

A 900-2400 MHz AC-DC Rectifier Circuit for Radio Frequency Energy Harvesting

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Abstract. This paper presents a 900-2400 MHz AC-DC rectifier circuit for radio frequency (RF) energy harvesting. The proposed circuit consists of a rectifier and charge pump. The multi-stage NMOS RF-DC rectifier circuit is designed to convert the AC signal to DC signal while the charge pump helps to amplify the DC amplitude. The proposed circuits are designed and simulated using CMOS 0.13- μm technology. The simulation results show that the proposed circuit able to produce 2.9 V DC voltage at 10 k Ω load with an input voltage of 150 mV.

1 Introduction

The growing of modern technologies interests people to have their own gadgets. Mobile phones, tablets, laptops and others bring a lot of advantages of their usefulness. The increment demand of wireless application devices especially mobile phones and computers shows that the important of wireless application in the whole world. The usage of these devices however required continuous supply or battery life in order to maintain the operating system. Without a doubt, the batteries have a limited life time and hazardous chemicals concern to safety matters.

Thus, the study of power energy harvesting now become an important topic in order to help the user to use the devices for a long period without worrying about the battery life. The idea is to make the devices to harvest the available surrounding power and transfer to the electrical power which can be stored in the battery. There are a lot of power energy sources lies around us such as radio frequency (RF), vibration, solar, wind and thermal [1-5]. Up to date, the present energy harvesting only generates small electrical power, which depends on technique and concept used in the system.

Among all energy harvest sources, the RF is available and easily found at any places every time. RF is an electrical oscillation, with a frequency ranging about from 3 KHz to 300 GHz and carrying an alternating current. With this concept, device like mobile phones can be used to call or access the internet connection while charging the battery at the same time.

Fig. 1 shows the block diagram of the proposed RF energy harvesting system. Basically in the system, the RF signal is received by an antenna. However, the antenna is not a part of this work, thus antenna design is neglected. The RF signal that went through antenna will be transferred to the rectifier block. In this process, the RF signal will be converted to DC

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voltage. The RF-DC converter should have the availability to operate at low input power levels and have a high efficiency to minimize the power loss. The DC voltage then goes to charge pump block. The charge pump is a DC-DC converter that will amplify the low input voltage to the desired output voltage. The output voltage, which should be in smooth and saturated in DC then will be stored in the capacitor. In real application, the DC voltage will be directly charge battery cell with the specific load and capacitance.

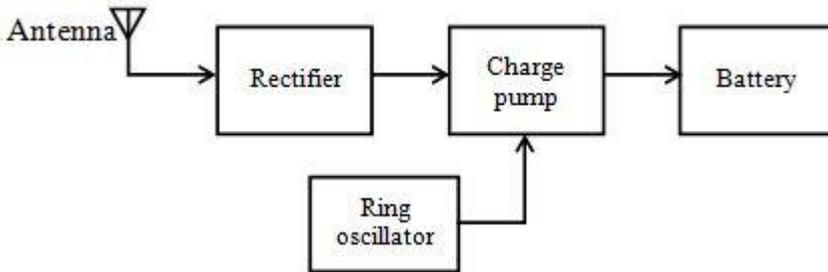


Fig. 1. Block diagram of RF energy harvesting system.

In this proposed design, the rectifier's operation is based on charging and discharging of the capacitors. Previous works mainly used the Schottky diode in order to rectify the signal [6], but the usage of diode only can be applied when the AC voltage is higher than the forward voltage. Somehow the amplitude of RF is most likely not reaching 500mV, which much lower than Schottky's forward voltage. Therefore the Schottky diode has a limitation and the study thereafter is focusing on the usage of a CMOS. Several proposed designs had been simulated before and the results proved that the usage of CMOS have much advantages compared to Schottky diode [7-13]. In this paper, selected CMOS 0.13 μm technology is proposed and implemented.

2 Methodology

2.1 Circuit implementation

2.1.1 Rectifier

A multi-stage NMOS RF-DC converter is used as the rectifier unit in the power conversion circuit. The circuit rectifies the AC input in both positive and negative cycle. As shown in Figure 2, each stage consists of NMOS transistors, a coupling capacitor and multiplying capacitor. The type of transistors and value of capacitors are selected based on the ability to convert as multi-range of RF frequency.

