DESIGN AND ANALYSIS OF A NOVEL MULTIBAND RECTIFYING CIRCUIT FOR RF ENERGY HARVESTING

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Abstract

Radio frequency energy harvesting has become an interesting research area in the recent years. In this paper the layout for execution of multiband rectifier circuit has been presented. Here we have implemented the rectifier circuit at 1.9 GHz. -10 dBm, 0 dBm, 10 dBm input power are taken for the design and simulation of the rectifier circuit. Variation of input power with respect to DC voltage is shown at resonant frequency 1.83GHz, 4.37 GHz and 5.53 GHz frequency. Alterations of Efficiency (%) with respect to input power (dBm) is presented when load 10kOhm,1Kohm,5Kohm with resonant frequency 1.83GHz,4.37GHz and 5.53GHz Change of DC output voltage with respect to load is depicted when input power -10dBm and10dBm and frequency 1.83GHz,4.37GHz and 5.53GHz. Here we have shown the variation of Efficiency with respect to load when input power -10dBm, 0dBm and resonant frequency 1.83GHz, 4.37GHz and 5. 53GHz.It is explained the variation of output DC voltage with respect to frequency when input power -10dBm and 0dBm and load 1kOhm, 5Kohm and 10Kohm. In this paper we have also presented the variation of real and imaginary part of input impedance (Zin) with respect to Frequency (GHz) when input power=-10 dBm and 0dBm and load =10Kohm. Here the authors have shown the change of return loss S (1, 1) (dB) with respect to frequency when input power -10dBm and load 10KOhm.

Keywords:

Rectifier, Return Loss, RF Energy Harvesting

1. INTRODUCTION

With the fast evolution of wireless sensor networks (WSNs), the linked RF energy harvesting technique is getting more and more recognition [1]-[3]. Nowadays, maximum sensors are battery-operated devices. Although, the substitution of the battery is normally hard and tedious. Ambient RF energy harvesting technique is regarded as a fascinating solution to increase the device's battery life or even acquire battery-free sensors [4]-[5]. Just now, there is a growing attentiveness in harvesting of medium energy obtainable in different frequency bands. Energy harvesters can be used as power sources for small devices and they comprise mostly of an antenna that catches RF energy and the antenna is connected to a rectifier via matching circuit. The rectifier, which turns the RF electromagnetic power into direct current (dc) power, is a essential part of a distinctive RF energy harvesting system. The RF-to-dc power conversion efficiency is the principal specification to assess the execution of rectifying circuits. To understand high efficiency, numerous designs have so far been explored, namely single-band, multi-band and broadband rectifiers. Normally, single-band rectifiers can be worked to understand high efficiency comfortably. Although, the accumulated RF energy of this perspective is low and the output voltage is habitually inadequate to turn on the low power devices (such as sensor circuitry). Broadband rectifiers can be employed to build more output power but the compromise might be the decreased peak efficiency. Consequently, multi-band rectifiers are fitting prospect for surroundings RF energy harvesting application. The rectifier circuit is employed to transform the received AC signal into a DC signal and it generally comprises of Schottky diodes that have impedances dependent on frequency as well as the input RF power. The matching circuit is employed to match the input impedance of the rectifier to that of the antenna to obtain maximum power transfer. There has been substantial research on energy harvesting systems handling on single band [6]-[11]. In [8], an antenna array is presented for harvesting at 915 MHz and its gain was 10.67 dBi. In [9], a rectifier antenna is presented for harvesting of the energy at 2.45 GHz to catch WiFi signals. As the medium energy available in single band is extremely little and not enough for actual implementations, more research is accomplished on dual-band and multi-band harvesting circuits. Normally, in multi-band systems more energy can be catched from numerous low-density power sources. There was a number of dual-band harvesting circuits which were presented in literature for divergent frequency bands of GSM-1800 and UMTS-2100 in [12], GSM-900 and GSM-1800 in [13], [14] and 915 MHz and 2.45 GHz in [15]. Those harvesters which are plotted by means of dual-band matching circuits formed as of short/open stubs and/or lumped elements. A number of additional research has been finished on multiband harvesters to catch extra energy. In multiband harvesting, the circuit normally enriches problematic and demanding in design. Two general methods to plot multi-band harvesting circuits can be accepted. Primary is to plot different rectifiers with single matching network for individual rectifier then merge the DC outputs of the rectifiers in combination. The second design method is formed on single rectifying circuit attached to a multiband matching circuit that can be complexed and demanding in design. Broadband antennas [16], [17] and multiband rectifier circuits [18]-[21] have been presented in literature for RF energy scavenging. A tri-band rectifier for the purpose of energy harvesting at the frequencies of 1050 MHz, 2050 MHz and 2600 MHz is presented in [18]. In [19] a four-band harvester is plotted at GSM 900, GSM 1800, UMTS and WiFi bands. In [20], a tetra-band rectifier antenna is presented to harvest RF energy and it works at GSM 900, GSM 1800, UMTS and Wi-Fi. Furthermore, a six band harvester is presented for RF energy harvesting in [21]. From the literature review it is mainly detected on single band and multiband harvesters that existing matching circuits are plotted throughout narrow bands and do not comprise the entire standard allocated frequency bands. Therefore, less energy is catched with those narrow band matching networks. Although, the multiband rectifier design is very demanding owing to its nonlinear feature of the rectifying device. This nonlinearity shows to the input impedance of the rectifier changes as a basis of frequency, input power level, and load impedance. So far, merely a small number of investigations have been depicted on multi-band rectifier design. In [22], a rectifier was introduced and it was working at 0.915 GHz and 2.45

