Journal of Advanced Research in Applied Sciences and Engineering Technology

Journal homepage:
https://semarakilmu.com.my/journals/index.php/applied_sciences_eng_tech/index
ISSN: 2462-1943

Design of 2.4 GHz RF to 1.33 V DC Conversion Circuit for Energy Harvesting

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ABSTRACT

This paper presents the design of a circuit for energy harvesting that converts 2.4 GHz radio frequency (RF) to 1.33 V DC. The demand for self-sustainable low-power electronic devices requires power to be supplied continuously. The battery has a life circle and is not able to sustain for a long time. Therefore, radiofrequency (RF) is one of the energy sources that can be obtained at any desired voltage for no cost and is widely available. A voltage regulator, charge pump, and rectifier make up the suggested circuit. All circuits are designed using 0.13-µm CMOS process. To convert the antenna's 2.4 GHz RF voltage to DC voltage, an RF rectifier is needed. After the rectifier's DC voltage is increased by the charge pump, the voltage regulator regulates the DC output voltage to the intended output value. At the voltage regulator, the desired DC output voltage will be controlled. The simulation's outcome demonstrates that an RF-DC rectifier circuit operating at 2.4 GHz frequency and a 10 kΩ load resistor may provide a DC output voltage of 78.51 mV. Next, the charge pump increased the rectifier's output voltage to 1.39 V. Lastly, the voltage regulator controlled the charge pump's output to produce a steady DC output of 1.33 V.

Keywords:

Radio frequency; Energy harvesting; Rectifier; Regulator; Charge pump

1. Introduction

Recently, energy harvesting devices based on radio frequency (RF) technology are among the most widely used worldwide. Low-power wireless sensors are powered by ambient electromagnetic waves, or RF energy, which transform environmental energy into DC electricity [1,2]. The RF energy harvesting circuits can provide sufficient power for the wireless sensors with efficient battery usage [3,4].

Energy scavenged from the environment might be utilized immediately to power the devices or stored for later use. There are various sources of electromagnetic wave including TV or radio broadcast, wireless internet, digital broadcasting as well as in satellite stations [5,6]. The RF electromagnetic waves have advantages as batteries replacement and always available all the time.

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https://doi.org/10.37934/araset.63.1.1726

In contrast, using batteries consumes space and needs to be maintained, and in the worst case, can cause harmful effects on the environment. However, in comparison to other ambient energy sources like thermal and solar energy, radiofrequency energy has a lower power density [7,8]. Therefore, designers are paying close attention to ambient RF technologies to make their energy sufficient for powering wireless sensors.

The RF energy harvesting circuits require electromagnetic wave detecting by an antenna, which converts the detected alternating current power into direct current power [9]. The RF-DC rectifier is the most crucial component of the RF to DC converter, which is made up of several blocks. A block diagram of the RF energy harvesting system is shown in Figure 1 [10,11]. A TV/radio base station, wireless internet, a mobile phone, or even a Wi-Fi router can serve as the system's RF energy source (RF in) [12,13]. The RF power is received by the energy harvester antenna and fed into an RF-DC rectifier. A charge pump is used as a booster DC signal from RF-DC rectifier [14-17]. Finally, the desired DC voltage is regulated at the voltage regulator in the output load.

This paper discusses the design of a 2.4 GHz RF to 1.33 V DC converter circuit for energy harvesting. The design and implementation of the voltage regulator, rectifier, charge pump, and entire 2.4 GHz RF to 1.3 V DC conversion circuit are covered in the first section. The second section presents the suggested circuit's simulation results along with a discussion. Lastly, the final portion provides the conclusion.

Fig. 1. Block diagram of RF energy harvesting

2. Design Implementation

The section that follows goes over the suggested circuit for RF to DC conversion. Regulator, charge pump, and rectifier make up the suggested conversion circuit. Every suggested circuit is executed using CMOS 0.13-µm technology.

