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Optimization of Rectifying Circuit for RF Energy Scavenging

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Abstract: This paper studies a rectifier design for radio frequency energy scavenging at 2.45 Ghz ISM band. The designs of a voltage doubler rectifier that enable RF to DC conversion consists of two units of Schottky diode. This paper also covers the analysis of six zero bias Schottky diodes. The Schottky rectifier is widely used due to their switching speeds that can approach zero time and give very small forward voltage drops. It does allow the circuit to operates at very high frequency and very low power input signals. The rectifying circuit is designed, simulated and measured in this study by using Agilent Advanced Design System (ADS) at 2.45 GHz. The conversion efficiency of proposed rectifier with HSCH-9161 diode gives 31.16%. The rectifier reaches the highest efficiency at 20 dBm input power, which reliable to commercial Wi-Fi access point that operates at 10 to 25 dBm. The higher output voltage is 10.32 V at 20 dBm.

Keywords: Rectifier, voltage-doubler, zero bias diode, Schottky diode, energy scavenging.

1. Introduction

Radio frequency (RF) power is available at everywhere due to the evolvement of communication technology. The RF power can be converted to DC power using rectifiers (Salvador, 2019). Due to the challenge of capturing the communication signal, a good quality rectifier which converts RF to DC signal, this study will be focused on the method to get the maximum throughput. It should have high efficiency to change as much of that energy as possible to usable power. In addition to the challenge of transmitting the communication signal, a good rectifier which convert RF to DC signal, is needed so as to maximize the throughput (Alneyadi et al., 2014).

A block diagram of a complete RF energy harvesting is shown in figure 1 which consist of antenna, impedance matching, RF to DC conversion circuit and DC load circuit. This study only covers on rectifying circuit, and the consideration is to get the efficiency to convert as much of RF energy to be used in DC load circuit by manipulating the diode used in voltage doubler circuit.

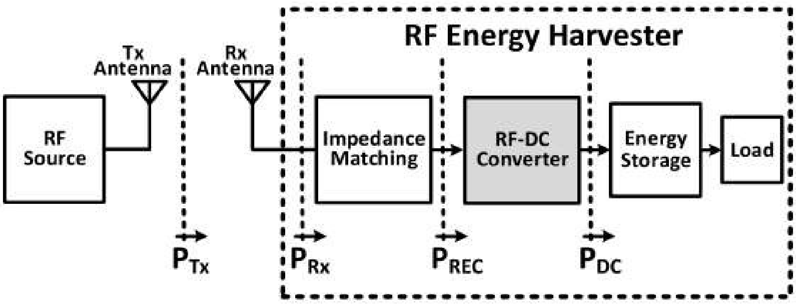

Figure 1. Block diagram of an RF energy harvesting (Khan et al., 2020).

2. The Design of Rectifier

2.1 The Voltage Doubler Rectifier Circuit

The microwave rectifier can be arranged in several configurations. The widely used is a single serial and shunt arrangement, in terms of high DC output; a voltage doubler is recommended solution (Alneyadi et al., 2014). In this study, the circuit stated by Almorabeti, Rifi & Terchoune (2019) circuit is shown in figure 2 is a single stage voltage multiplier or voltage doubler topology that involve two diodes, one attached in serial and another one in parallel, to produce a larger output voltage. The rectifier consists of two capacitors and two units of Schottky diode. The HSMS 286B diode pairs were selected as their performance is optimized for the chosen frequency band. Furthermore, Amilhajan

(2014) stated, the diode does not involve external biasing, and the critical for RF study is an insufficient microamperes of bias current are difficult to produce. In addition, these diodes have relatively low barrier height and high saturation current likened to externally biased detector diodes (Chandra et al., 1996). So that, the results get higher output voltage at low power levels. The SPICE parameters of the diode is shown in table 1.

Table 1: SPICE parameters for HSMS286B

Parameters	Units	HSMS286B
BV	V	7
*CJ*0	pF	0.18
EG	Ev	0.69
IBV	A	1E-5
IS	A	5E-8
N	No units	1.08
RS	ö	6.0
PB (*VJ*)	V	0.65
PT (XTI)	No units	2
M	No units	0.5

The design of this rectifier is separated to three steps, involve the design of the lumped element of rectifier, then converted the circuitry to microstrip line presentation and lastly evaluate the design using Agilent Advanced Design System (ADS) Momentum that can give the simulation with desired substrates.