GHz respectively. When the input power is 14.6 dBm, the peak RF-to-dc PCEs are 77.2% and 73.5% at 0.915 GHz and 2.45 GHz, respectively. Lumped elements were used to obtain a dual-band impedance matching network and involved in rectifier design [23]. Although, the lumped elements are normally obtainable only for a little variety of values and lossy at high frequency bands, which lower the RF-to-dc PCE. A dual-band (2.45 GHz and 5.8 GHz) rectifier with 10 dBm input power level was presented in [24]. Its highest power conversion efficiencies at the two desired operating bands were 66.8% and 51.5%, respectively. In [25], a triple-band differential rectifier was introduced. Even so, the triple-band impedance matching network was very complex. A four-band rectifier was introduced in [26] and its PCEs are 47.8%, 33.5%, 49.7% and 36.2% at the frequencies of 0.89 GHz, 1.27GHz, 2.02GHz and 2.38GHz, respectively. A quad-band (1.3 GHz, 1.7 GHz, 2.4 GHz, and 3.6 GHz) rectifier having its impedance matching network by four T-type networks was introduced in [27]. In this case, each T-type sub-network was employed to execute impedance matching at one operating frequency.

This paper is concentrating on designing a concurrent multi band rectifier with high conversion efficiency for RF energy harvesting. Rectifier is the principal element in a power supply design for RF energy harvesting. In this paper, a triple-band rectifier design is presented for the surrounding RF energy harvesting. Given the growing demand of Wireless Sensor Nodes (WSN) for the Internet of Things (IoT) application, a multi-band rectifier design provides a very good choice as power supply. The multiband mode has the benefits of reaching higher RF-to-DC conversion efficiency than the normal single band mode, while retaining the overall size of the circuit compact. The circuit works at three frequency bands 1.83GHz, 4.37 GHz and 5.53 GHz frequency, and is capable to attain high RF-to-DC conversion efficiency, reaching 42.65% at input power of -10 dBm.

2. RECTIFIER DESIGN

The task of the rectifier is to directly change microwave RF energy into DC electrical energy. Schottky Diodes (SMS7630-079LF) are preferred as if at all possible low forward bias voltage of 0.15 V with fast switching at high frequencies which is necessarily acceptable for extensively little RF input power functions. Here we have plotted the rectifier with matching network worked at 1.9 GHz shown in Fig.1. DC output voltage of rectifiers relies on different features for instance width, length of layer etc. The circuit is etched on the substrate having Dielectric constant = 3.55 and h=0.813mm, T=0.017mm. The circuit was considered and optimized utilizing Advance Design System (ADS). In order to enhance the RF-DC conversion efficiency, three blocks that act as matching and filtering sections should be attached between the antenna and the rectifier and between the rectifier and the load. The receiving antenna catches the incident RF power and the diode based converter altered it into DC power. At the output, a DC filter (low pass filter) is employed to decrease the harmonic components. An input matching network is employed to match the rectifier impedance to the antenna impedance. The Fig.2 shows the 3D view of the presented rectifier.

