A CMOS RF-to-DC Converter with 99.9% Efficiency for RF Energy Harvesting

J. Jafny Moniza[1] A. Beno[2]
[1]PG Scholar [2]Associate Professor
[1,2]Department of Electronics & Communication Engineering
[1,2]Dr.Sivanthi Aditanar College of Engineering, India

Abstract— This paper proposes an RF to DC power converter for ambient wireless powering that is efficient, highly sensitive and less dependent on load resistance with an extended dynamic range. The proposed rectifier design is fabricated using a 90nm standard CMOS technology. The designs of rectifiers are discussed and the double entered rectifier topology chosen was simulated using Ansoft Nexxim designer. The energy harvesting circuit module includes an impedance matching circuit to avoid loss of energy derived by the antenna unit to achieve maximum power conversion efficiency (PCE) and sensitivity. The measured result achieved 99.9% power conversion efficiency (PCE) for below 10 GHz of frequency which almost covers major RF application band source frequencies and can serve for future low-maintenance SoC applications.

Key words: CMOS, RF-to-DC Converter, RF Energy Harvesting

I. Introduction

Power consumption is one of the most critical issues when designing low- cost electronic devices, such as sensing nodes in wireless sensor networks. To support their operation, such systems usually contain a battery; however, when the battery has consumed all its energy, the node (e.g. the sensor) must be retrieved and the battery needs to be replaced. If the node is located in a remote and non- accessible placement, battery replacement can become an expensive and even impossible task [4]. This way, energy harvesting has emerged as a suitable alternative to supply low- power electronic systems, by converting ambient energy into electric power. Scavenged energy can be used to directly supply the circuits, or stored to be used when needed. There is an active research area investigating a number of alternative ways to extract energy from the environment and convert it into electrical energy for energizing low power electronic circuits directly or store it for later use. One such energy is from radio frequency. RF Energy harvesting from the ambient will have an important role in the future microelectronic circuits. RF energy harvesting from ambient sources have great potential to impact on the cellular phones and other electronic gadgets. This concept needs an efficient antenna along with a circuit that is capable of converting RF signals to DC voltage, so as to replace the need of the battery. The author proposed a power harvester that has been designed and fabricated in a CMOS 0.18- µm process that operates at the UHF band of 920 MHz of frequency. The circuit employs an impedance transformation circuit to boost the input RF signal [1]. The technique presented an analytical model for power harvester circuit used in low power applications to replace batteries. An exact analytical model for the Dickson rectifier working in sub threshold regime for MOS devices was derived and also effect of the compensation voltage was also included in the model [2]. Also the 90nm CMOS Technology is most recently used for better switching speed of the transistors. Another efficient energy harvester for RF-powered sensor networks based on an improved multi-stage rectifier is designed, which exploits a fully passive threshold self-compensation scheme to overcome the limitation due to the input dead zone [5]. Importance of this paper is that the rectifier exhibit low input power threshold to deliver a 1-V dc output voltage to a capacitive load with a very small input power of 24 dBm (4 W) [3]. The design method for the co-design and integration of a CMOS rectifier is described in standard 90nm CMOS technology. An efficient RF to DC conversion system to convert the far field RF energy to DC voltage design using floating gate transistors as rectifying diodes was presented [6].

II. CMOS RF-to-DC Converter

Rectifier (RF to DC Converter) is an electrical device that converts alternating current (AC) which periodically reverses direction to direct current, which flows in only one direction. This Process is known as rectification since it straightens the direction of current. Rectifying is the most popular application of diodes, which refers to the conversion of AC current to DC current. In terms of power harvesting application, the RF signal retrieved in the antenna has a sinusoidal waveform. The signal after the transformation through impedance matching network (IMN) would be rectified and boosted to meet the power requirements of the application. The MOSFET (Metal Oxide Semiconductor Field Effect Transistor) technology is overcoming the limitations of diodes and becoming an alternative solution for rectifying and boosting. A diode- connected transistor is a method of creating a two terminal rectifying device (a diode) out of a three terminal transistor. A characteristic of diode-connected transistors is that they are always in the saturation region for metal-oxide-semiconductor field effect transistor. The MOS RF to DC converter can be classified into Dickson rectifier, fully cross coupled rectifier (FX), Self-biased rectifier, Single-sided architecture and Double-sided architecture. The comparison of these types of CMOS rectifiers are shown in table 1.

