An Energy Harvesting Circuit for Self-Powered Sensors

Jorge R. Fernandes, Miguel Martins, Moisés Piedade, and Hugo Gonçalves

***Abstract*—In this work we present a prototype circuit to harvest energy from radio waves or through magnetic coupling based on a stack of full-wave rectifiers with transistors working on sub-threshold region. This circuit will use as an input a field-to-voltage converter capable of outputting a 200mV waveform and is able to self-start without any other energy sources. The circuit presented here is a proof of concept energy-harvesting circuit powering a low frequency ring oscillator which acts as the load. The circuit is designed, simulated and tested in a standard CMOS process, AMS CMOS 0.35 µm.**

***Index Terms*—power-harvesting, full wave rectifier**

I. INTRODUCTION

RECENT trends and advances on circuits and systems employing nano-devices, both CMOS and non-CMOS devices, has increased the usage for silicon sensors. These are expected to have a huge growth and to be used everywhere, within electronic products, gadgets, and even medical and life sciences [1].

To increase functionality new sensors include electronics for processing and communications, and furthermore, wireless sensors are looking for ways to be self- powered and extend its autonomy and independence.

Batteries are the most used and led to this huge growth market reality, however they are now limiting its continuing growth since they can be expensive, bulky, they require replacement and disposal, and in certain applications special care has to be taken due to the chemicals inside. Ways to recharge the batteries, or even better to replace them, using energy harvesting techniques are being researched [2-3].

Most common energy harvesting techniques for low power applications are to convert light, mechanical, or magnetic energy into electric energy.

To convert light to electric energy it is necessary a photovoltaic cell (commonly referred to as a solar cell if the source is the sunlight) which are grouped into solar panels or solar modules.

To convert mechanical energy into electrical energy piezoelectric materials or micro electromechanical systems (MEMS) are used to harvest energy from ambient vibrations [4-5].

These two techniques have been useful for certain niche applications with the drawback of combining different technologies which limits cost reduction and integration. Furthermore the light approach has the drawback of requiring a larger area and to limit the use of the sensors in environments with light, while in the MEMs approach it is required that the sensor is not static.

An alternative is to harvest energy from radio waves [6], which is the method used for powering RFID tags and has become increasingly popular. In RFID applications it is used a high energy source nearby, however the procedure can be extended to harvest energy from radio waves emitted from TV or radio transmitters, WiFi transmitters, cell-phone antennas, or any other sources present in urban environments.

Many applications using sensors do not need a full time working processing unit and a standard radio link to communicate: they just require a very simple control and processing unit with a low data-rate radio link, with low area and low power where low-cost is the key feature, especially for disposable units.

In this paper we present a prototype circuit to harvest energy from radio waves or through magnetic coupling based on a stack of full-wave rectifiers with transistors working on sub-threshold region. Equivalent circuits exist for many years (the authors traced it back to 1919, by Heinrich Greinacher) in a context where high voltage values (kV) were used as input and the circuits worked as ideal voltage doublers. More recently several implementations of the full-wave rectifier has been used (examples of it in [2-6]) as a way to rectify the electric signal recovered by the input stage, either piezoelectric or radio wave. Then, a larger voltage is generated by the subsequent stages. The circuit presented here is a low voltage energy-harvesting circuit, without further processing, powering a low frequency ring oscillator which acts as the load. The circuit is designed, simulated and tested in a standard AMS 0.35 µm CMOS process.

This paper is organized in six sections. In section II we review the energy harvesting building blocks and present our circuit main block. In section III we present a prototype circuit with example simulations. In section IV and V we present the test environment and the experimental results. Finally in section VI we draw some conclusions.

II. ENERGY HARVESTING TECHNIQUES

Generally, energy harvesting circuits have to convert an AC voltage into a DC voltage, store it and, in special cases, multiply it. Well known techniques are to use a half- or full-

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wave rectifier followed by a voltage regulator, which in its simpler form can be just a capacitor. In case the DC voltage is lower than the value needed, voltage doublers can be used to obtain the necessary voltage. Most of these systems are used with a battery that ensures that certain control mechanisms can work on power-up, being the power harvesting circuit just a way to recharge a battery and ensure it lasts longer. Furthermore, they are usually considering the use of larger voltage signals to accommodate diodes full conduction.