2.1 Rectifier Circuit

Figure 2 shows the schematic of a multilayer NMOS RF to DC converter circuit. The circuit is designed using Cadence software using the 0.13-µm CMOS technology. The positive and negative cycles of the alternating current (AC) input are rectified by the circuit. The drain-to-source voltage (VDS) is negative when the AC signal is in the negative half cycle, NM1 is reverse biased, and the signal is cutting out. NM2, on the other hand, is a forward-biased switching transistor. The current that flows through NM2 and C2 charges C1. NM1 is forward biased and turns on at the conclusion of the negative cycle, allowing the charged current from C1 to pass through C9. Each charged capacitor produces a bias voltage as the subsequent cascade stages increase the corresponding charged output current until ripples are reduced and the AC signal is saturated. Consequently, the circuit's additional NMOS RF to DC converter stages produce a high DC output voltage. The dimensions of all NMOS transistors are fixed at 40 µm/0.13 µm. The RLoad is 10 kΩ, while the decoupling capacitors C1–C18 and CLoad are selected at 10 pF. The RLoad receives the AC input voltages, which span from 50 mV to 500 mV at a frequency of 2.4 GHz.

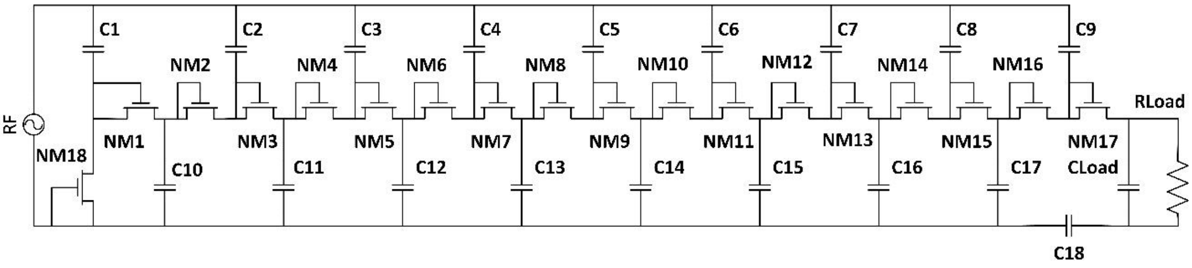


Fig. 2. Multilevel NMOS RF to DC converter schematic

2.2 Charge Pump Circuit

A charge pump is a DC-DC converter that stores energy in capacitors. To increase the DC voltage from the rectifier circuit, a charge pump is needed. The charge pump is utilized since it is anticipated that the rectifier output would have a low DC voltage. The charge pump employs an external cycle pulse as a biasing device to accomplish the same purpose as a transformer. The pulse was employed to induce the charge transfer in this arrangement. The pumping gain is determined by the pumping capacitor charge and pulse amplitude. A charge pump for an energy harvesting system is shown in Figure 3. Two pulses are required to generate for a charge pump. The first pulse with a 50 % duty cycle frequency needs to be generated, while the other pulse needs to have a phase shift of 50 % between the two pulses. These pulses will bias the low DC voltage from the rectifier circuit. Therefore, a pulse frequency should be used as little external power as possible. The charge pump circuit's efficiency rises as the rectifier's DC input voltage rises because it saturates the current required to bias the voltage. There is a 1 pF capacitor and a 10 kΩ load resistor employed, respectively.