Types	Technology(µm)	Power Conversion Efficiency (%)
Dickson	0.18	34
FX	0.18	73
Self-Biased	0.18	54
Single-sided	0.18	76
Double-sided	0.18	86

Table 1: Comparisons of Rectifier Topologies

By the comparison of rectifier topologies, it is analyzed that the double-sided rectifier architecture has the maximum power conversion efficiency (PCE) of RF-to-DC converter. So for this thesis, double-sided rectifier is chosen with improved parameters to increase further the PCE of the rectifier circuit.

III. DOUBLE-SIDED RECTIFIER

In this architecture design in figure 1, the added diodes (D3, 4) are reverse biased for the RF signal and forward biased for the dc signal. This way, the double sided architecture can provide an even better performance with better sensitivity and higher PCE. When the instantaneous RF power at the cathode of D3, 4 is larger than V_{SS}, D3, 4 remains OFF and the whole architecture acts as the single-sided design. In contrast, when the instantaneous RF power at the cathode of D3, 4 is smaller than V_{SS} by V_{diode}, D3, 4 turns ON and supports M1, 3 by draining more current from the negative terminal of the load. In other words, while D1, 2 enhances the PCE and DR by reducing I_{REV}, D3, 4 enhances the PCE and sensitivity further by increasing I_{FWD}. Note that D3, 4 does not change the operating points of M1, 3, unlike D1, 2. This is because the dc voltages at the cathodes of D3, 4 are always larger than V_{SS}, no dc current can flow through. Also, since the optimum dc voltages at the gates of M2, 4 are different compared to M1, 3, two extra coupling capacitors are connected to the gates of M1, 3. The double-sided design maintains a higher IFWD (compared to the self-biased) and a negligible IREV hence, it has the highest net charge, which is equal to 38.7 fCol/Cycle, translating to more than 13% charge conversion efficiency versus both FX and self-biased structures. This enhancement is reflected on the PCE performance.

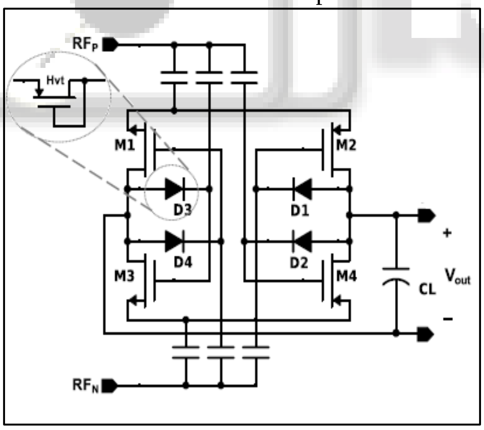

Fig. 1: Double-Sided Rectifier

IV. SIMULATION RESULTS & DISCUSSION

The various types of RF to DC converters have been discussed [2]. In this paper, the higher Power conversion efficiency (PCE) is met with the topology of Double ended rectifier which is implemented using Ansoft Nexxim as shown in figure 2.

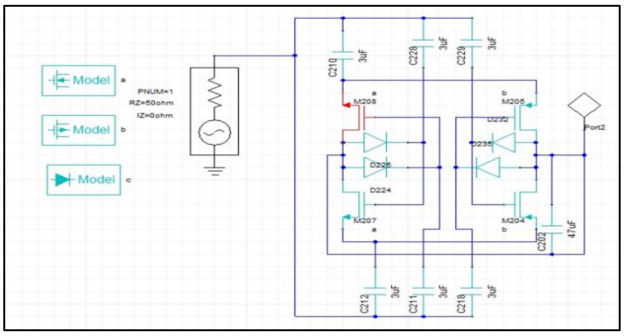

Fig. 2: Double-Sided Rectifier in Ansoft Designer

The channel length of both PMOS and NMOS are set to 90 nm Standard CMOS technology. The input AC input is applied as 230 mV since the antenna acquires only millivolts of RF signal in Energy harvesting system. The respective output for the AC voltage of 230 mV for the rectifier circuit produces the dc voltage of 230 mV for the frequency range of below 10 GHz as shown in figure 4. The Power Conversion Efficiency is 99.99% below 10 GHz for this design. The gain plot of the double ended rectifier circuit with the maximum gain is below 7 GHz of frequency is shown in figure 5.