Here we try to use older techniques that do not require switches and batteries. The system exploits a stack of full-wave rectifiers with MOS transistors operating in sub-threshold region that can be used to recover energy from radio waves or through magnetic coupling. This circuit is intended to be designed with a sensor that will act as a field-to-voltage converter that is able to give a 200mV peak-to-peak amplitude signal.

We are using MOS transistors from a 0.35µm technology with a threshold voltage on the order of 500mV well above the available source voltage of 200mV. Therefore, we have the transistors operating in the sub-threshold region where the dependence between I_D and V_{GS} is exponential (weak inversion) by [7],

$$I_D = I_M \exp\left(\frac{V_{GS}-V_M}{n.\phi_t}\right)\left[1-\exp\left(-\frac{V_{DS}}{\phi_t}\right)\right] \qquad (1)$$

where I_M is dependent on the technology and transistor dimensions, $\phi_t = kT/q$ is the thermal voltage, V_M is a term lower than the threshold voltage and n is a variable dependent on technology and biasing that usually takes values from 1.2~1.8.

The main block used in our prototype is represented in Fig. 1. It is important to notice that the input is going to be obtained by a field-to-voltage converter which is not grounded, therefore a reference voltage can be used (V_{REF}) which acts as a transformer secondary with middle point.

The circuit represented in Fig. 1 was simulated varying several parameters to get a flavor of what are the absolute values to be expected for such a circuit in these operating conditions. The nominal values for the circuit are C=400fF, $M_{1\text{-}4}$ have dimensions of $10\times(W/L)=10\times(25\mu m/0.35\mu m)$, V_{REF}=100mV, $v_{in+}-v_{in-} = A \sin(2\pi f t)$ being A=200mV, f = 10kHz (note: the value of 10 kHz is used as a reference value for transient simulation feasibility as the circuits are simulated up to 40s to ensure final values). These values are used to obtain the results described through tables 1 to 4 (highlight in grey background) except for one which is varied.

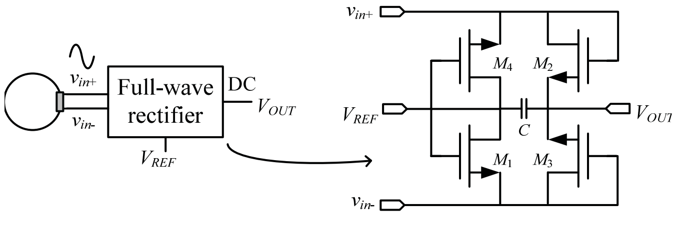


Fig. 1. Full-wave rectifier with NMOS transistors.

TABLE I
V_{REF} VARIATION

C=400fF, $M_{1\text{-}4}$ =10×(25µm/0.35µm), A=200mV f = 10kHz	
V_{REF}	**V_{OUT}**
0 V	100 mV
100 mV	197 mV
500 mV	574 mV

TABLE II
A VARIATION

C=400fF, $M_{1\text{-}4}$ =10×(25µm/0.35µm), V_{REF} =100mV f = 10kHz	
A	**V_{OUT}**
200 mV	197 mV
400 mV	343 mV
600 mV	491 mV

TABLE III
f VARIATION

C=400fF, $M_{1\text{-}4}$=10×(25µm/0.35µm), A=200mV, V_{REF}=100mV	
f	**V_{OUT}**
10 kHz	197 mV
100 kHz	196 mV
1 MHz	191 mV
10 MHz	166 mV

TABLE IV
W/L VARIATION

C=400fF, A=200mV, V_{REF}=100mV, f = 10kHz		
W/L	**V_{OUT}**	**Rise time: 0 to 163 mV**
10×(1µm/0.35µm)	187mV	47.3 ms
10×(5µm/0.35µm)	192 mV	21.5 ms
10×(25µm/0.35µm)	197 mV	5.3 ms
10×(125µm/0.35µm)	197 mV	1.6 ms

From Tables 1 and 2 we observe that the voltage drop on the “diode connected” transistors reduce the maximum voltage achievable on a full-wave rectifier and that its’ influence with amplitude and reference voltage increases with these parameters as expected from (1). Table 3 shows that as frequency increases the voltage becomes smaller as expected due to bandwidth limitations. Table 4 shows that transistor dimensions influence more the time response of the circuit than the final voltage to be obtained.

