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Design and Implementation of Ambient RF Energy Harvesting Circuits

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***Abstract* - This paper presents design strategies and measurements of two RF energy harvesting circuits working at UHF frequencies (around 480 MHz). Ambient RF sources are considered so for the circuit designs low power levels have been assumed. The circuits were implemented and the RF/DC conversion efficiency was measured.**

***Index Terms* – Matching network, RF energy harvesting, schottky diode, voltage doubler.**

I. INTRODUCTION

In general the energy harvesting denotes all processes through which the energy, coming from alternative sources, as sun and wind, is caught and stored, a particular technique is the RF energy harvesting where the irradiated RF energy is processed. On the other hand, the electrical power levels, generated using this technique, are very low, some milliwatts, but still enough to drive low power devices.

The block diagram of an energy harvesting system is shown in Fig.1, it is composed by the matching network, the multiplier and the DC-load circuit [1]. In this system the matching network permits to maximize the power transfer whereas the voltage multiplier performs the effective conversion from RF to DC. Consequently, the conversion efficiency depends on the type and number of nonlinear devices, which form the multiplier, and is affected by the matching structure.

In addition the characteristics of the RF signal have a direct effect on the RF/DC conversion efficiency, which is characterized by the ratio between the DC power and the RF power.

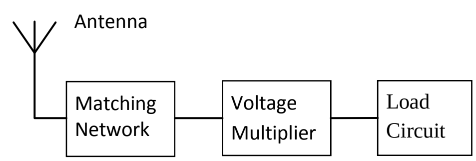

Fig.1. Block diagram of an energy harvesting system.

The RF energy sources can be parted into three general groups: intentional sources, known and unknown ambient sources [2]. This work considers known ambient sources, as antennas that radiate in the UHF frequencies around 480 MHz. In particular, this study is aimed at identifying the potential efficiency of an RF/DC conversion system made with hybrid technology using Schottky diodes and capacitors. Therefore, the voltage multiplier is examined in its simplest form: the voltage doubler. Selected the voltage doubler structures, the study was carried out throw the following steps, firstly, a particular Schottky diode was chosen and its model was implemented on the CAD software used to synthesize the circuits. Secondly, voltage doublers and matching networks were synthesized and realized; successively the achieved circuits were tested in order to verify their correspondence with what was designed. Finally, the real target of this study, measurements to define the RF/DC power conversion were carried out.

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II. SELECTION AND MODELING OF THE DIODE

Schottky diodes can be parted in two basic categories: diodes realized using n or p silicon; the first are characterized by relatively high barrier and low series resistance, consequently they are suitable for detectors and mixers where DC bias is available. On the other hand, the p silicon diodes are characterized by low barrier and high series resistance; these devices were accomplished for application where DC bias can not be used. Therefore, taking into account studies reported in [3], [4] where diode performances are examined the schottky diode HSMS-285C from Agilent were selected. The HSMS-285x family includes zero biased diodes which are optimized for low signal (<-20dBm) applications at frequencies below 1.5GHz.

The diode parameters are reported in the Agilent data sheet in particular the nonlinear behavior of diode is described by the SPICE parameters reported in Table 1[5].

Table 1: SPICE parameters

Parameter	Units	Value
B_V (Vbr)	V	3.8
C_{JO}	pF	0.18
E_G	eV	0.69
I_{BV}	A	3.0E-4
I_S	A	3.0E-6
N	-	1.06
R_S	Ohms	25
P_B (Vj)	V	0.35
P_T (XTI)	-	2
M	-	0.5

The SPICE parameters permit to model the diode chip, however to obtain accurate linear and nonlinear analysis also the package equivalent circuit must be considered [6].

Fig.2 shows the equivalent circuit of the HSMS-285C package (SOT-323) and the component values.

III. VOLTAGE DOUBLERS

The considered voltage doublers are the Greinacher and Delon circuits, the first, shown in Fig. 3, is composed by a Villard cell and a peak detector.

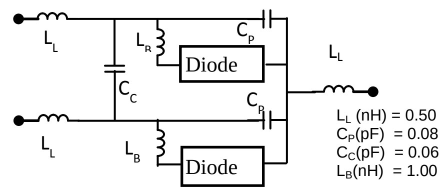

Fig.2. Model of the SOT323 package.

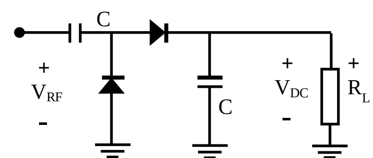

Fig.3. Greinacher circuit.