Firstly, the lumped element of rectifier has shown in figure 2, then the figure 2 present the layout of voltage doublers rectifier in microstrip transmission line. After that ADS momentum symbol will be generated and simulated. The HB - simulated DC output of the rectifier shown in figure 4. The output shows the comparison of lumped element, microstrip and ADS momentum analysis. The graph presents that the microstrip design and analysis by ADS Momentum comply the lumped element design specifications.

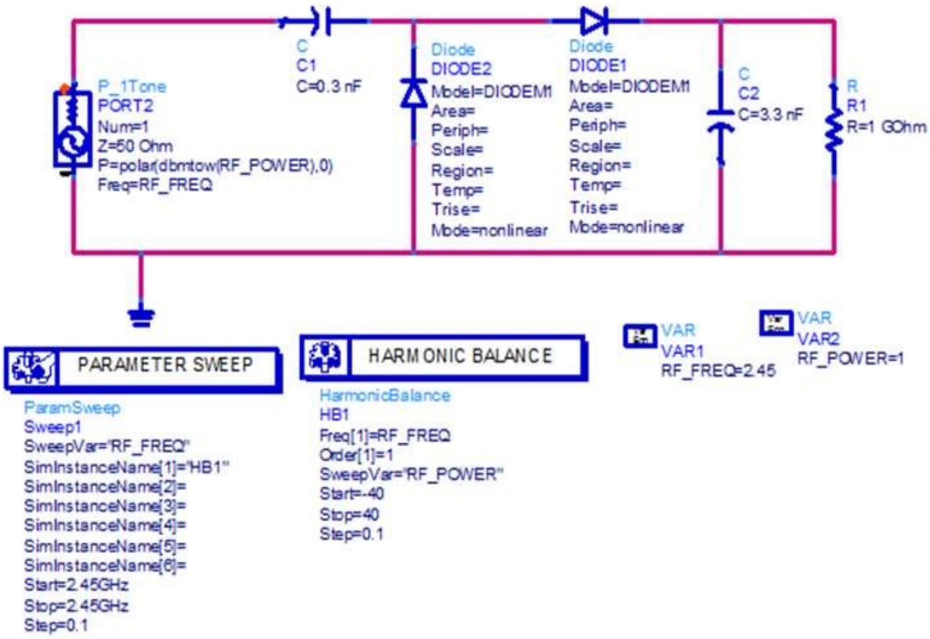

Figure 2. Voltage doubler rectifier circuit

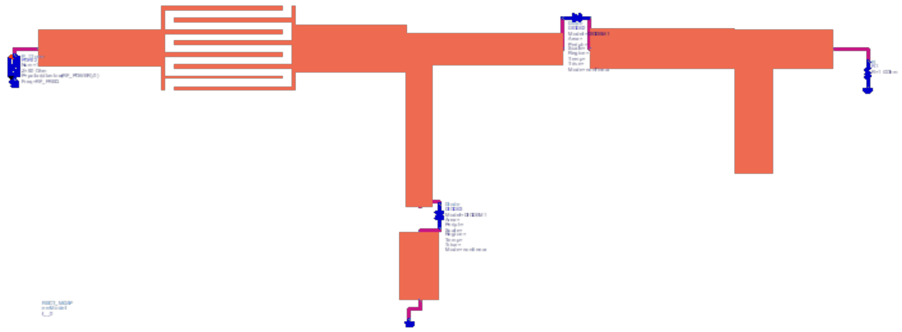

Figure 3. Microstrip transmision line presentation for voltage doubler rectifier circuit