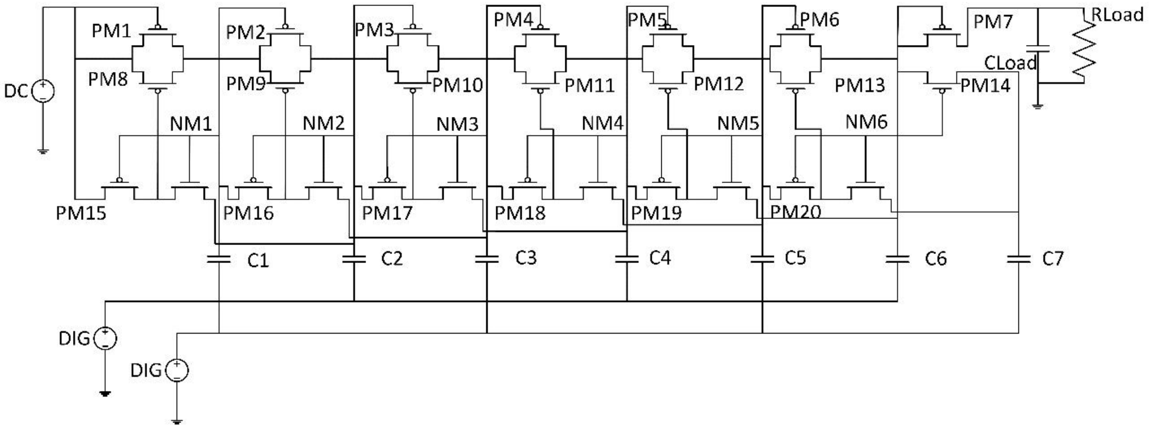


Fig. 3. The equivalent circuit for RL series to parallel transformation

2.3 Voltage Regulator Circuit

A charge pump circuit's output voltage is significantly influenced by the frequency and strength of the input signal, which can lead to extremely large voltage swings. The battery may not be able to handle the voltage variations in real life. There should be a set of input voltages for each battery or power source. Therefore, a constant DC output voltage of 1.33 V with a maximum current load of 100 µA is what the suggested regulator circuit is set to offer. Figure 4 displays a voltage regulator circuit schematic. It is made up of feedback resistors, a pass element, and an error amplifier. The erroneous signal is amplified by a circuit by an error amplifier. The reference voltage and feedback voltage are the two primary inputs of an error amplifier. The error amplifier's primary output source will be the feedback resistors because the reference voltage is fixed at a specific level. When the input voltage gets close to the intended output value, the error amplifier drives the gate-to-source voltage (VGS). The PM1, PM2, and PM5 transistors with size of 4µm / 0.13µm are used. Meanwhile, NM1-NM7 transistors with size of 3µm / 0.13µm are employed. R2 is a 30 kΩ feedback resistor, while R3 is a 100 kΩ feedback resistor. There is a 0.47 nF load capacitor, CLoad. The reference voltage Vref for this regulator design is set at 1.2 V.

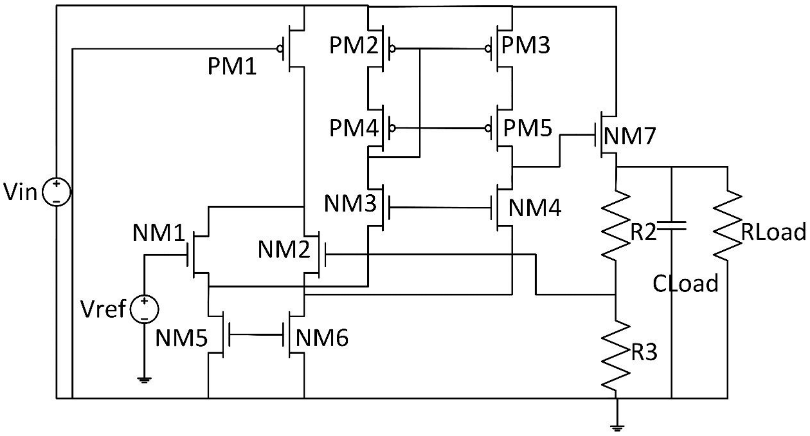


Fig. 4. The Complete 2.4 GHz RF to 1.3V DC conversion circuit

2.4 Complete 2.4 GHz RF to 1.3 V DC Conversion Circuit

Figure 5 shows the full schematic of the suggested RF to DC conversion circuit. The charge pump increases the DC voltage produced by the rectifier circuit, which converts the RF input. Ultimately, the regulator controls the charge pump's input to produce an output voltage of 1.33 V.