During the negative half cycle, drain-to-source voltage is in a negative value; making M1 is in a reverse biased condition and it is turned off. While M2 is a forward biased and it is turned on. This allows the current going through M2 and charge in C2. As the negative cycle ends, M1 becomes forward biased and turned on, allowing the current from C2 to charge through Cc. As more stages cascaded, each capacitor charged will provide a bias voltage, therefore increasing the corresponding charged current at the end until the AC signal is saturated and the ripples is minimal.

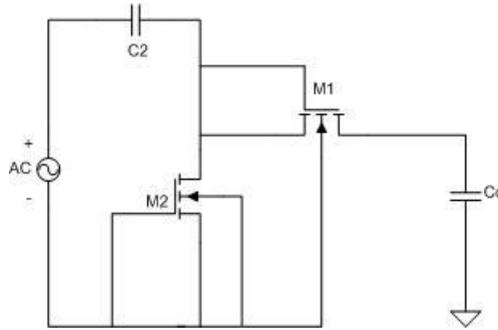


Fig. 2. NMOS RF-DC converter.

2.1.2 Charge pump

The output from rectifier is assumed to contain a small DC voltage and here come the usage of charge pump. The objective of charge pump is same as transformer, but with the external cycle pulse as a biasing. Charge pump is DC-DC converter that uses the capacitors as energy storage element to create either higher or lower voltage power source. In this design, the charge pump used the pulse generated by ring oscillator to generate the charge transfer. The pumping gain is determined by the pulse amplitude and the pumping capacitor charge. Fig. 3 shows the basic schematic of proposed charge pump used in energy harvesting system. The ring oscillator will generate two signals, θ_1 and θ_2 where the signals have same 50% duty cycle and frequency but with different phases. The small DC voltage from rectifier circuit will be biased by these pulses. The frequency of the pulse should be considered to minimize the external power resources. As the DC input voltage from rectifier increases, the current needed to bias the voltage will be saturated hence the efficiency of the charge pump circuit will be increased. The circuit also has to be cascaded so the output voltage can be optimized as much as possible.

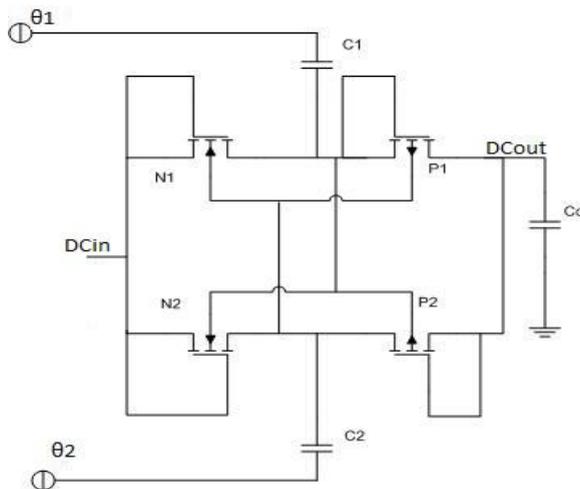


Fig. 3. Schematic of charge pump (TBC).

3 Results and discussion

Table 1 shows the data of proposed rectifier output voltage at different frequencies. The simulation is done using variation of AC input voltage, ranging from 50 mV to 500 mV with two frequencies, 900 MHz and 2400 MHz. Figure 4 shows the rectifier output voltage versus input voltage. As can be seen in Table 1 and Figure4, the rectifier circuit reacts to both input frequencies with the same output. It means the proposed rectifier design has the ability to rectify wide frequency from 900 MHz to 2400 MHz.

Table 1. Proposed rectifier output voltage with different input frequencies.

Vin (mV)	Vout (mV)	
	Freq=900 MHz	Freq=2.4 GHz
50	14.44	14.71
100	57.79	58.21
150	130.46	130.11
200	235.62	234.42
250	361.3	362.48
300	495.94	492.04
350	641.32	637.32
400	789.76	788.05
450	944.60	937.06
500	1102.4	1098.6

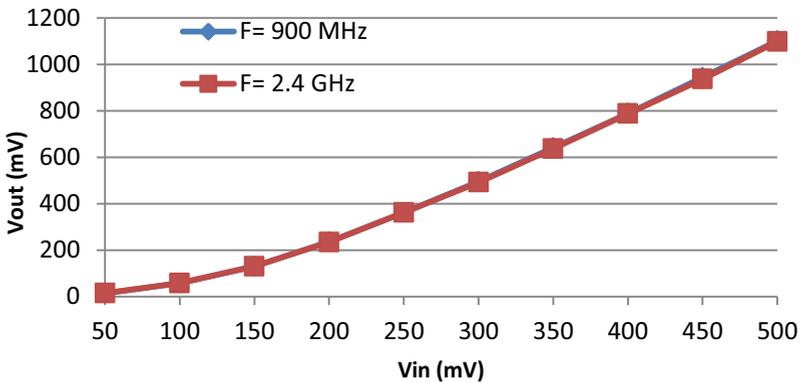


Fig. 4. Rectifier output voltage vs input voltage (variant input frequencies).