In energy harvesting system, the multiband planar antenna is capable to respond to various RF application frequencies that help harvesting energy required for the system. The energy captured by the multiband antenna receive AC signal will be very low in the order of micro or milli watts. So the input voltage to the double-sided rectifier is given as 230 mV as shown in figure 3.

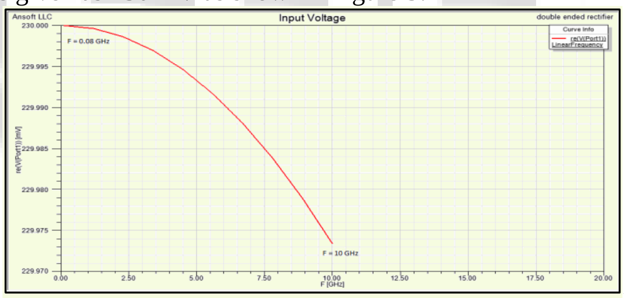

Fig. 3: Input voltage vs. Frequency

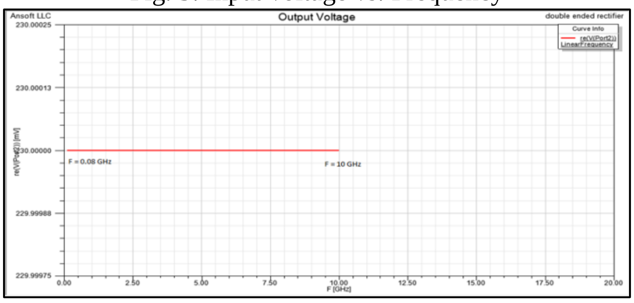

Fig. 4: Output Voltage vs. Frequency

The respective output for the AC voltage of 230 mV for the rectifier circuit produces the dc voltage of 230 mV for the frequency range of below 10 GHz. So that the Power Conversion Efficiency is 99.99% below 10 GHz for this design.

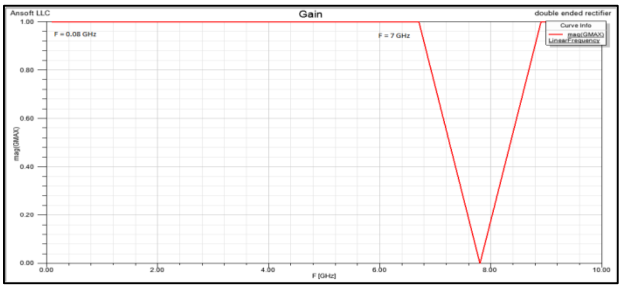

Fig. 5: Gain Plot of Double-Sided Rectifier

The maximum gain is obtained for the frequency 0.08 GHz to 7 GHz is obtained from the gain plot.

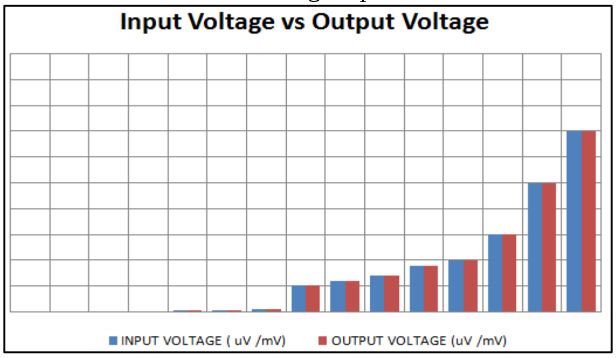

Fig. 6:

V. Conclusion

This paper presents the double ended CMOS RF to DC converter and design is simulated using Ansoft Nexxim designer. An AC input of 230mV is given to the rectifier circuit which converts to a DC signal of 230 mV. The simulation reveals that the AC-DC conversion is performed without loss till the operating frequency is raised till 10 GHz. The simulation results show that while using the Double ended rectifier topology in 90nm standard CMOS technology, the resulted gain was unity over the interested frequency range with 99.9% of overall Power Conversion Efficiency for the specifications considered. Thus this simple analysis helps to design an effective energy harvesting circuit to drive low power SoC VLSI circuits.

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