diode HSMS 2860, one to six stage circuit proposed to prefer the better one. The single-stage circuit was selected due to its optimal efficiency, which falls within the required range for low-power devices across various input power levels ranging from -20 to 35 dBm as illustrated in Fig. 8.

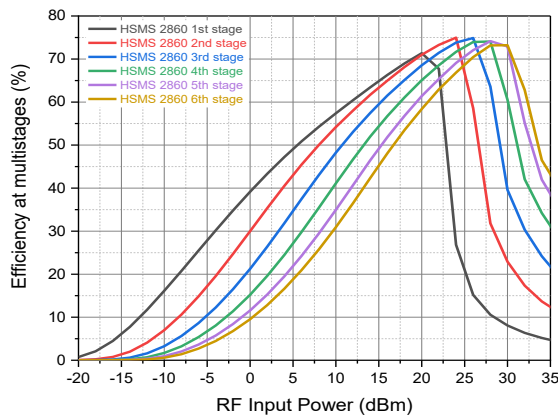


Fig. 8. The simulated RF-to-DC conversion efficiency as a function of RF input power of different stages for the rectifier circuit based on HSMS 2860 SBD at the operating frequency

The DC output voltage and power is changed with different stages of the rectifier circuit design at the same operating frequency. The DC output voltage increased with increasing number of stages as shown in Fig. 9. In order to optimum efficient rectifier circuit design, both the input impedance of the proposed VDR rectifier and the optimum load resistor must be calculated as a function of different RF input power at the proposed operating frequency. Figure 10 shows the simulated optimum load resistor (R_L) which gives the highest conversion efficiency at 2.2 k Ω . In addition, the simulated input impedance (Z_{in}) of VDR based on HSMS 2860 SBD at different input power as shown in Fig. 11.

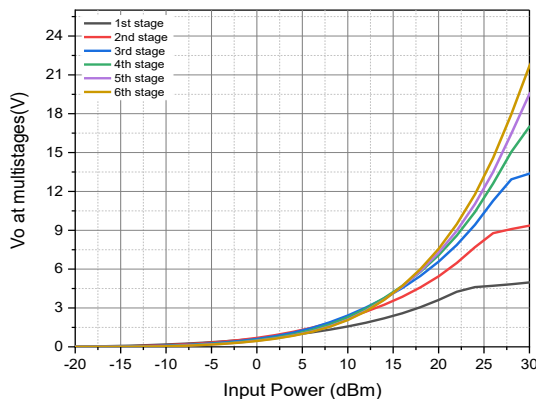


Fig. 9. The simulated DC output voltage (V_{out}) as a function of input power for one to six stages of chosen diode at an operating frequency

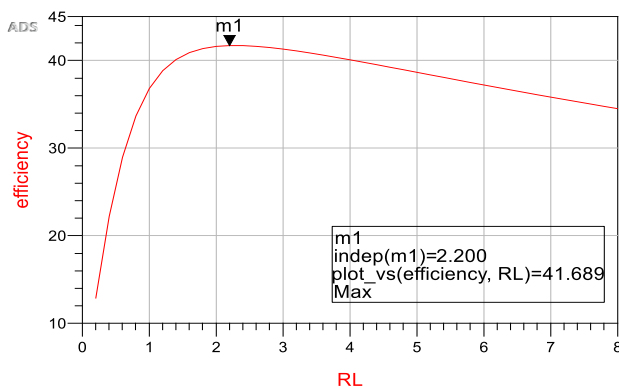


Fig. 10. Simulated efficiency by various values of R_L in [k Ω]