The effect of the first cell is to shift up the RF waveform so that the negative peaks are clamped to about 0 V. The second cell reduces the ripple providing a DC voltage about equal to the double of RF signal amplitude.

The Delon circuit, shown in the Fig.4, is realized connecting in series two peak detectors, the first detects the positive peak and the second the negative peak, and the total DC voltage is provided across the two capacitors.

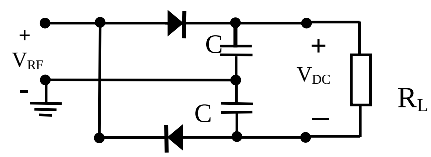

Fig.4 Delon circuit.

In general, the capacitors C do not affect significantly the output voltage. However, the fundamental requirement is to keep their related

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impedance low with respect the diode impedance. So capacitors with a value of 100pF are used, they present at the 480MHz frequency a reactance much less than the impedance of a single diode operating at -30dBm. Consequently, the capacitors are short-circuits and the Schottky diodes are put in parallel.

IV. VOLTAGE DOUBLER DESIGN

Chosen the diode, selected the voltage doublers and implemented both on the used CAD software, Advanced Design System (ADS) by Agilent Technoklogies, the design problem consists in the achievement of a matching network between the source at 50□ and the voltage doubler input impedance. It is important to note that the diode has an impedance function of the power levels of the RF signal [3],[4]. Therefore, the matching network was synthesized considering a reference power level equal to -30 dBm. In particular, to reduce losses due to passive components, the simplest circuit solutions have been chosen, namely the L networks.

The Fig.5 shows the achieved Greinacher doubler, where the matching network is constituted by the components C_1=0.8pF and L_1=56nH. The element HSMS285C represents the pair of diodes and the package model.

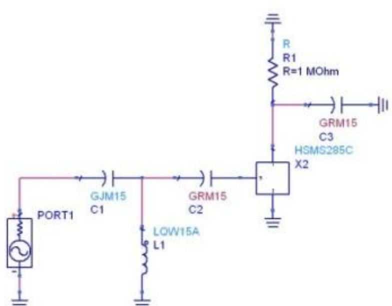

Fig.5. Simplified scheme of Greinacher doubler.

The resulting input impedance of the doubler, without and with matching network, is shown in Fig.6.

The Fig 7 shows the Delon doubler, where in the L matching network C_1=0.9pF and L_1=68nH result. Fig. 8 describes the doubler input impedances without and with the L network.

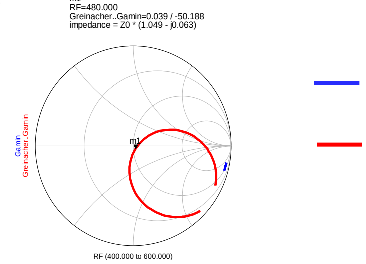

Fig.6 Greinacher doubler input impedance.

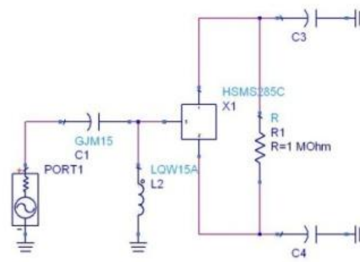

Fig.7 Simplified scheme of Delon doubler.

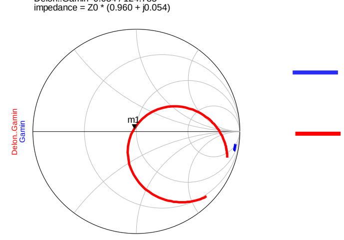

Fig.8 Delon doubler input impedance.

For simplicity in the schemes shown in Fig.5 and Fig. 7 the microstrip connections are not reported. However, in the real design, microstrips, vias have been taken into account. Moreover, to ensure a good match between simulations and measurements the structure discontinuities have been characterized using the Momentum, which is electromagnetic simulator of ADS.

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For the two doubler achievements is assumed the use of FR4 (e_r = 4.35, substrate thickness =1.6 mm, conductivity = 5.8 e7 S/m, conductor thickness = 35 μm, tan δ = 0.018).

V. VOLTAGE DOUBLER REALIZATION

In order to perform the desired measures the two voltage doublers have been realized and the obtained circuit photos are shown in Fig. 9 and Fig. 10.

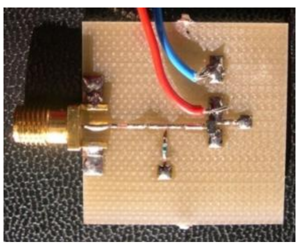

Fig.9. Greinacher doubler photo.

