DESIGN AND EXPERIMENTS OF A 2.4-GHZ VOLTAGE MULTIPLIER FOR RF ENERGY HARVESTING

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Abstract: This paper focuses on the design, fabrication and measurements of a 2.4-GHz Cockcroft-Walton voltage multiplier circuit, dedicated to RF energy harvesting. The proposed circuit is designed and optimized using ADS (Advanced Design System) software, so as to operate with low RF power levels of around -15 dBm. It contains 6 cascaded stages based on Skyworks SMS 7630 Schottky diodes. The topology of the circuit has been carefully chosen so as to propose a compact structure of 46 mm per 45 mm. Experimental characterization shows that it is possible to reach an output dc voltage of 850 mV at -15 dBm input RF power and more than 3 V at -5 dBm, over a 100 MΩ output resistive load. The developed circuit is dedicated to wireless powering of a MEMS transducer.

Keywords: RF energy harvesting, RF-to-dc converter, Cockcroft-Walton voltage multiplier, Schottky diode

INTRODUCTION

The growing proliferation of wireless communication devices like sensors, sensor nodes and actuators, raises the issue of their energy autonomy. The wireless powering by converting ambient RF electromagnetic waves can be an interesting solution, in the way that it avoids conventional power sources embedded inside the device.

The main component of an RF energy harvester is called rectenna, for rectifying antenna. A block diagram of such a system is illustrated on Fig. 1. It contains a receiving antenna followed by an RF-to-dc rectifying circuit and optionally an energy storage device. A rectifier is often made up of a combination of Schottky diodes, an input RF filter and an output bypass capacitor. The input filter, localized between the receiving antenna and diodes, is a low-pass filter which rejects unwanted high order harmonics created by the non linear behavior of the diodes. It also acts as an impedance matching network between the antenna and the rectifier [1]-[2].

The microwave rectifier can take several configurations, the single serial [2]-[3]-[4] and shunt configurations [2]-[5] are however the most used. To reach high dc output voltage, a voltage doubler [2]-[6]-[7] can be a possible solution.

For a given input RF power level, the RF-to-dc conversion efficiency is particularly affected by the diode losses and the input impedance mismatching, the diode losses usually being dominant.

In this study, we focus on the RF energy conversion at 2.4 GHz, frequency greatly used due to its low attenuation through the atmosphere, low cost technology and location at the center of an un-licensed ISM (Industrial-Scientific-Medical) frequency band [8].

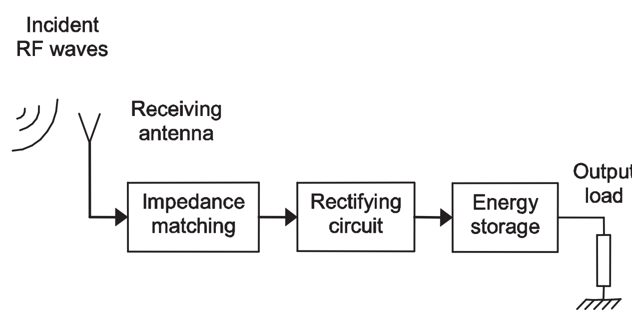

Fig. 1: Block diagram of an RF energy harvester

This paper reports a complete study, ranging from design to experimental characterization, of a Cockcroft-Walton voltage multiplier at 2.4 GHz. This circuit contains 6 cascaded stages. It is designed and optimized by using a global analysis technique [9]. The reported design is able to provide an output dc voltage of 850 mV at -15 dBm and more than 3 V at -5 dBm input RF power, over a 100 MΩ resistive load.

The ADS simulations were achieved by coupling Momentum electromagnetic simulator and Harmonic Balance (HB). In a first time, and after the optimization step, the distributed part of the circuit is simulated using Momentum and the scattering matrix

(S parameters) is calculated. In a second time, harmonic balance uses this scattering matrix and the packaged models of lumped linear and non-linear elements to simulate the circuit.

Usually, when designing rectenna circuits, the main issue consists of maximizing the electrical energy delivered to the load or the RF-to-dc conversion efficiency [10]-[11]. Indeed, a new and efficient dual-diode rectenna was reported in [10]. More than 80 % global efficiency and 2.6 V dc output voltage over a 1050 Ω resistive load have been achieved at a power density of 0.22 mW/cm² (E ~ 29 V/m). A compact and efficient 2.45 GHz rectenna was presented in [11] where a circularly polarized shorted ring-slot antenna was used. The reported rectenna exhibits a maximum efficiency of 69 % and an output dc voltage of 1.1 V at a low power density of 20 µW/cm² (E = 8.7 V/m).