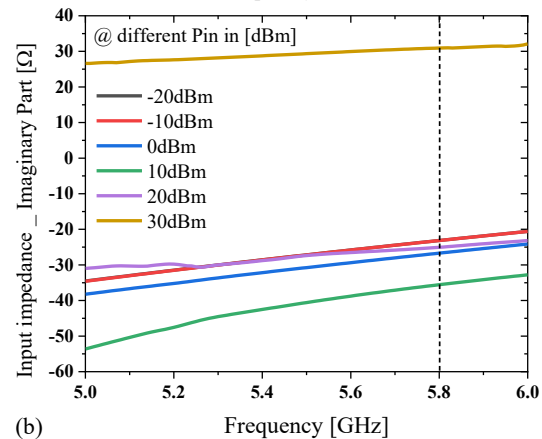
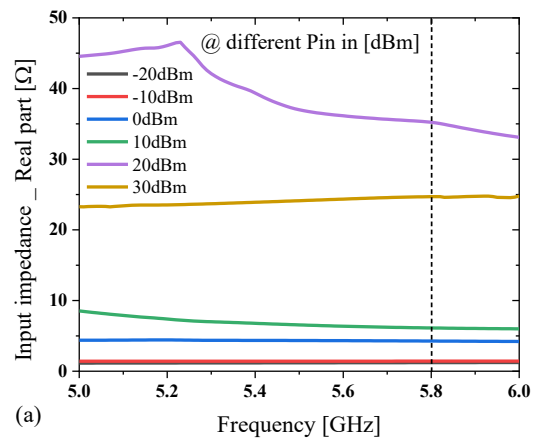


Fig. 11. The simulated input impedance of VDR circuit at an operating frequency and different RF input power: (a) Real part of Z_{in} , (b) Imaginary part of Z_{in}

The input matching network (IMNs) play a key role at the maximum power transfer from the received antenna (50 Ω) to output termination (load resistor). Different matched circuits such as L-match, T-match, and π -match have been simulated and designed using LC lumped elements and transmission line (MTL) technique. Figure 12 shows the simulated RF-DC conversion efficiency of VDR circuit based on HSMS 2860 SBD at the operating frequency for different IMNs circuits. It can be observed that the conversion efficiency of VDR has been obtained using different methods of IMNs circuits that are completely matched. In addition, π -match impedance matching network achieves the highest efficiency among the L, T, π , and MTL networks.

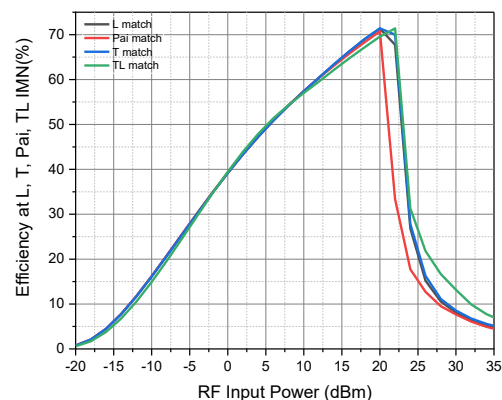


Fig. 12. The simulated conversion efficiency of VDR as a function of input power at different methods of matched circuits

The full circuit design of the VDR rectifier based HSMS 2860 SBD diode has been simulated and investigated with π IMNs network using lumped elements and MTL technique. Figure 13 shows the circuit diagram designed using ADS software consists of π IMN network, SBD diode, and DC filter to smooth output voltage. In addition, the layout of the circuit design has been simulated and investigated by Roger RO5880 material substrate.

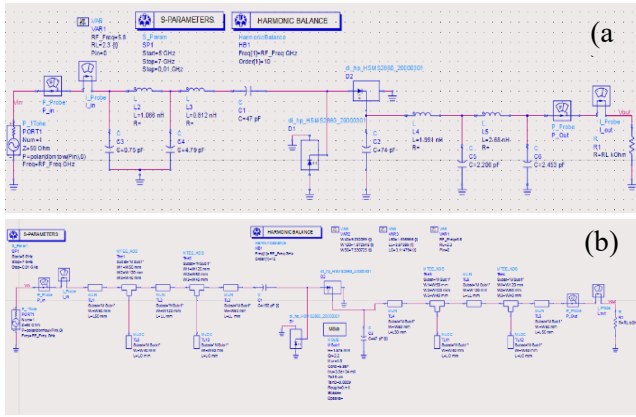


Fig. 13. The simulated circuit diagram of VDR circuit based HSMS-2860 SBD using π matched network and both: (a) lumped element, (b) MTL technique