Table 2 shows that the proposed rectifier output voltage at different loads. The simulation is done by using different AC input voltages, ranging from 50 mV to 500 mV. The resistance loads to be tested are 10 kΩ, 50 kΩ and 100 kΩ. Table 2 and Figure5 proved that the output voltage is proportional to the value of resistance load. Fig. 5 shows the rectifier output voltage versus input voltage. It is observed that, the output voltage increased when the load resistance increases from 10 kΩ to 100 kΩ.

Table 2. Proposed rectifier output voltage with different output load.

Vin (mV)	Vout (mV)		
	Rload = 10 kΩ	Rload = 50 kΩ	Rload = 100 kΩ
50	4.50	11.63	14.71
100	17.20	45.89	58.21
150	38.07	101.98	130.11
200	67.16	181.14	234.42
250	102.40	275.98	362.48
300	140.18	380.27	492.04
350	181.18	489.60	637.32
400	225.01	605.02	788.05
450	271.97	721.40	937.06
500	317.86	844.35	1098.6

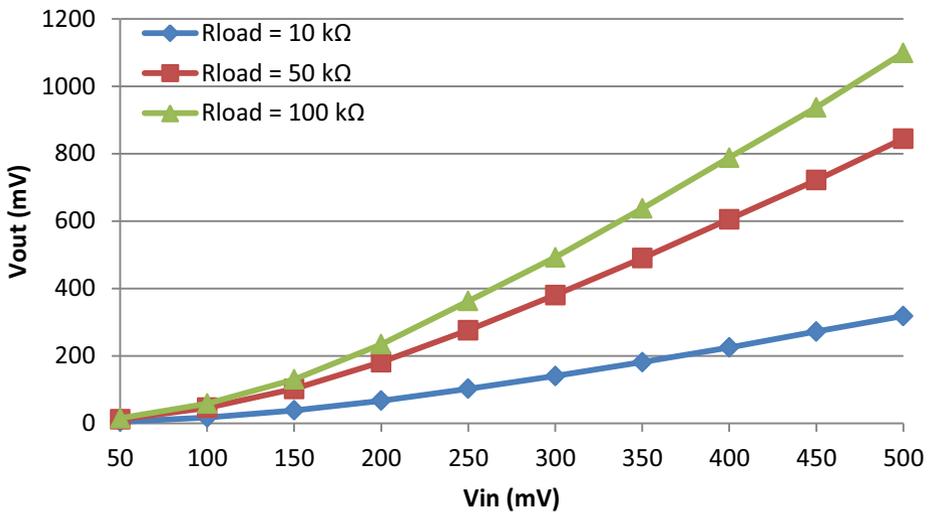


Fig. 5. Rectifier output voltage vs input voltage (variant output load).

Table 2 and Figure 5 proved that the output voltage is proportional to value of resistance load. We can see from the graph that by using Rload=100kΩ the output voltage is produced compared to Rload=10kΩ.

Table 3 shows the proposed charge pump output voltage at different loads. The data is taken using different resistance loads, 10 kΩ, 50 kΩ and 100 kΩ while the DC input voltages are 100 mV, 500 mV and 1000 mV, respectively. Charge pump output voltage versus input voltage is depicted in Fig. 6. The output voltage would be increased for higher load.

Table 3. Proposed charge pump output voltage with different load.

Vin (mV)	Vout (V)		
	Rload = 10 kΩ	Rload = 50 kΩ	Rload = 100 kΩ
100	3.39	5.91	6.44
500	3.56	6.20	6.78
1000	3.79	6.58	7.14