In this work, our goal consists of maximizing the output dc voltage in order to power a MEMS transducer. The use of a conventional topology like the single serial, the single shunt or even the voltage doubler was shown to be inefficient. Other topologies, less conventional, should be used. The Cockcroft-Walton voltage multiplier with several cascaded stages can be an interesting solution [12]-[13].

VOLTAGE MULTIPLIER DESIGN

The voltage multiplier scheme is shown in Fig. 2 (a). It consists of a number of identical cascaded stages, each stage contains two Skyworks SMS 7630 Schottky diodes (D_1 and D_2) [14] and two equal capacitors (C_1 and C_2) as illustrated in Fig. 2 (b).

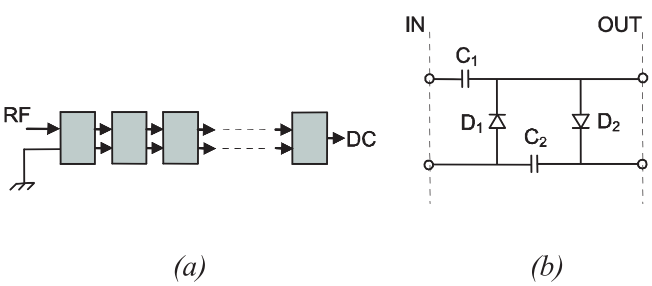

Fig. 2: Voltage multiplier scheme (a); one stage multiplier (b)

To show the impact of the number of stages and the value of capacitors C_1 and C_2 on the dc output of the circuit, parametric studies were achieved.

Figure 3 shows the HB-simulated dc voltage against the number of stages (from 1 to 15), for several RF power levels (-20, -15 and -10 dBm). The capacitors are considered ideal and set to be 100 pF, the output load is fixed to 100 MΩ. For each simulation, the input impedance matching with the RF generator is satisfied. The results clearly show that the output dc voltage increases when the number of stages increases. However, taking into account the different losses (substrate, electromagnetic couplings, parasitic elements …) in the circuit could reverse the trend from a number of stages, when these losses become more important than the gain provided by adding several stages.

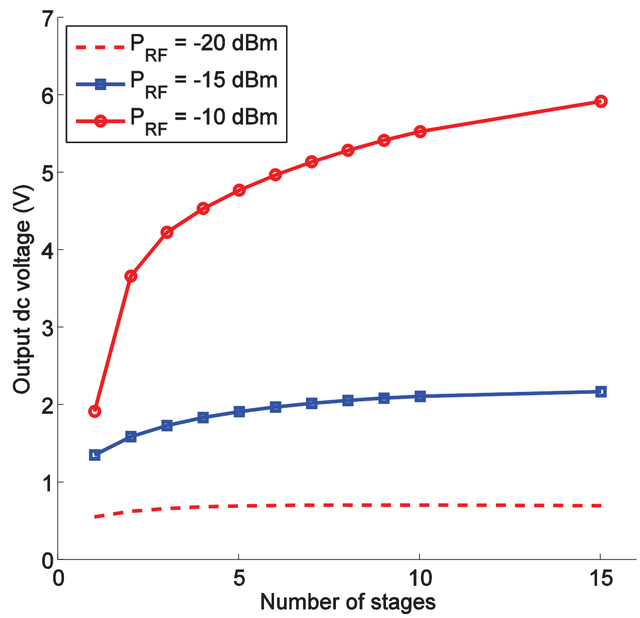

Fig. 3: Influence of the number of stage on the output dc voltage (HB simulations)

Figure 4 depicts the impact of the capacitors value (C_1 = C_2) on the output dc voltage. The number of stages was chosen to be 6 and the output load is set to be 100 MΩ. For each simulated point, the input impedance matching with the RF generator is achieved. The simulated results show that the dc voltage value, for each RF power level, becomes nearly constant from a capacitor value greater than 10 pF. However, the amplitude of the fundamental component at 2.4 GHz remains greater than 8 % compared to the dc component. It is necessary to exceed 60 pF to get a value less than 1 %.