The IMNs network is designed and simulated using open and short stub microstrip transmission lines (MTL). To determine the electrical length and width of MTL for IMN, the ADS software for Roger RO5880 substrate is used at the operating frequency and impedance characteristics. The specification of the substrate material is dielectric constant (ϵ_r) of 2.2, Permeability (μ_r)=1, Conductivity (σ) is 5.8×10^{-7} S/m, Cover height (H_u) = 3.9×10^{-34} mil, thicknesses of substrate and conductor about 1.575 mm and 35 μ m respectively. The size of the circuit board is maintained to about (60 mm $\times$ 10 mm).

The full schematic of the layout rectifier circuit designed based on HSMS 2860 SBD diode for operating at the frequency of 5.8GHz. The actual layout circuit design consists of input matched network, two single Schottky diodes are connected in parallel, DC filter, and optimum load resistor as shown in Fig. 14. The proposed rectifier circuit is mounted on dielectric board Rogers RO5880 which has a ϵ_r of 2.2, a loss tangent angle of 0.0009, thickness of conductor and substrate of 35 μ m and 1.575 mm respectively. In this design, the capacitors (C_1 and C_2) are 47pF, the optimum load resistor of the current output is 2.2k Ω .

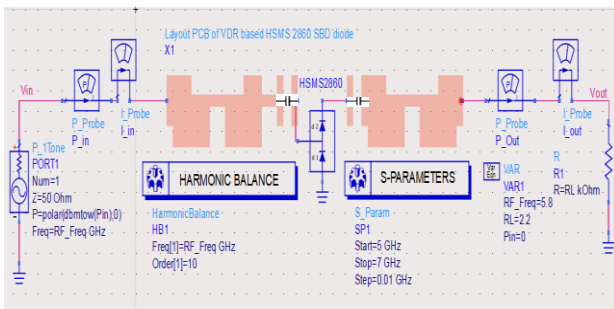


Fig. 14. The layout circuit design of VDR based SBD diode

The final optimized parameters of the IMNs and DC filter are electrical width of resistance, capacitance, and inductance are $W_{50}=7.53$ mm, $W_{40}=9.03$ mm, and $W_{120}=1.87$ mm by respectively. Whereas, the electrical length of these same elements (L_{50} , L_L , and L_C) are (1.53mm, 3.67mm, and 3.112mm) for resistor, capacitor, and inductor elements respectively.

The rectification efficiency (η) is one of the most important factors for evaluating the operation of the rectifier circuit design. The RF-to-DC means the ability to convert RF energy into usable DC power which can be determined by:

$$\eta = \frac{P_{DC}}{P_{RF}} * 100\% = \frac{\frac{V_{DC}^2}{R_L}}{\frac{1}{2} \times R \{U_{RF} \times I_{RF}\}} * 100\% \quad (5)$$

Where P_{DC} is the power received by the receiver antenna of the energy harvesting system, P_{DC} is the input RF power, and V_{DC} is the DC output voltage. As we can say, the conversion efficiency is the main challenge for the energy harvesting systems to guarantee a long life for smart WSN devices. As consequently, in this work, the proposed VDR circuit achieved the higher efficiency about 74% at the input RF power of 20dBm as shown in Fig. 15. It can be observed that the RF-DC conversion efficiency has been obtained using different design ways that are matched completely.