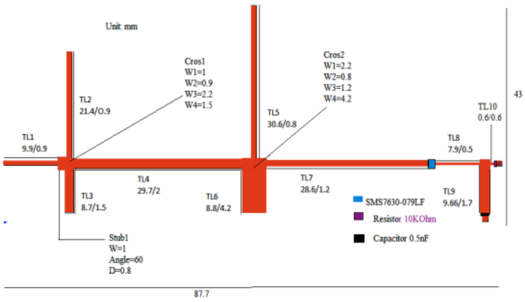

Fig.1. Layout of the Rectifier Circuit

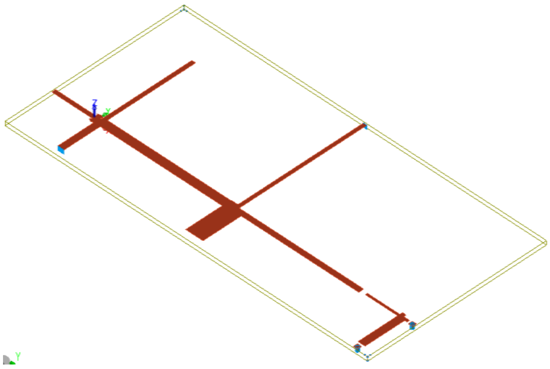

Fig.2. 3D view of Rectifier Circuit

3. RESULTS AND DISCUSSION

In Table.1, we have shown the Variation of input power vs. output dc voltage in different frequency 1.83GHz, 4.37GHz and 5.53GHz with load10kohm. The Table.1 represents the variation of Output DC voltage (Volt) with respect to input power (dBm) when load 10kOhm and also represents the output of DC voltage at different frequency level. At 1.83GHz frequency, we obtained the output DC voltages 0.529V, 0.925V, and 0.954V with input power -10dBm, 0dBm and 10dBm respectively and at frequency 4.37GHz we obtained the output voltages 0.344V, 0.846V and 0.954Vwith input power-10dBm, 0dBm and 10dBm respectively and at frequency 5.53GHz we obtained the output voltages 0.113V, 0.475V, 0.954V with input power -10dBm, 0dBm and 10dBm respectively. From Table.1 it is revealed that maximum output DC Voltage is obtained at 1.83 GHz frequency and 10dBm input power when load is 10KOhm. From Table.1, it is clear that we can get the output DC voltage at any change of input power.

Table.1. Variation of input power vs. output dc voltage in different frequency 1.83GHz, 4.37GHz and 5.53GHz with load=10kohm

Input Power (dBm)	**Output DC Volt when Frequency**			**Remarks**
	4.37 GHz	**1.83 GHz**	**5.53 GHz**	
-10	0.344V	0.529V	0.113 V	load= 10kΩ
-9	0.380V	0.589V	0.132 V	
-8	0.481V	0.654V	0.153 V	
-7	0.459V	0.725 V	0.178 V	
-6	0.503V	0.802 V	0.206 V	

-5	0.550V	0.886 V	0.239 V	
-4	0.600V	0.935 V	0.275 V	
-3	0.655V	0.945 V	0.317 V	
-2	0.714V	0.949 V	0.364 V	
-1	0.777V	0.951 V	0.416 V	
0	0.846V	0.952 V	0.475 V	
10	0.954 V	0.955 V	0.954 V	

Table 2. Variation of Efficiency (%) vs. input power (dBm) in difference frequency 1.83GHz,4.37GHz, and 5.53GHz with different input power-10dB and 0dB and when load=10kohm

Input Power (dBm)	Efficiency (%) when freq=4.37 GHz	Efficiency (%) when freq=1.83 GHz	Efficiency (%) when freq=5.53 GHz	Remark
-10	17.11%	42.65%	01.27%	load= 10kΩ
-9	17.29%	43.58%	01.38%	
-8	17.38%	44.39%	01.48%	
-7	17.38%	45.08%	01.59%	
-6	17.32%	45.67%	01.70%	
-5	17.19%	45.97%	01.80%	
-4	17.01%	37.52%	01.91%	
-3	16.80%	26.60%	02.01%	
-2	16.54%	19.44%	02.10%	
-1	16.26%	14.68%	02.19%	
0	15.96%	11.36%	02.27%	
10	01.61%	02.09%	00.94%	