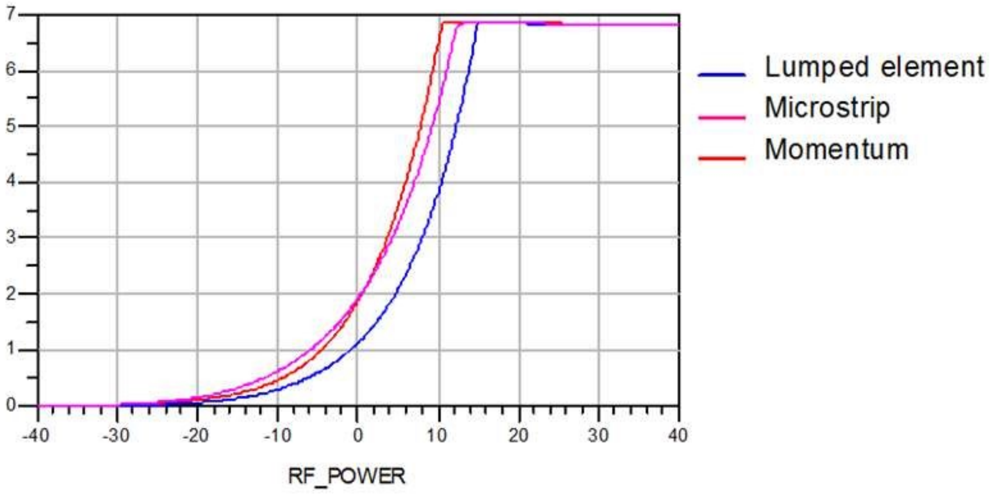

Figure 4. DC output voltage verses RF input power for voltage doubler rectifier circuit

2.2 The Optimization Using Schottky Diode

The second part of this study is to find the most efficient zero bias Schottky diodes as a rectifying element. Each diode has a different effect due to maximum breakdown voltage and do not require external biasing, which is crucial in microampere application where it is difficult to generate the current.

Six zero bias Schottky diode were choose to find the maximum voltage output in RF energy scavenging. The diodes have low barrier height and high saturation current instead of externally biased detector diodes. So that, the higher output voltage will be produced even at low power level (Rifi & Terchoune, 2019). Meanwhile, Mouapi, Hakem & Delisle (2018) stated the sensitivity of the rectifier circuit to convert the harvested RF signals into a DC signal is directly associated to the sensitivity of the used rectifying diode.

Then, Abdelhady et al (2020) mentioned the influencing factor on rectenna efficiency is diode efficiency due to the value of breakdown voltage of the diode and choose HSMS-2862 and HSMS-2852 diodes in his research. The study found that the HSMS-2852 diode series get better performance.

The parameter of the diode that effect maximum power conversion efficiency point due to its breakdown voltage, zero-bias junction capacitance, activation energy and reverse breakdown current as illustrated in Spice parameters in table 2.

Table 2: SPICE parameters for HSMS-2820, HSMS-2860 and HSMS-2850

Parameter	Units	HSMS 2820	HSMS 2860	HSMS 2850
BV (Vbr)	V	9	7	3.8
CJO	pF	0.7	0.18	0.18
EG	eV	0.69	0.69	0.69
IBV	A	10E-4	10E-5	3.0E-4
IS	A	2.2E-8	5.0E-8	3.0E-6
N	-	1.08	1.08	1.06
RS	ohms	5	5	25
PB (Vj)	V	0.56	0.65	0.35

PT (XTI)	-	2	2	2
M	-	0.5	0.5	0.5

The simulation setup is done by Agilent Advanced Design System shows the first rectifier using HSMS-2820 package, according to Agilent HSMS-282x, this diode featuring low series resistance, low forward voltage at all current levels and good RF characteristics. The second diode using HSMS-2860 package, this diode is DC biased detector diodes have been designed and optimized for use from 915 MHz to 5.8 GHz. Agilent HSMS-286x stated HSMS-2860 is ideal for RF/ID and RF Tag applications as well as large signal detection, modulation, RF to DC conversion or voltage doubling.

Then, the third diode use HSMS-2850 package, also similar to HSMS-2860 package properties but have difference in certain properties such as breakdown voltage and current at breakdown voltage.

To simulate the diode performance as well as the rectifier performance, figure 4 shows the simulation results of DC output voltage at 2.45GHz. The range of input signals for this rectifier circuit has been set from -40 dBm to 40 dBm in ADS simulation.

The output shows HSMS-2820 gets the highest DC voltage at 9.08 V at 19.53 dBm, followed by HSMS-2860 gets 7V at 15.30 dBm and HSMS-2850 gets 3.88 V at 9.71 dBm. The reading at 0 dBm shows HSMS-2860 and HSMS-2850 get 1.25 V and HSMS-2820 gets 0.58V.