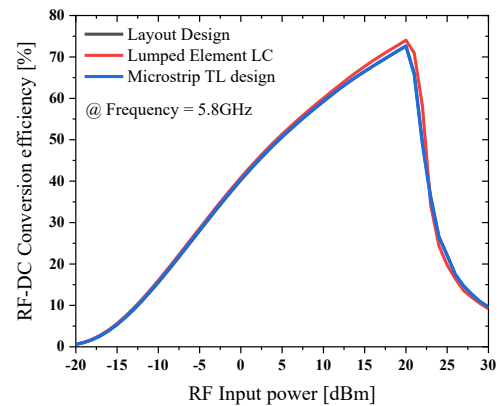


Fig. 15. The simulated RF-DC conversion efficiency of the proposed VDR circuit designed by three methods at the frequency of 5.8GHz

The S-parameter analysis of the rectifier circuit design has been simulated and investigated using reflection coefficient (S_{11}) as shown in Fig. 16. It observed that the minimum peak value of S_{11} data is about (-20dB) less than -10dB which occurred at the operating frequency of 5.8GHz for different methods of design at the input RF power of 0dBm. Therefore, this rectifier circuit is a candidate for rectification at 5.8GHz.

The single stage of the proposed VDR rectifier circuit based on HSMS 2860 SBD diode presents a peak value of the DC output voltage to reach about 3.85V at the 20dBm of RF input power. In this paper, the simulated DC output voltage (V_{out}) has been investigated using different designs (LC elements, MTL, and layout board) as a function of various input power that ranging from -20dBm to 30dBm at the optimum load resistance of 2.2k Ω and the operating frequency of 5.8GHz as shown in Fig. 17. It observed that the output voltage at the load terminator increases with increasing RF power. In order to increase V_{out} for the certain application, the multi-stages can be used. In addition,

the load resistance is affected by the overall performance of the rectifying circuit, the conversion efficiency decreases with increasing the load resistance as shown in Fig. 18.

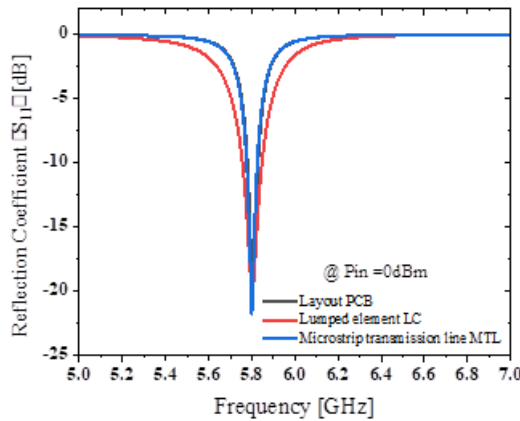


Fig. 16. The simulated S11 data of VDR circuit for different designs at the frequency of 5.8GHz and RF input power of 0dBm

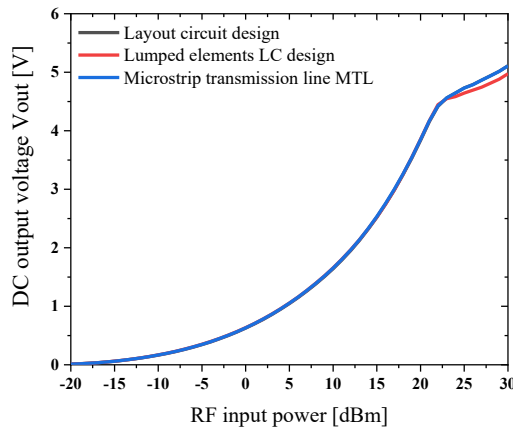


Fig. 17. The simulated DC output voltage (Vout) of VDR circuit for different designs at the frequency of 5.8GHz and optimum load (R_L) of 2.2k Ω