The Table.2 depicts the Variation of Efficiency (%) vs. input power (dBm) in different frequency 1.83 GHz, 4.37 GHz, and 5.53 GHz with different input power -10dBm and 0dBm and when load 10kohm. The Table.2 represents the variation of Efficiency (%) with respect to input power (dBm) when load 10 KOhm and frequency 1.83GHz, 4.37GHz and 5.53GHz. At 1.83 GHz frequency, we obtained the Efficiency 42.65%, 11.36%with input power -10dBm, 0dBm respectively and at 4.37 GHz frequency, we obtained the Efficiency 17.11%, 15.69% with input power -10dBm, 0dBm respectively and At 5.53 GHz frequency, we obtained the Efficiency 1.27%, 2.27% and with input power -10dBm, 0dBm respectively. From Table.2, it is revealed that maximum Efficiency 45.97% is obtained at 1.83 GHz frequency and -5dBm input power when load is 10KOhm.

Table.3. Variation output dc voltage (V) vs. load in different frequency 1.83GHz, 4.37GHz and 5.53GHz with different input powers=-10dBm and 0dBm

Load KΩ	Input Power=-10dBm			Input Power= 0dBm		
	1.83 GHz	4.37 GHz	5.53 GHz	1.83 GHz	4.37 GHz	5.53 GHz
	Output DC Voltage (V)					
1.00	0.198V	0.140V	0.055 V	0.727 V	0.555 V	0.311 V
1.50	0.260V	0.191V	0.067 V	0.903 V	0.651 V	0.358 V
2.00	0.311V	0.226V	0.075 V	0.924 V	0.703 V	0.386 V
2.50	0.353V	0.251V	0.081 V	0.932 V	0.735 V	0.404 V
3.00	0.385V	0.269V	0.086 V	0.937 V	0.758 V	0.417 V
3.50	0.410 V	0.282V	0.089 V	0.940 V	0.775 V	0.427 V
4.00	0.430V	0.293V	0.093 V	0.943 V	0.787 V	0.435 V
4.50	0.446V	0.301V	0.096 V	0.944 V	0.797 V	0.441 V
5.00	0.460V	0.308V	0.098 V	0.946 V	0.806 V	0.446 V
10.00	0.529V	0.344V	0.113 V	0.952 V	0.846 V	0.475 V

The Table.3 represent Variation of output DC voltage (V) vs. load in different frequency 1.83GHz, 4.37GHz and 5.53GHz with different input powers -10dBm and 0dBm. At 1.83 GHz frequency, we obtained the output DC voltages 0.198V, 0.460V, 0.529V with varying load of 1KOhm, 5KOhm and 10KOhm respectively when input power -10dBm and when input power 0dBm then output DC voltages 0.727V, 0.946V, and 0.952V with varying load 1 KOhm, 5 KOhm and 10 KOhm respectively. At the frequency 4.37 GHz we obtained output DC voltages 0.140V, 0.308V and 0.344V with load 1 KOhm, 5 KOhm and 10 KOhm respectively when input power -10dBm and when input power is 0dBm we obtained output DC voltages 0.555V, 0.806V and 0.846V with load 1KOhm, 5KOhm and 10KOhm respectively. At the frequency 5.53GHz we obtained output DC voltages 0.055V, 0.098V, 0.113V with load 1KOhm, 5KOhm and 10KOhm respectively when input power -10dBm and when input power is 0 dBm we obtained output DC voltages 0.311V, 0.446V, 0.475Vwith load 1KOhm, 5KOhm and 10KOhm respectively.

Table.4. Variation of Efficiency (%) vs. load in different frequency 1.83GHz, 4.37GHz and 5.53 GHz and different input power=-10dBm and 0dBm

Load KΩ	Input Power=-10dBm			Input Power= 0dBm		
	1.83 GHz	4.37 GHz	5.53 GHz	1.83 GHz	4.37 GHz	5.53 GHz
	Efficiency (%)					
1.00	45.57%	23.72%	03.03%	65.65%	44.44%	09.69%
1.50	48.94%	28.63%	02.97%	65.17%	43.27%	08.55%
2.00	51.48%	30.30%	02.80%	51.85%	40.07%	07.44%
2.50	53.84%	30.24%	02.61%	42.53%	36.85%	06.53%
3.00	54.71%	29.45%	02.44%	35.99%	33.97%	05.80%
3.50	54.71%	28.38%	02.29%	31.18%	31.46%	05.21%
4.00	54.23%	27.22%	02.15%	27.50%	29.27%	04.73%
4.50	53.47%	26.07%	02.03%	24.59%	27.36%	04.33%
5.00	52.55%	24.96%	01.92%	22.24%	25.68%	03.99%
10.00	42.65%	17.11%	01.27%	11.36%	15.96%	02.27%