We propose in this paper a new design of a microstrip Walton-Cockcroft voltage multiplier at 2.4 GHz (Fig. 5), containing 6 cascaded stages. It is fed by a microstrip line (Z_c = 50 Ω) and etched on Arlon 25N substrate (ε_r = 3.4, thickness = 1.524 mm, tanδ = 0.0025). It is based on Skyworks SMS7630 Schottky diodes. Series capacitors (C = 68 pF) were properly optimized and modeled, by taking into account their parasitic effects. A quarter wavelength radial stub (L_6, θ) isolates the output load from RF incident power. In order to achieve an impedance matching between the RF generator (or the receiving antenna) and the rectifier, an open circuit stub (L_5, W_2) and a quarter wavelength transformer (L_2+L_3+L_4,W_3) were calculated and used. The circular topology of the design and the arrangement of the different components are carefully chosen so as to reduce the dimensions of the ground plane.

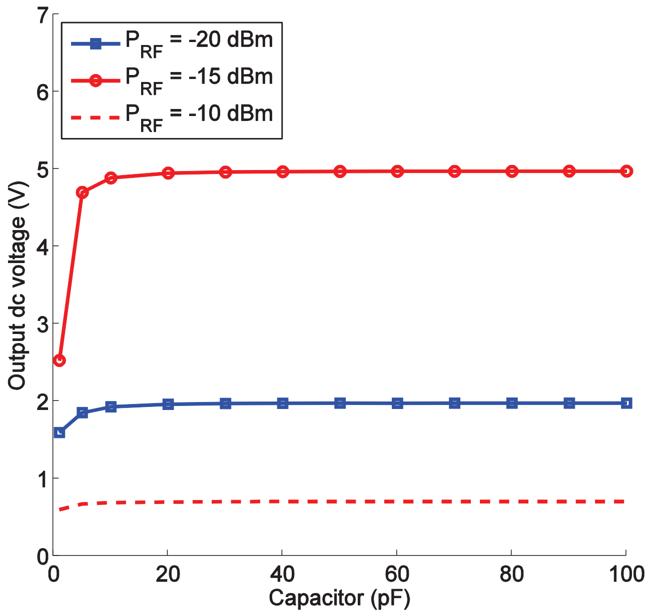

Fig. 4: Influence of the capacitors value on the output dc voltage (HB simulations)

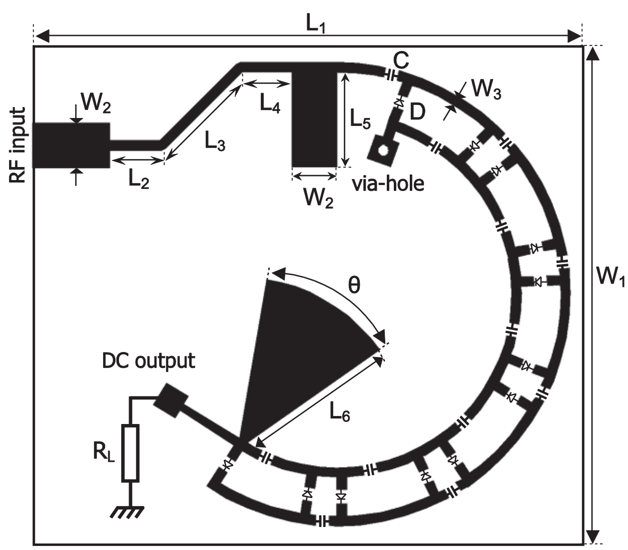

Fig. 5: Geometry of the proposed circuit: L_1=45, L_2=4, L_3=8.4, L_4=4, L_5=7.3, L_6=12.5, W_1 = 46, W_2=3.5, W_3=0.8, θ=45° (dimensions are in millimeter)

EXPERIMENTAL CHARACTERIZATION

The optimized and designed structure has been fabricated and experimentally characterized. Measured results in terms of output dc voltage are compared with ADS simulations. Figure 6 shows the simulated and measured output dc voltage against the frequency in the range of 0.5 – 4 GHz. The input RF power and resistive load are set to be -15 dBm and 100 MΩ, respectively. At 2.4 GHz, the measured dc voltage is 0.85 V and that achieved by ADS simulation is 1.05 V. Good agreement can be observed between theoretical and experimental results.