III. ENERGY HARVESTING PROTOTYPE

One common way to increase the DC voltage from a DC source is to use a voltage doubler by stacking half- or full-wave rectifiers. These techniques are very efficient to double the voltage for each stage and are often called voltage multipliers. This is not the case because the transistors used in this work cannot be considered as ideal rectifiers as when used with very high voltages. With the most simple models

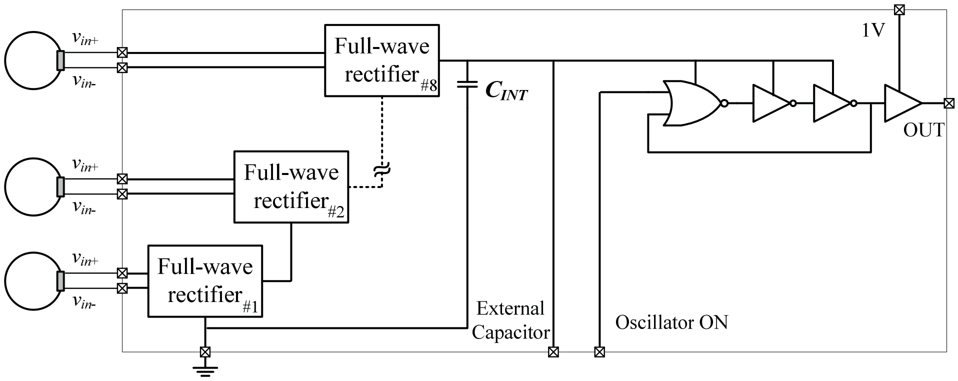


Fig. 2. Prototype of an 8-stage power harvesting circuit with a test ring oscillator in-chip.

commonly used for the MOS transistors (MOS models level 1~3) the transistors would be cutoff and the currents would be considered zero. As we saw in section II the current below the transistor threshold voltage has an exponential characteristic with V_{GS}, but having very low values. For the wanted application we can consider having it harvesting the energy for long time periods, store it, and then use for a short period to send a small amount of data.

The prototype circuit is represented in Fig. 2 where each full-wave rectifier output is connected to the above reference input. We have targeted to have a circuit functioning at 400mV and to obtain such a voltage level with the present technology we need 8 stages of full-rectifiers. We recall the conclusions drawn in Section II from Table 1 and 2 to explain why we need so many stages. These effects are shown in Fig. 3 where it can be observed that as the V_{REF} increase the voltage difference between stages decrease, as expected.