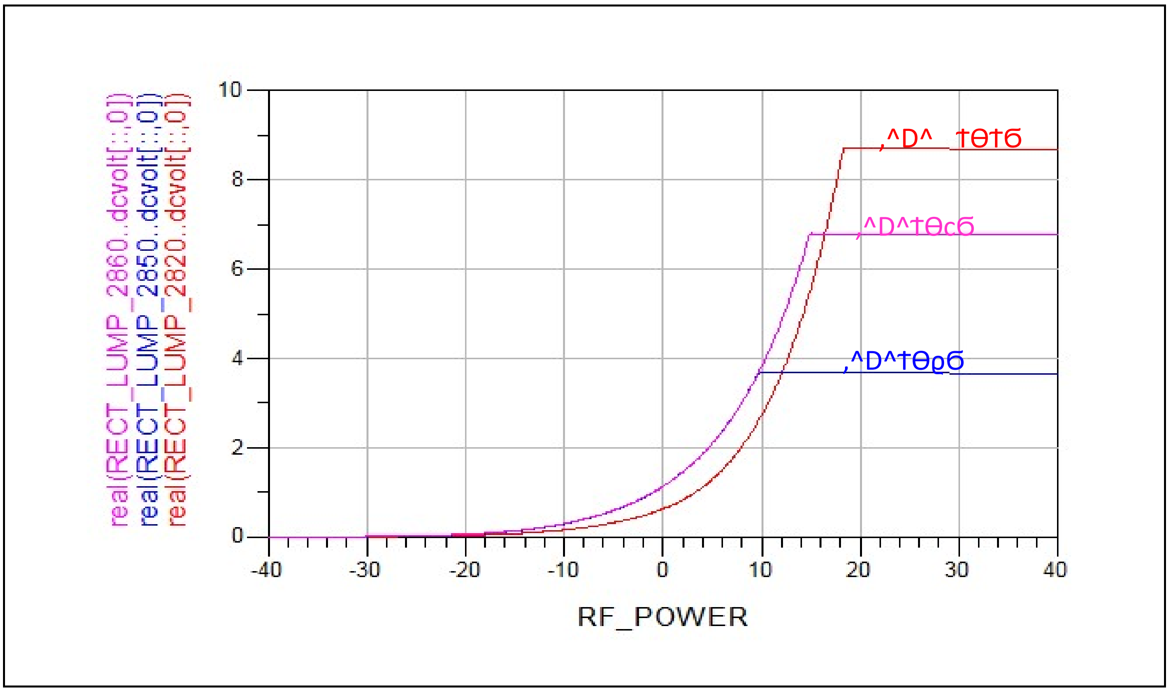

Figure 5. DC output voltage verses RF input power for voltage doubler rectifier circuit using HSMS-2820, HSMS-2860 and HSMS-2850 package

Then, three HSCH diodes was selected to get the optimization in the voltage doubler circuit. The fourth diode is HSCH-9161 package, the millimeter waves zero bias Gallium arsenide (GaAs) Schottky diode that drives in applications below 10 GHz, the DC bias is not available and where temperature sensitivity is a design consideration, the HSCH- 9161 by Hewlett Packard offers superior stability when compared to silicon zero bias Schottky diodes.

The fifth diode is HSCH-9101 Beam Lead GAAs Schottky by Avago is a barrier diode that optimized for use in mixer applications at millimeter wave frequencies, and use in rectifier circuit. This diode is low series resistance, low capacitance and high cutoff frequency diode. The last diode is HSCH-5316 package by Hewlett Packard is Beam Lead Silicon Schottky diode. The beam lead diode is ideally suitable for use in stripline or microstrip circuits. Its small physical size and uniform dimensions provide it low parasitic and repeatable RF characteristics through K-band and ideal for mixer and detector operates 1 to 26GHz. The Spice parameter is shown in table 3. The simulation result of HSCH diodes shows in figure 6.