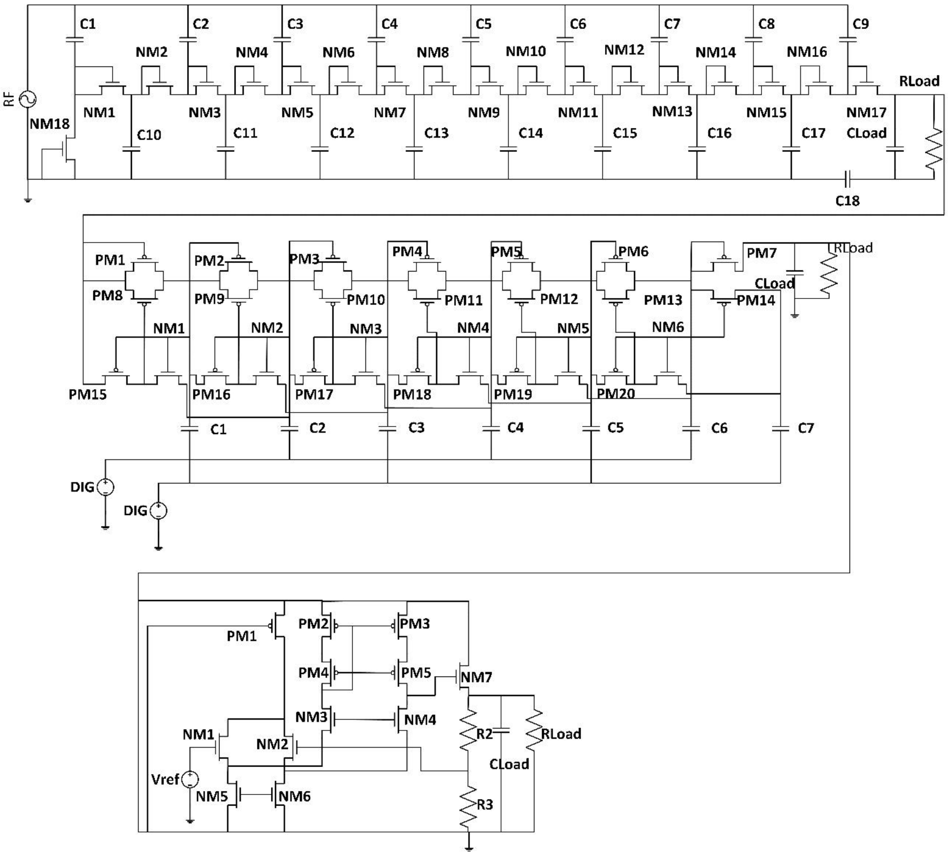


Fig. 5. Detailed schematic of the proposed circuit for RF to DC conversion

3. Simulation Results

The suggested rectifier circuit's simulation results are displayed in Table 1. To run the simulation, the AC voltage is changed at a frequency of 2.4 GHz from 50 mV to 500 mV. The 10 kΩ load resistor is configured. It is evident that the output voltage is raised correspondingly from 6 mV to 383 mV.

Table 1
Simulation results of the proposed rectifier at 2.4 GHz frequency

Vin (mV)	Vout (mV)
50	6.13
100	15.30
150	58.83
200	105.88
250	152.78
300	200.59
350	251.11
400	297.80
450	337.80
500	383.07

The output voltage is plotted against the input voltage in Figure 6. It is evident that the input and output voltages have a linear connection circuit for converting RF to DC.

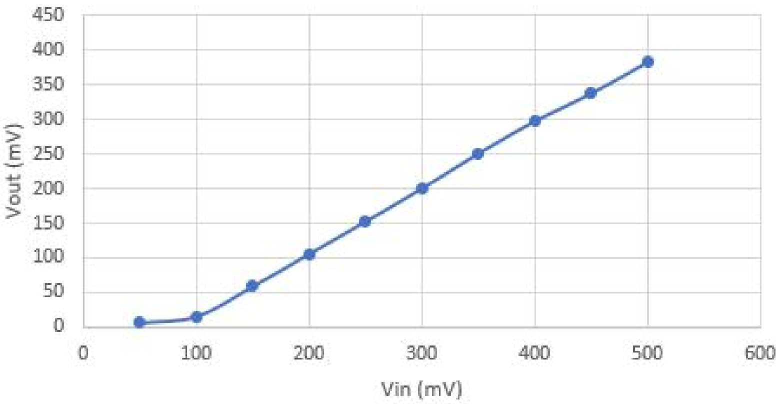


Fig. 6. Input voltage against output voltage of a rectifier

The simulation results of the rectifier circuit for resistance loads of 10 kΩ and 50 kΩ are shown in Table 2. Table 2 illustrates how the output voltage rises with increasing load resistance. The load resistance cannot be too large because it consumes large area on silicon and dissipated more heat. The selection of load resistance needs to be compromised with the required output voltage.