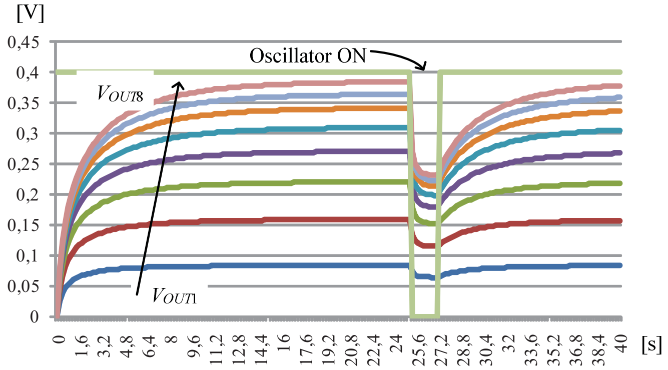


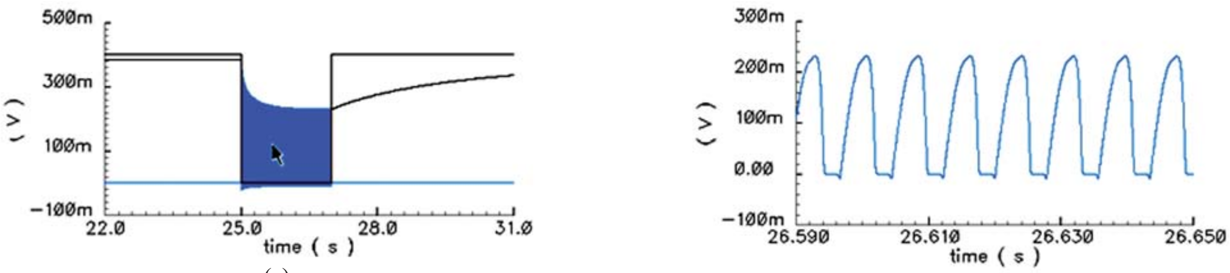
Fig. 3. 8-stage power harvesting circuit outputs and the effect of loading it with the test ring oscillator.

The circuit in Fig. 2 has a 25pF internal capacitor and was simulated with a 100pF external capacitor. Higher values are obviously possible but they would increase the simulation time accordingly. The ring oscillator is composed of three gates, one NOR and two inverters, designed to have the transfer characteristic center point adjusted to half the 400mV wanted voltage. The NOR gate allows to turn on and off the ring oscillator as wish for testing purposes. The circuit also comprises an output stage for testing purposes, to drive larger capacitances at higher frequencies.

In Fig. 4 we have the last stage voltage output, the oscillator control voltage and the test ring oscillator which acts as a load. The loading effect reduces with the capacitance increase but so do the simulation time. Simulations that include Monte Carlo analysis with process and mismatches variations showed that the circuit behavior is maintained with variation on the output voltage value. Further results are expected to be obtained from the test chip.

The circuit was designed (shown in Fig. 5, with an area of 1890×210 μm^2), extracted and simulated after extraction, showing it is robust to parasitic capacitances which only add to the existing ones improving the storage capability of the circuit. The circuit does not require pads with protection circuitry because the transistors are large; the pads are connected to sources, and the voltage increase slowly to low values. Extra observation points are left inside the circuit for observation of the individual full-wave rectifiers output.

Fig. 5. Prototype circuit (1890×210 μm^2).



(a) (b)

Fig. 4. Power harvesting circuit and test ring oscillator outputs (a) during 2s (b) zoom of the oscillator output.

Being a prototype circuit, these test features allows the circuit to be characterized beyond the scope of this application, with larger values of capacitance or higher frequencies. In these cases it is much simpler to characterize it by testing than by simulation, where the combination of larger values of frequency with larger values of capacitance make transient simulations too long to be practical.

IV. TESTBENCH LAYOUT

As referred in Section II this circuit was developed to be incorporated with a field-to-voltage converter which would serve as the power source with an input voltage in the order of 200 mV. For testing purposes in order to mimic this system as well as isolate the circuit a transformer was connected to each circuit input as shown in Fig. 6. This circuit (Fig. 5) was tested with a function generator (UNAOHM EM 193B) connected in parallel with the transformers (Coilcraft PWB1010-1L) it was also included a 50 Ω impedance matching circuit to adapt the transformers to the function generator output impedance.

The output buffer is powered with an external DC source (1.2 V) and the oscillator switch on (OSC_{on}) is controlled by a square wave generator. The primary winding of the 8-Transformer Array is shorted to ground and the secondary winding is connected to the circuit V_{in-} and V_{in+}. With this setup we ensure circuit isolation and DC decoupling.

V. EXPERIMENTAL RESULTS

Figure 7 shows the rectifier output voltage when the circuit is idle collecting energy from the energy source. The overall results show that the circuit behaves better at 10 MHz where it is closer to the simulated voltage values with 380 mV output voltage with 350 mV input. These values are relatively lower than expected, which is due to impedance mismatch between the transformers and the function generator, and a higher bonding inductance and encapsulating parasitics.

The preceding results show that: (1) the voltage stored by each rectifying stage is below the input voltage because the transistor operates at one third of the threshold voltage; (2) operating in sub-threshold with higher v_t technologies makes imperative good isolation between rectifying stages for better circuit performance; (3) the input stage of the circuit must have a good impedance match to minimize losses; (4) the cutoff voltage of this circuit is approximately 200 mV.