Table 3: SPICE parameters for HSCH-9161, HSCH-9101 and HSCH-5316

Parameter	Units	HSCH 9161	HSCH 9101	HSCH 5316
BV (Vbr)	V	10	5	5
CJO	pF	0.030	0.04	0.2
EG	eV	1.42	1.43	0.69
IBV	A	10E-12	10E-5	10E-5
IS	A	12E-6	1.6E-13	3E-10
N	-	1.2	1.2	1.08
RS	ohms	50	5	5
PB (Vj)	V	0.26	0.65	0.65
PT (XTI)	-	2	2	2
M	-	0.5	0.5	0.5

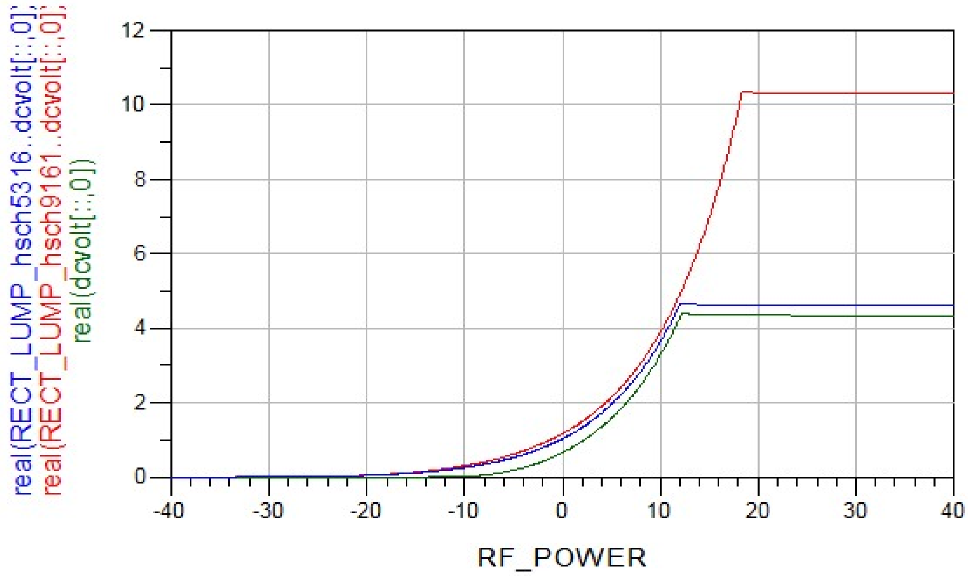

Figure 6. DC output voltage verses RF input power for voltage doubler rectifier circuit using HSCH-9161, HSCH-5316 and HSCH-9101 package

The simulation in figure 6 shows HSCH-9161 gets 10.25 V at 18 dBm, follows by HSCH -5316 package reads 4.56 V and HSCH-9101 gets 4.38 at 12 dBm. While, at 0 dBm, HSCH-9161 package gets 1.05 V, HSCH-5316 gets 0.97 V and HSCH-9101 gets 0.56V.

Comparing figure 5 and figure 6, the maximum output voltage produce is 10.25V at 18 dBm and remain constant even though the input signal achieves 40 dBm.

3. Results And Discussion

Then, the rectifier voltage attained from the simulation at the load of 1G ohm resistor shows in table 4. The result displays the value of voltage against RF Power in Schottky Diode of HSMS-2820, HSMS-2860 and HSMS-2850. The highest voltage at 20 dBm is diode HSMS 2820 which is 8.689V. While, the lowest at 20 dBm is HSMS 2850 with 3.667V. HSMS-2860 leads the output voltage from -10 dBm until 16 dBm input signals, then remain stagnant after reach 15dBm.

Table 4: Output Voltage for HSMS Diode

RF power	Input voltage	HSMS 2820	HSMS 2860	HSMS 2850
-10	70.711 mV	0.155V	0.297V	0.291V

-5	125.743 mV	0.135V	0.539V	0.589V
0	223.607 mV	0.632V	1.129V	1.128V
5	0.398 V	1.333V	2.093V	2.098V
10	0.707 V	2.821V	3.824V	3.673V
15	1.257 V	5.682V	6.794V	3.669V
20	2.236V	8.689V	6.778V	3.667V

