Energy Harvesting Circuit with High RF-to-DC Conversion Efficiency

Mohammad Alibakhshikenari[1]*, Bal Singh Virdee[2], Chan Hwang See[3,4], Raed A. Abd-Alhameed[5], Francisco Falcone[6],and Ernesto Limiti[1]

[1]Electronic Engineering Department, University of Rome "Tor Vergata", Rome, ITALY

[2] London Metropolitan University, Center for Communications Technology & Mathematics, London, UK

[3] School of Engineering & the Built Environment, Edinburgh Napier University, Edinburgh, UK

[4] School of Engineering, University of Bolton, Bolton, UK

[5] Faculty of Engineering and Informatics, University of Bradford, Bradford, UK

[6] Electrical and Electronic Engineering Department, Public University of Navarre, Pamplona, SPAIN

*alibakhshikenari@ing.uniroma2.it

***Abstract*—This paper presents an energy harvesting circuit for high efficiency performance. The proposed circuit consists of an RLC shunt resonance circuit integrated to an RF antenna. The resonance circuit is used to (i) selectively pick the desired signal whose output is fed to a Cockcroft–Walton voltage multiplier circuit; and (ii) match the impedance of the antenna with the Cockcroft–Walton voltage multiplier circuit for optimum power (DC) transfer. The proposed circuit exhibits an efficiency of 68% for an input power of 200 μW.**

***Keywords*— Antenna, energy harvesting circuit, radio frequency (RF) energy, impedance matching circuit, resonance circuit, Cockcroft–Walton (CW) voltage multiplier.**

I. INTRODUCTION

Wireless sensors are increasingly been deployed in remote, hostile and inaccessible environments to monitor specific parameters such as temperature, pressure, stress, and air quality [1]. There usage will greatly proliferate with the emergence of 5G and Internet of Things (IoT). Such sensors are usually powered by batteries with finite lifetime, which is a limiting factor to the long-term operation of such devices. Energy from solar cells is not viable where the sensors are buried inside structures such as buildings and bridges. The solution to this issue is to harvest the ambient radio frequency (RF) energy to realize a sensor with a perpetual lifespan without the need of recharging or replacing batteries [1,2]. In practice, the harvested energy is inherently time-varying in nature, and of a low magnitude that is stored in a sensor battery of limited capacity. Therefore, the main challenge lies in satisfying wireless devices exclusively powered by such inexhaustible but uncontrollable and unstable low energy supply.

With a relatively low density of ambient RF signal energy, it is therefore important to design highly efficient RF energy harvesting electronic circuitry. A suitable source for RF energy harvesting is radio frequency identification (RFID) systems that operate in the 800-1200 MHz band. This frequency band has low consumption, high diffraction performance, and a maximum transmitter power output of 24 dBm. In the past various energy harvesting circuits have been investigated using transistors [3] or diodes [4–6]. Sensor circuits based on diodes are simpler and more cost-efficient than the transistors. The main components of energy harvesting circuits are diodes and capacitors, and the basic circuits are based on either single-stage [4] or dual-stage [5]. Since the RF energy resources are usually of low power region, so the harvesting circuit should be designed to provide better performance in low power region. Under low input power scenarios, major challenge in the RF energy harvesting process includes low conversion efficiency and availability of negligible DC voltage. The maximum efficiency obtainable by these energy harvesting circuits is around 80% at 940 MHz when input power is 10 mW in the 800-1200 MHz band [6]. Unfortunately, this efficiency declines substantially as the low harvested energy is dissipated by the parasitic resistance in the diodes and capacitors. Therefore, a highly efficient circuit is needed for input power which is less than 1 mW. Cockcroft–Walton circuit can be used to overcome the issue with low input power [7].

It has been shown that to boost the magnitude of the weak RF signal a resonant circuit can be employed prior to applying it to the Cockcroft–Walton circuit [8]. The resonator circuit consists of discrete inductor and capacitor. It exhibits resonant behavior at frequencies of interest and the frequency at which maximum amplification is achieved is its resonant frequency. Simulation results in [9] show high power conversion efficiency can be realized by using an impedance matching network using discrete inductor and capacitors. However, at RF frequencies these discrete components must be realized using transmission lines and therefore the circuit will need to be analyzed using electromagnetic theory. The matching network will need to be optimized to the input impedance of the antenna to maximize the power conversion efficiency.

In this paper, a matching circuit constructed from shunt resonance circuit is placed between the Cockcroft–Walton rectifier and antenna to enhance the efficiency of the RF energy harvesting circuit. The proposed circuit amplifies the voltage of the input signal and matches it to the impedance of the antenna. The size of the proposed circuit is smaller than other RF energy harvesting circuits.

II. Circuit Design

The proposed energy harvesting network is interfaced to the RF antenna, as shown in Fig. 1. The antenna is connected to an impedance matching and *RLC* shunt resonance circuits, the output of which is fed to the Cockcroft–Walton voltage multiplier rectifying circuit. Hence, the very weak input RF signal picked up by the antenna is first amplified by the *RLC* shunt resonance and its impedance transformed to the input of Cockcroft–Walton circuit. The output of from this network is a boosted DC voltage.