Table 2
The voltage of the rectifier with a load of 10 kΩ and 50 kΩ

Vin(mV)	Vout (mV)	
	10 kΩ	50 kΩ
50	6.13	19.11
100	15.30	64.15
200	105.88	246.38
300	200.59	548.72
400	297.80	894.10
500	383.07	1257.43

Similarly, Figure 7 shows the output voltage vs the input voltage.

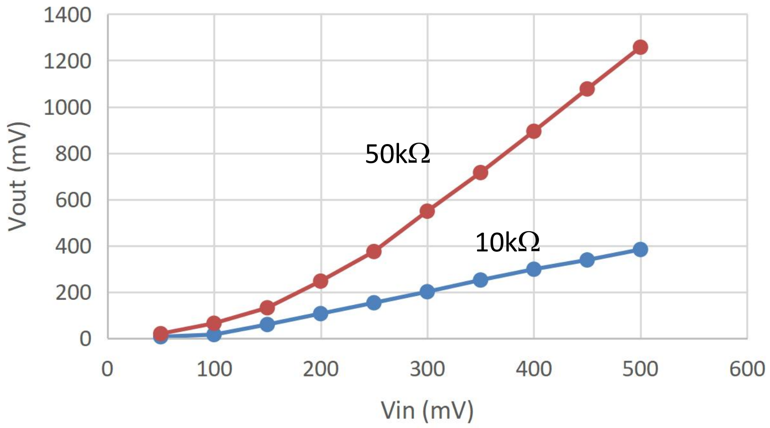


Fig. 7. Rectifier output simulation result at 10 kΩ and 50 kΩ load

A charge pump's output voltage is shown in Table 3 with different loads. Resistance loads of 10 kΩ, 50 kΩ, and 100 kΩ are used while the DC input voltages are 100 mV, 500 mV, and 1000 mV.

Table 3
Charge pump circuit simulation results with varying loads

	Vout (V)		
Vin (mV)	Rload = 10 kΩ	Rload = 50 kΩ	Rload = 100 kΩ
100	1.39	3.91	4.44
500	1.56	4.2	4.78
1000	1.79	4.58	5.14

Figure 8 shows the relationship between the output voltage and the input voltage of the charge pump. When the load is increased, the output voltage is raised.