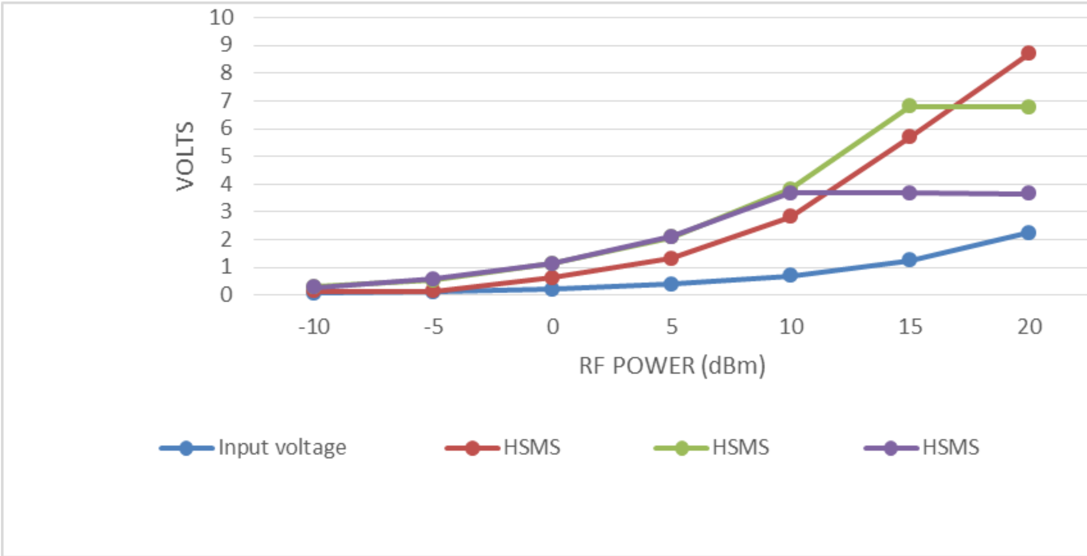

Figure 7. Output voltage for voltage doubler rectifier circuit using HSMS-2820, HSMS-2860 and HSMS-2850 package compared to input power

The output for HSCH-9161, HSCH-5316 and HSCH-9101 package show in figure 8 and table 5. At 0 dBm, all diode package gets the output voltage. The highest goes to HSCH-9161 gets 1.107 V and the lowest goes to HSCH9101 gets 0.662V, from the figure 8, obviously the HSCH-9161 leads the output reading by showing the exponential line of output voltage.

For HSCH diode, the highest output voltage at 20 dBm is HSCH-9161 with 10.327V while the lower and lowest for HSCH diode is HSCH-5316 and HSCH-9101 respectively. Thus, the best diode for HSCH diode is HSCH -9161.

Table 5: Output Voltage for HSCH Diode

RF power	Input voltage	HSCH 9161	HSCH 9101	HSCH 5316
-10	70.711 mV	0.036V	0.019V	0.257V
-5	125.743 mV	0.617V	0.187V	0.527V
0	223.607 mV	1.170V	0.662V	1.032V
5	0.398 V	2.154V	1.591V	1.962V
10	0.707 V	3.904V	3.298V	3.659V
15	1.257 V	7.017V	4.355V	4.639V
20	2.236V	10.327V	4.346V	4.635V