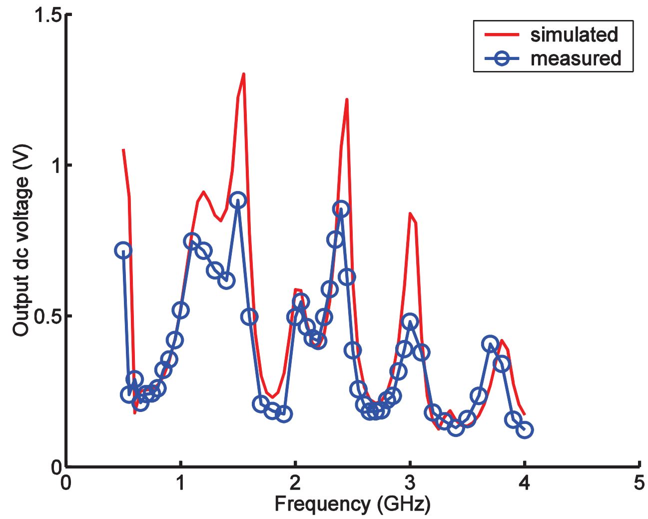

Fig. 6: Output voltage vs. frequency (R_L = 100 MΩ)

Figure 7 depicts a comparison between the curves of simulated and measured dc voltage, as a function of input RF power from -25 to -5 dBm. Over an output load of 100 MΩ, output dc voltages of 3.16 and 3.36 V have been obtained by ADS and experiment, respectively.

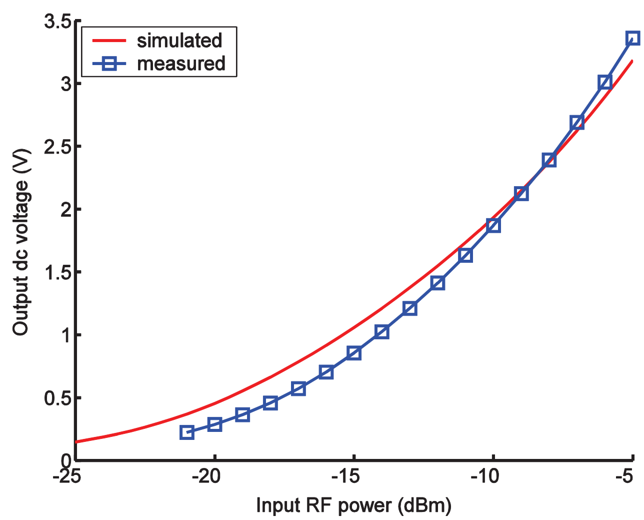

Fig. 7: Output voltage vs. input RF power (R_L = 100 MΩ)

Figure 8 represents the ADS-estimated and measured dc voltage for several input power levels (-20, -15, -10 and -5 dBm) against output load. We can notice that the dc voltage increases when the output load increases. However, from a load of about 10 MΩ, the increase becomes insignificant.

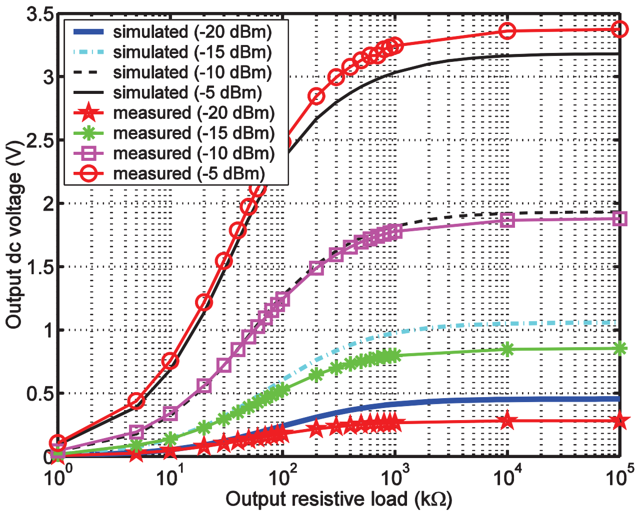

Fig. 8: Output voltage vs. output resistive load

CONCLUSION

In this paper, we propose a low RF power Cockcroft-Walton voltage multiplier at 2.4 GHz ISM frequency band. The reported circuit was fabricated and characterized. The measured results show to be in a good concordance with ADS-simulated results. This circuit is dedicated to wireless powering of a MEMS transducer. It is able to provide an output dc voltage of 850 mV at -15 dBm and more than 3 V at -5 dBm, over a 100 MΩ resistor.

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