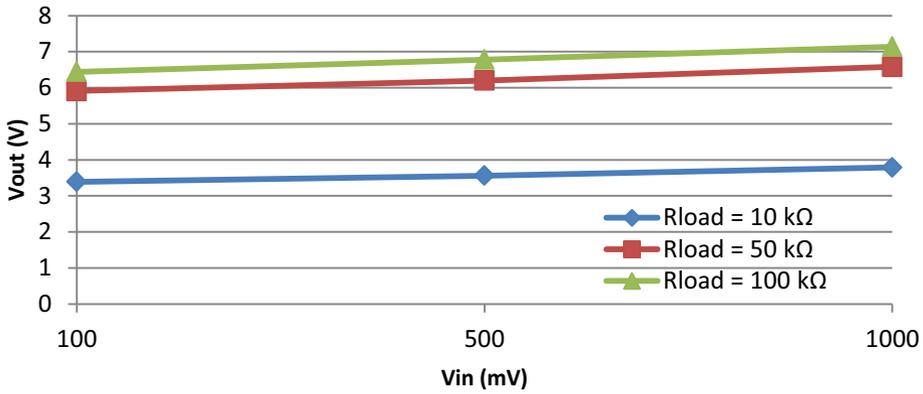


Fig. 6. Charge pump output voltage vs input voltage (variant output load).

Finally, the complete circuit is simulated with different load resistances are shown in Table 4. Figure 7 shows output voltage versus load resistance. The AC input voltage of 150 mV is used with different resistance loads at the range of 1 kΩ to 100 kΩ. As can be seen in Figure 7, the DC output voltage is proportional to the increment of the load resistance.

Table 4. Circuit output voltage vs resistance load.

Vin (mV)	Vout (V)						
	R= 1kΩ	R= 5kΩ	R= 10kΩ	R= 20kΩ	R= 50kΩ	R= 75kΩ	R= 100kΩ
150	0.544	1.991	2.914	3.715	4.385	4.558	4.648

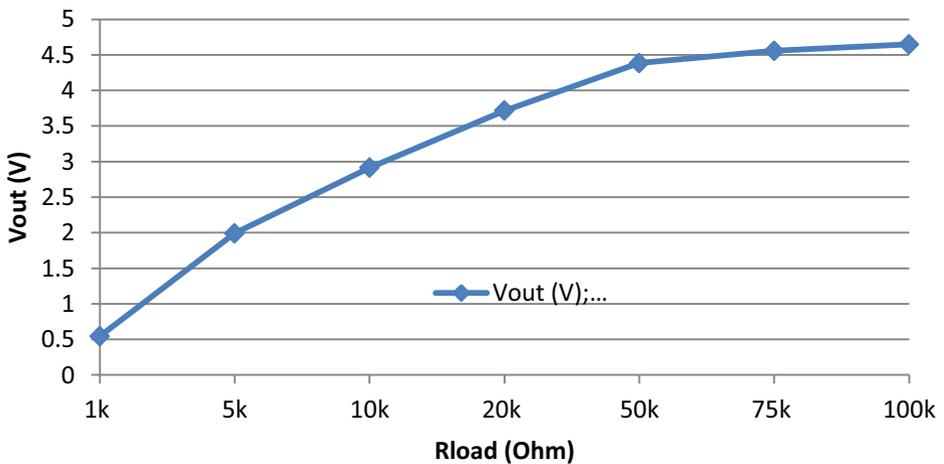


Fig. 7. Circuit output voltage vs input voltage (variant output load).

Table 5 shows the comparison between this works with previously published works. Even the resistance load can be used as higher as possible to generate higher output voltage, but it will affect the charging rate. Therefore, it can be proved that with lower load, this work can produce much higher output voltage compared to other topologies. Even [15] has the advantage in frequency range, but the range from this work also can't be compared since

the objective of the study is to design a circuit for RF energy harvesting, which targeting WSN frequency that are commonly in the range from 900 MHz to 2.4 GHz.

Table 5. Comparison with other previous work.

Reference	[8]	[9]	[15]	This work
Technology (CMOS)	0.13- μm	0.18- μm	0.65- μm	0.13- μm
Topology	Cross-coupled charge pump	5-stage CMOS rectifier	3-stage Dickson charge pump	Multi-stage NMOS
Load (k Ω)	100	150	12.5	10
Input Power (dBm)	-6	-10	-10	-16.478
Frequency (MHz)	900	900	700-2400	900-2400
Output Voltage (V)	2.05	2.6	0.5	2.9

4 Conclusion

From the graphs plotted, it can be proved that the proposed AC-DC rectifier is successfully designed and simulated. The usage of multistage NMOS topology as a rectifier converts the AC signal to DC signal efficiently. The AC signals that can be converted are in wide range, from 900 MHz to 2400 MHz which is commonly used in wireless application. While the charge pump boost the DC level for higher output voltage. The proposed design AC-DC rectifier circuit is able to produce DC output voltage of 2.9 V at 10 k Ω load resistor with frequency of 900 MHz to 2400 MHz.

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