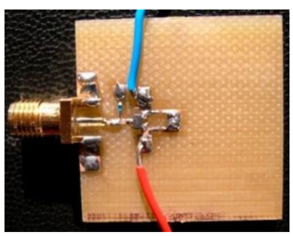

Fig.10. Delon doubler photo.

Measurements by using Anritsu 37397D VNA were done to verify the fitting between designs and produced circuits, and S_{11} measures and simulations were compared for different signal power levels. In particular Fig.11 and Fig.12 show the return loss, obtained assuming a power level equal to -30 dBm.

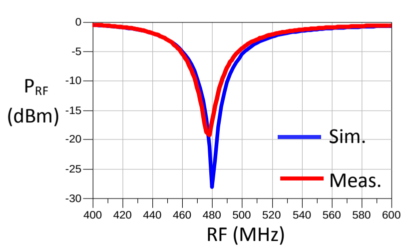

Fig.11. Return loss of the Greinacher doubler.

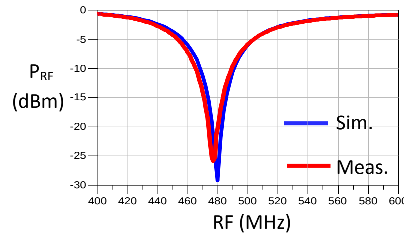

Fig.12. Return loss of the Delon doubler.

VI. MEASUREMENTS

Verified the correspondence between design and implementation for the voltage doublers, measurements were carried out to obtain the DC voltage values resulting from the RF input. This result was achieved using as RF source the Agilent E4438C vector signal generator. Several measurements were made for different loads and RF power levels; Fig.13 and Fig.14 show the obtained voltage values for RF power levels equal to -40, -30 and -20 dBm for the two selected configurations.

The best performance are obtained around 480MHz and, for a load equal 10MΩ, an input RF power of 1μW produces about 70 mV. Obviously, for lower load values, the results decrease, so at 100KΩ and 10KΩ the DC voltage values are around 55 mV and 25 mV for an input RF power equal to 1μW.

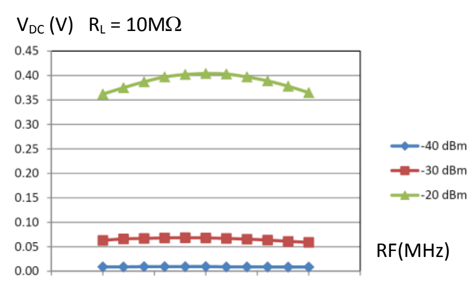

Fig.13. Voltage values by Greinacher doubler.

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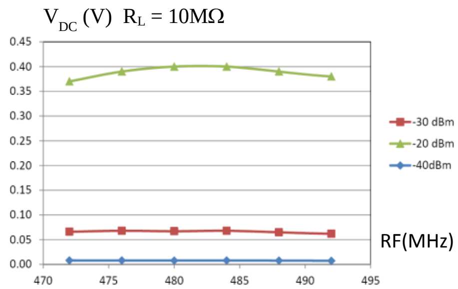

Fig.14. Voltage values by Delon doubler.

The collected measurements were processed in order to achieve the RF/DC power conversion efficiency. The Fig.15 shows the conversion efficiency values obtained for different power levels and different loads. So at a 1μW the greatest conversion efficiency value is about 6% achieved with a load of 10KΩ.

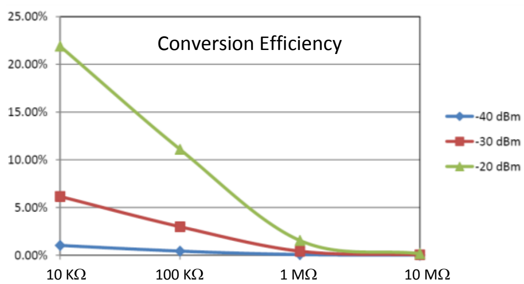

Fig.15. RF/DC conversion efficiency by Greinacher doubler.

VII CONCLUSION

This work was aimed to acquire knowledge on the RF/DC conversion efficiency values which can be achieved by hybrid technology, using Schottky diodes and capacitors. UHF TV broadcasting frequencies around 480 MHz have been taken into account. The desired result was performed, firstly designing and realizing two different RF/DC conversion systems and then measuring and processing the collected data. In particular, for a load equal 10 MΩ with an input RF power of 1μW a DC voltage equal 70 mV was achieved.

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[4] Agilent technologies application note note 1088, "Designing the virtual battery ".

[5] Agilent technologies data sheet, "HSMS-285x Series Surface Mount Zero Bias Schottky Detector Diodes".

[6] Agilent technologies application note 1124, "Linear Models for diode surface mount packages ".