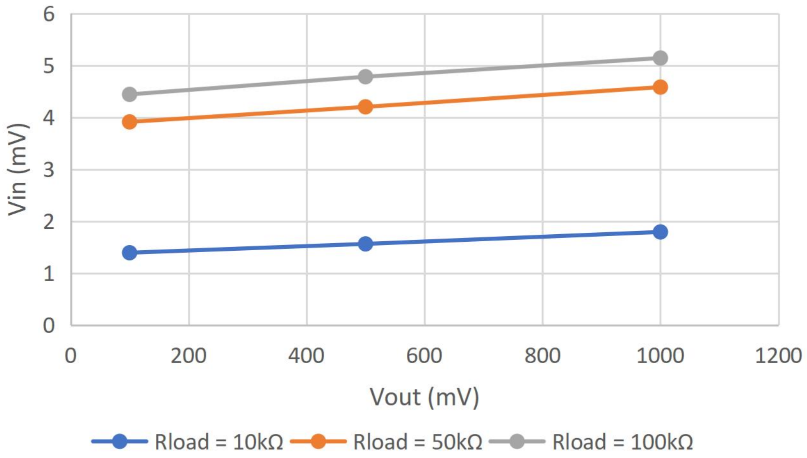


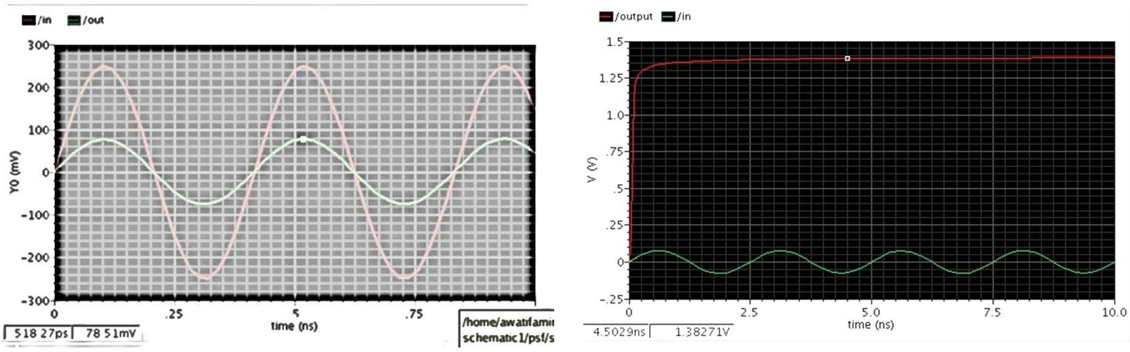
Fig. 8. Charge pump simulation result

Table 4 displays the full circuit input and output from the regulator, charge pump, and rectifier. The rectifier's input receives the 50 mV, 2.4 GHz input voltage. At the charge pump, the rectifier's output voltage of 78.51 mV is increased to 1.39 V DC voltage. With a 10 kΩ resistance load, a constant DC output voltage of 1.33 V is provided by the voltage regulator controlling the charge pump's output voltage.

Table 4
Results of the proposed rectifier's simulation at 2.4 GHz

	Vin (mV)	Vout (mV)
Rectifier	50	78.51
Charge pump	78.51	1390
Voltage regulator	1390	1330

The transient behaviour of the entire RF to DC conversion circuit is displayed in Figure 9. The AC input signal of 78.51 mV at 2.4 GHz is amplified to 250 mV at the output charge pump, as shown in Figure 9(a). Additionally, Figure 9(b) shows the output voltage regulator's DC output voltage of 1.33 V.



(a) (b)

Fig. 9. The transient response of the complete RF to DC conversion circuit. (a) rectifier and charge pump, (b) voltage regulator

The performance comparison between the suggested RF to DC conversion circuit and previously published studies is displayed in Table 5. High load resistance was needed in [18,20] in order to provide DC voltage. In Lee *et al.,* [19], a cross-coupled rectifier and matching network are used to provide a high DC voltage. In this paper, a multi-stage NMOS rectifier with a cross-coupled charge pump is used in the proposed design to convert RF to DC 1.33 V output voltage at a frequency of 2.4 GHz with low resistance load.

Table 5

Comparing the proposed RF to DC converter circuit's performance to those of related works

Reference	[18]	[19]	[20]	[21]	This work
Technology	0.13-µm	0.13-µm	65-nm	0.18- µm	0.13-µm
Topology	Cross-coupled charge pump	Cross-coupled rectifier and the matching network	Fully cross-coupled rectifier and self-biased technique	Pre-stage and drive-stage rectifiers	Multi-stage NMOS rectifier with cross coupled charge pump
Frequency (GHz)	0.9-2.4	0.9	2.4	2.4	2.4
Input Power (dBm)@(µW)	-16@25.0	-15@31.6	-14.44@36.3	-35@0.31	-16@25.0
Load (kΩ)	50	10	20	1000	10
Output Voltage (V)	1.25	4.70	1.29	0.50	1.33

4. Conclusions

An energy harvesting circuit for converting 2.4 GHz radio frequency to 1.33 V DC has been effectively constructed. Using 0.130-µm CMOS technology, the multistage RF-DC rectifier is successfully constructed. Cadence software was used to implement every design and simulation. A multi-stage NMOS architecture as a rectifier effectively converted a 2.4 GHz RF signal to DC voltage. The DC level is increased by the charge pump to a higher output voltage. A 2.4 GHz frequency can be converted by the suggested RF to DC conversion circuit to a DC output of 1.33 V at the voltage regulator. The proposed circuit has been compared with similar works, and it is achieved a comparable result with other researchers.

Acknowledgement

There was no grant used to finance this research. But the authors also want to thank Khoo Qi You, an Electronic Program final-year project student from the Faculty of Electronic Engineering & Technology, Universiti Malaysia Perlis, for her assistance for providing the simulation data for this paper.

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