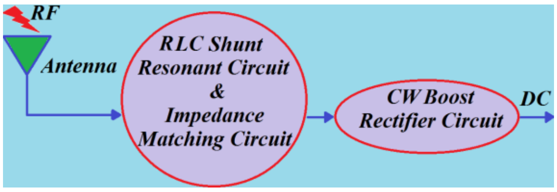

Fig.1. Block diagram of the proposed energy harvesting network.

Circuit model of the proposed energy harvesting network is shown in Fig. 2. The Cockcroft–Walton voltage multiplier circuit is constructed from chip capacitors and diodes (HSMS-286K-G, Broadcom). A Schottky diode (SBD) is used here because of its high frequency operation and lower threshold voltage compared to other diodes. The diode constituting the Cockcroft–Walton multiplier circuit essentially behaves like a capacitor. The *RLC* shunt resonance circuit is chosen to compensate for the impedance of the Cockcroft–Walton voltage multiplier circuit. The circuit was analyzed using Advance Design System (ADS™) by Keysight Technologies.

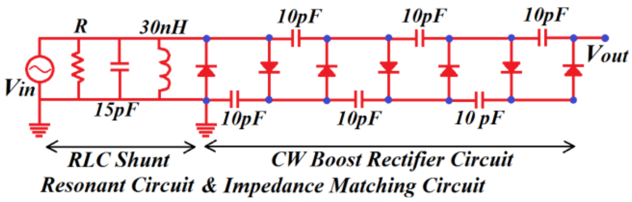

Fig.2. Schematic of the Cockcroft–Walton multiplier rectifying circuit.

The output voltage of the Cockcroft–Walton voltage multiplier circuit $V_{C_{out}}$ is given by $V_{C_{out}} = V_{C_{in}} \times 2N$, where $V_{C_{in}}$ is the input voltage to the rectifying circuit, and N is the number of capacitors and diodes employed. In the initial circuit design stage, the primary objective was to increase the output voltage. This required the use of a Cockcroft–Walton voltage multiplier circuit. Fig.3 shows the simulation results of $V_{C_{out}}$ as a function of *N*. In this case, $V_{C_{in}}$ is 150mV at 1200 MHz, and the load is open-circuited. The results show the above expression is not satisfied. This is because of the parasitic elements of the diodes. $V_{C_{out}}$ is optimum for $N = 6$.

To improve the energy harvester's efficiency, a *RLC* shunt resonant circuit is arranged before the Cockcroft–Walton voltage multiplier circuit. The quality factor of the *RLC* shunt resonant circuit essentially amplifies the input voltage.

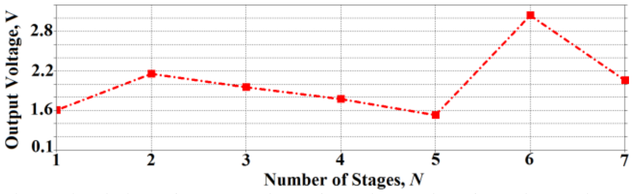

Fig.3. Simulation of output voltage from the Cockcroft–Walton voltage multiplier circuit versus number of capacitor and diode stages.

The low efficiency from the above circuit results from the power dissipated by the internal resistance of the diodes. The only solution immediately available is to reduce the number of diodes but this is at the cost of the output voltage. The diode in the Cockcroft–Walton voltage multiplier circuit can be represented by a capacitor, as shown in Fig.4. The capacitance value of this *RLC* circuit is combined with the resonance and the matching circuits to thus reduce the number of elements. The value *R* represents the antenna input impedance.

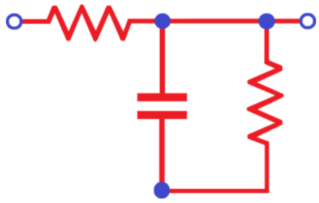

Fig.4. Schematic of an equivalent circuit of the diode.

The Q ($=1/\omega CR$) value is increased when either R or C values are decreased. By doing this the input voltage is amplified and efficiency is improved. Fig.5 shows the proposed circuit of Fig.2 exhibits a steady-state DC voltage in the time-domain response. It is evident from Fig.5 that when the antenna impedance R decreases, the DC output voltage increases. In fact, when R is 10Ω, the DC output voltage is 10.5 V at an input RF voltage of 150 mV across 800-1200 MHz band. When the value of the load resistance is 10 kΩ, the maximum efficiency obtained from the circuit is 68% with an input voltage of 200 μW.

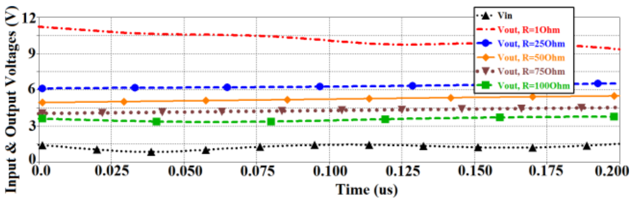

Fig.5. Input and output voltage transient response as a function of R.

III. Conclusion

In this paper the design for a RF energy harvesting circuit was shown to provide high efficiency. It comprised an antenna whose input is applied to an *RLC* shunt resonance circuit and a Cockcroft–Walton voltage multiplier circuit. The *RLC* shunt resonance circuit was chosen to compensate for the impedance of the Cockcroft–Walton multiplier circuit system.

Acknowledgments

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