In Fig. 8 it is represented the oscillator circuit output (the figure is obtained from a simulation of the full testbench in Fig. 6, because it was not possible to take a snapshot of the circuit working with the oscillator On). The ring oscillator kicks-off when OSC_{on} is low (zero Volts). The decrease in the oscillating frequency in time is to be expected as the voltage source of the ring oscillator decreases overtime with the discharge of the external capacitor.

The results show that the energy harvesting circuit, using a standard CMOS process with v_t as high as 600 mV and with the transistor working in the sub-threshold region is able to charge.an external capacitor, being then capable of powering a small circuit (in this case a ring oscillator) for a short period of time.

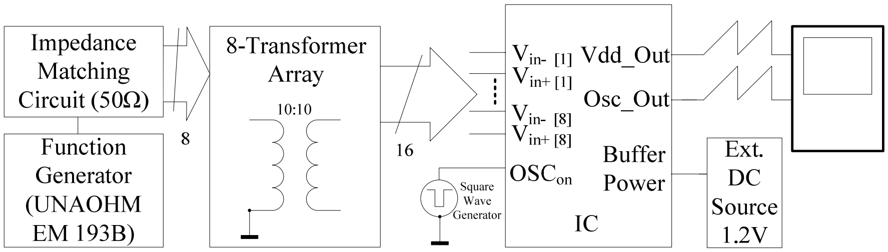


Fig. 6. Testbench circuit

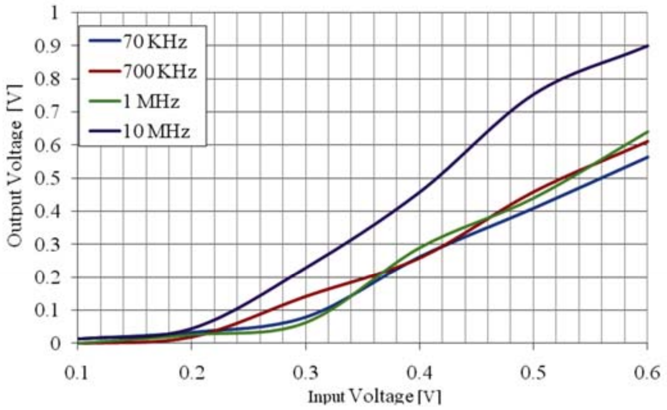


Fig. 7. Output voltage at the 8th stage (experimental).

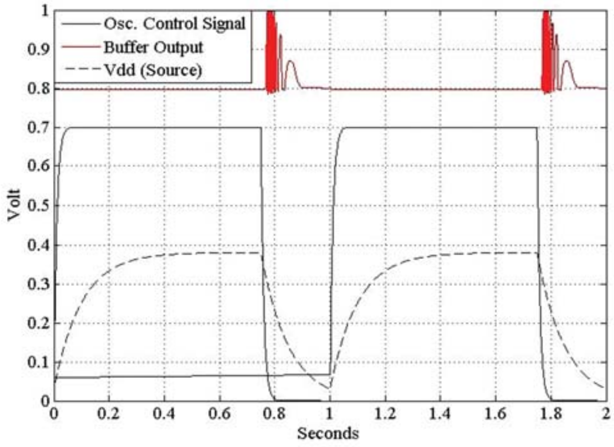


Fig. 8. Oscillator Output with control signals (simulation).

VI. CONCLUSIONS

We present a power harvesting circuit to be used in a low cost self-powered sensor. The circuit uses a stack of full-wave rectifiers as a common voltage multiplier and in this paper it is evaluated its feasibility for low voltages below the transistors threshold voltage. The circuit has no switches or any other energy source as in more complex approaches and comprises a ring oscillator to act as a load.

The full-wave rectifier is evaluated based on a sub-threshold model and under parametric evaluation which leads to the confirmation of the expected behavior and with the absolute values obtainable giving the designer useful guidelines.

Experimental results show that the circuit has an output voltage of approximately 380 mV with 350 mV input and the stored energy is enough to power a small circuit (ring oscillator). The differences between the simulated and experimental results are discussed.

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