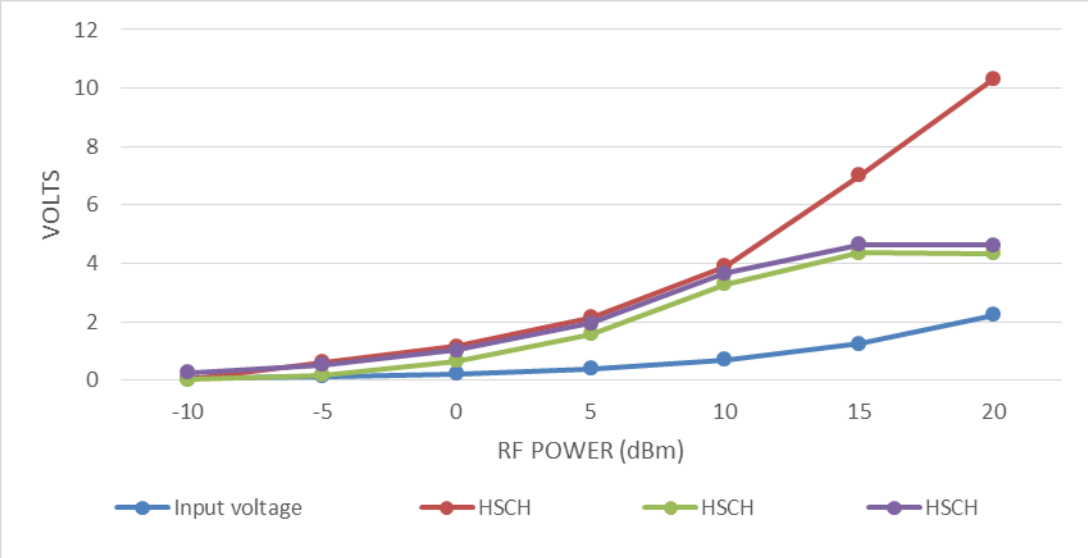

Figure 8. Output voltage for voltage doubler rectifier circuit using HSCH-9161, HSCH-5316 and HSCH-9101 package compared to input power

4. Conclusion

Finally, the comparison of percentage of conversion efficiency of simulation using ADS had been visualized in graphical to ease an understanding. To plot the data, figure 9 show the efficiency percentage for input power from 10dBm to 20 dBm. The highest efficiency of simulation is 31.16% at 15 dBm for HSCH-9161 Schottky diodes package.

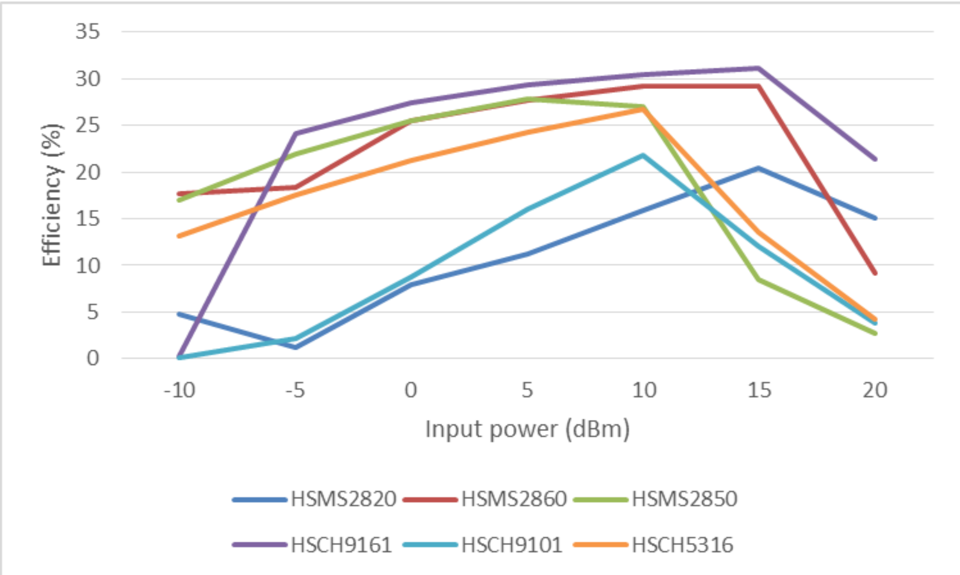

Figure 9. Efficiency of the proposed rectifier verses input RF power.

The figure 9 shows all diode packages give significant output in getting the output voltage at low input power. At 0 dBm input power, the lowest efficiency is HSMS-2820 package gets 8.76% or 0.632V output voltage. The highest efficiency at 0 dBm is HSCH-9161 gets 27.38% or 1.032V.

Since the can rectify at low input power starts at 0 dBm input power, means this circuit able to be used with lowpower wireless sensor networks application such as agriculture, target tracking, emergency relief and temperature sensor. This design also eases and new of design since it has used microstrip line elements instead of conventional one. Another benefit is this design has support green technology since it has been used RF energy which is one of the ambient energy resources.

The choices of diode are considered a requirement to increase the rectifier efficiency, but there are lots of requirement need to be considered in increasing the percentage of efficiency in rectifier circuit such as the number of rectifier stage, the load impedance, the antenna return loss and also the microstrip substrates.

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