In Table.4 we have shown the Variation of Efficiency (%) vs. load in different frequency 1.83GHz, 4.37GHz and 5.53GHz and different input power -10dBm and 0dBm. At 1.83 GHz frequency, we obtained the Efficiencies of 45.57%, 52.55%, 42.65% with load 1KOhm, 5KOhm and 10KOhm respectively. Similarly, when input power is -10dBm and at same frequency we obtained the Efficiencies of 65.65%, 22.24%, 11.36% with load 1KOhm, 5KOhm and 10KOhm respectively when input power is 0dBm. At 4.37 GHz frequency, we obtained the Efficiencies of 23.72%, 24.96% and 17.11% with load 1KOhm, 5KOhm and 10KOhm respectively when input power is -10dBm and at same frequency we obtained the Efficiencies of 44.44%, 25.68%, 15.96% with load 1KOhm, 5KOhm and 10KOhm respectively when input power is 0dBm. At 5.53 GHz frequency, we obtained the Efficiencies of 3.03%, 1.92% and 1.27% with load 1KOhm, 5KOhm and 10KOhm respectively when input power is -10dBm and at same frequency we obtained the Efficiencies of 9.69%, 3.99%, 2.27% with load 1KOhm, 5KOhm and 10KOhm respectively when input power is 0dBm. It is revealed that maximum Efficiency 65.65% is obtained at 1.83 GHz frequency and -0dBm input power when load is 1KOhm.

Table.5. Variation of output dc voltage (V) vs. Frequency when load=1KOhm, 5kOhm and 10kOhm and input power=-10dBm and 0dBm

Freq.	**Input Power=-10dBm**			**Input Power= 0dBm**		
	1kΩ	**5kΩ**	**10kΩ**	**1kΩ**	**5kΩ**	**10kΩ**
	Output DC Voltage(V)					
1.81	0.192V	0.330V	0.364V	0.679 V	0.933 V	0.946 V
1.82	0.200 V	0.391 V	0.437V	0.726 V	0.943 V	0.951 V
1.83	0.198 V	0.460 V	0.529 V	0.727 V	0.946 V	0.952 V
1.84	0.193 V	0.490 V	0.621 V	0.707 V	0.946 V	0.952 V
1.90	0.054 V	0.096 V	0.112 V	0.349 V	0.532 V	0.584 V
3.09	0.029 V	0.056 V	0.067 V	0.225 V	0.315 V	0.341 V
4.35	0.136 V	0.240 V	0.263 V	0.466 V	0.636 V	0.669 V
4.36	0.143 V	0.274 V	0.302 V	0.512 V	0.717 V	0.752 V
4.37	0.140 V	0.308 V	0.344 V	0.555 V	0.806 V	0.846 V
5.52	0.013 V	0.030 V	0.038 V	0.338 V	0.456 V	0.482 V
5.53	0.011 V	0.026 V	0.032 V	0.311 V	0.446 V	0.477 V
5.54	0.009 V	0.022 V	0.028 V	0.270 V	0.360 V	0.386 V

The Table.5 represent the variation of output DC voltage with respect to frequency when input power -10dBm and 0dBm and load 1KOhm, 5kOhm and 10kOhm respectively. We obtained the DC voltages 0.952V, 0.846V, 0.477V when input power 0dBm and load 10Kohm and we obtained the DC voltages 0.529V, 0.308V, 0.026V when input power is -10dBm and load 10kOhm. We obtained the DC voltages 0.727V, 0.555V, and 0.311V, when input power 0dBm and load 1KOhm.