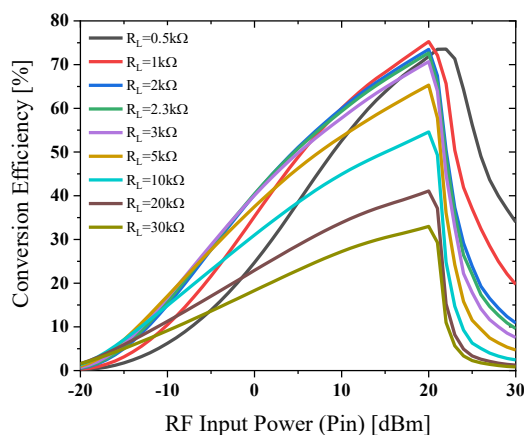


Fig. 18. The simulated efficiency of VDR circuit as a function of various RF input power at different load resistance R_L and the frequency of 5.8GHz

The proposed single-stage rectifier circuit demonstrates an efficiency of over 39% at 0 dBm, with a peak efficiency exceeding 74% at 20 dBm. The DC output voltage reaches 3.85V at an input power of 20 dBm, and the output DC current

and power reach 2 mA and 6.45mW respectively as reported by Table II. Table III shows the comparison of literature review with the performance of the proposed VDR rectifier circuit design based on HSMS 2860 SBD diode at the operating frequency of 5.8GHz.

TABLE II
THE EFFICIENCY, VOUT, POUT OF THE RECTIFIER CIRCUIT AT DIFFERENT OF PIN

Pin [dBm]	DC Vout [V]	DC Pout [W]	Efficiency [%]
-20	0.011	0.057 μ W	0.591
-10	0.155	12 μ W	14.929
0	0.6	174 μ W	39.442
10	1.56	1.2 mW	58.960
20	3.85	6.45 mW	74

TABLE III
PERFORMANCE COMPARISON OF THE PROPOSED RECTIFIER CIRCUIT WITH LITERATURE REVIEW

Ref. / year	Freq. [GHz]	Rectifier topology / diode	Conversion efficiency [%] / Pin [dBm]	DC Vout [V] @ R_L [k Ω]
[17]	2.4	HWR /	63 / 13	1.4@0.15
2020	5.2	HSMS 2860	65 / 13	1.53@0.15
[18]	2.45	VDR /	64.1 / 10	1.8@2.5
2020		SMS 7630		
[19]	2.45	VDR /	47 / 0	1.36@1
2021	5.8	HSMS 2860	42 / 0	1.28@1
[20]	2.45	VDR /	60 / 13	1.85@2.7
2021	5.8	SMS 7630	47 / 13	
[21]	2.4	VDR /	71 / 20	3.6@1.25
2022	5.8	HSMS 2850	52 / 20	
[22]	2.45	VDR /	52 / 0	2.17@10
2023		HSMS 2852		
[23]	2.45	VDR /	65 / 11	2.96@1.2
2024	5.8	HSMS 2852	38 / 11	2.41@1.2
[16]	5.8	FWR /	59.6 / 16.7	4.1@0.6
2024		HSMS 286B		
This work	5.8	VDR / HSMS 2860	74 / 20	3.85@2.2

HWR: Half wave rectifier, FWR: Full wave rectifier, VDR: Voltage doubler rectifier

CONCLUSIONS

Significant promise is shown by the suggested design of a high-efficiency RF energy harvesting rectifier circuit for powering Wireless Sensor Network (WSN) nodes. The single-stage rectifier circuit was determined to have the best output voltage and efficiency for low-power devices over a range of input power levels using the Advanced Design System (ADS) software. Over 40% efficiency at 0 dBm and over 74% efficiency at 20 dBm were the peak efficiency values for the rectifier circuit, with the π -type impedance matching network obtaining the highest efficiency. At an input power of 30 dBm, the DC output voltage reached 5 V, indicating that utilizing RF energy harvesting as a sustainable power source for WSN nodes is practical.

ACKNOWLEDGEMENTS

The authors are very grateful to the University of Mosul/College of Engineering for their provided facilities, which helped to improve the quality of this work.

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