Table.6. Variation of Efficiency (%) vs. Frequency with different load=1Kohm, 5Kohm, and 10Kohm and different input powers=-10dBm and 0dBm

Freq.	**Input Power=-10dBm**			**Input Power= 0dBm**		
	1kΩ	**5kΩ**	**10kΩ**	**1kΩ**	**5kΩ**	**10kΩ**
	Efficiency (%)					
1.81	47.04%	45.47%	35.43%	67.85%	41.29%	22.36%
1.82	46.47%	49.42%	38.99%	68.25%	28.08%	14.54%
1.83	45.57%	52.55%	42.65%	65.65%	22.24%	11.36%
1.84	44.24%	48.74%	44.20%	64.23%	20.54%	10.41%
1.90	16.75%	13.85%	10.11%	46.68%	33.47%	22.91%
3.09	00.87%	00.67%	00.47%	5.23%	02.10%	01.23%
4.35	25.01%	18.58%	12.26%	36.95%	18.84%	11.56%
4.36	25.71%	21.90%	14.68%	41.13%	22.08%	13.59%
4.37	22.72%	24.96%	17.11%	44.45%	25.68%	15.96%
5.52	03.77%	02.42%	01.59%	12.16%	04.55%	02.56%
5.53	03.03%	01.92%	01.29%	09.69%	03.99%	02.27%
5.54	02.98%	01.68%	01.10%	07.47%	02.72%	01.56%

The Table.6 illustrate the Variation of Efficiency (%) vs. Frequency with different load 1Kohm, 5Kohm, and 10Kohm and different input powers -10dBm and 0dBm. We obtained the Efficiencies of 45.57%, 22.27% and 3.03% with frequencies of 1.83GHz, 4.37GHz and 5.53GHz respectively when input power is -10dBm and Load 1Kohm. Similarly, we obtained the Efficiencies of 65.65%, 44.45% and 9.69% with frequencies of 1.83GHz, 4.37GHz and 5.53GHz respectively when input power is 0dBm and Load 1Kohm. Also we get the maximum efficiency 68.25% when input power is 0dBm and frequency 1.83GHz.

Table.7. Variation of Real and Imaginary part vs. Frequency when load=10KOhm and input power=-10dBm

Freq (GHz)	**Real Part (Z_{in}) Ω**	**Imaginary Part (Z_{in}) (X)**	**Remarks**
1.81	17.95	70.69	When load =10KΩ and Input power=-10dBm
1.82	30.47	77.23	
1.83	57.65	77.16	
1.84	90.85	31.87	
1.90	2.60	37.77	
3.09	31.24	6.35	
4.35	15.73	35.45	
4.36	20.11	29.21	
4.37	26.37	42.21	
5.52	37.25	-16.38	
5.53	50.72	2.47	
5.54	72.78	24.16	

Variation of real part of input impedance (Z_{in}) and also Variation of imaginary part of input impedance imag (Z_{in}) with respect to Frequency (GHz) is shown in Table.7. It is noticed when input power is -10dBm and load 10Kohm, perfect matching occurs at 5.53GHz frequency and then Real part and imaginary part will be 50.72 Ohm and 2.47.

The Fig.10 depicts the Variation of Reflection Coefficient with respect to Frequency when load is 10KOhm and input power -10dBm. Here three resonant frequencies 1.83GHz, 4.37GHz and 5.53GHz are obtained from Fig.10. Variation of return loss S_{11} (dB) with respect to frequency is shown in Fig.10 when input power -10dBm and load 10 KOhm. -19.30dB, -14.52dB, and -23.57dB return losses are obtained at frequencies of 1.83GHz, 4.37GHz and 5.53GHz for our proposed rectifier.

4. CONCLUSION

Accomplishment of the multiband radio frequency energy harvesting is performed here. Impedance matching is realized throughout the entire allotted standard frequency bands employing microstrip shunt and radial stubs. The output DC voltage is simulated for single-tone input signals with input power levels from -10 dBm to +10 dBm and the outcomes appeared increase in output voltage when increasing the input power. The RF-DC conversion efficiency is simulated over frequency for different input power levels (-10 dBm, 0 dBm and +10 dBm). The simulations manifested that higher efficiency is acquired with larger input power level. In this paper, an extremely efficient triple band rectifying circuit has been presented and plotted for surrounding RF energy harvesting application, derived from the power spectrum investigation. The multiband mode uses the highly congested frequency bands of 1.83 GHz, 4.37 GHz, and 5.53GHz. The circuit is extremely efficient at low input power range, which is proved via real-life testing. The result from this paper supplies a practical battery-less resolution for the autonomous wireless sensor network.

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