Maximizing DC Power in Energy Harvesting Circuits Using Multisine Excitation

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Abstract— **This paper presents an approach to signal excitation specially designed to improve the DC power obtained in a RF to DC converter and consequently its RF-DC efficiency conversion. In this sense a multisine signal is used as the excitation, and it is proved either theoretically, by simulations and by measurements, that a multisine signal with 0º phase relationship between the tones can give better DC values in an energy harvester, when compared with a single tone excitation with the same input average power.**

Index Terms— **Schottky Diode detectors, Nonlinear behavior, Energy Harvesting , Conversion efficiency, Multi-tone signals.**

I. Introduction

A radio-frequency energy harvesting system is basically composed by two components: a fixed RF energy transmitter, which broadcasts radio power to the medium and a mobile device to be powered which captures the RF energy and converts it into the appropriate DC power. A passive RFID system is certainly the most evident application of the energy harvesting concept. A passive RFID tag is entirely powered by energy coming from the reader. Diode-based envelope detectors are used to harvest DC power from incoming RF power to supply the tag electronics [1]. In its simplest form, an envelope detector is composed by a single RF Schottky diode followed by a low-pass filter (Fig. 1). Because tag sensitivity and reading range are critical in passive RFID and harvesting systems and it is important to maximize the amount of DC power collected, improved topologies have been employed. The circuit of Fig. 2 uses a cascaded N-level voltage multiplier to boost the DC voltage. The dashed circuit is a voltage doubler which provides twice the voltage obtained with a single diode envelope detector. System topologies, RD-DC conversion efficiency and signal excitation design are open research areas.

Concerning to signal excitation, conventional harvesting systems always use a single continuous carrier to remotely power the mobile device. In this paper we analyze the nonlinear behavior of single diode under multisine excitation and we propose an energy harvesting system using N-tone sinusoidal signals with 0º phase between the tones to remotely power the mobile device. This scheme will allow better conversion efficiency than the conventional single tone approach. Similar results were also obtained in [2] and [3]. We will demonstrate these results by first developing a mathematical description and then by simulations and measurements.

To do so we will conduct two different experiences. First a single carrier with P dBm power will be used to excite the diode detector. In the second experience the diode detector will be fed with a N-tone multisine signal with the same integrated RF power used in the single tone experiment, $P_{w1}+P_{w2}+\cdots+P_{wN}=P$. This is done in order to facilitate the comparison between the two cases. In this paper we will prove that if we use convenient phase's arrangements between the carriers, the DC voltage and consequently the DC power obtained in the second experience will be greater than the single tone case. This is, with the same RF input power, we will be able to harvest much more DC power if we use a multisine signal. Furthermore, if we use a low-frequency resonance at the output of the diode detector we would be capable of increase even more the DC, taking advantage of the long term memory effects reported in [4].

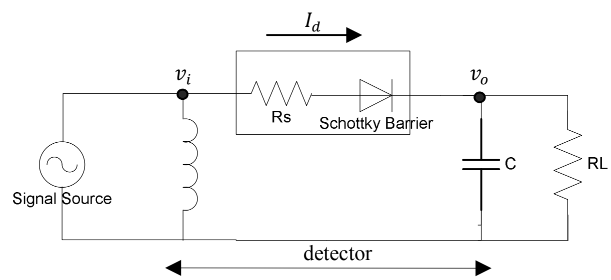

Fig. 1 Single diode detector

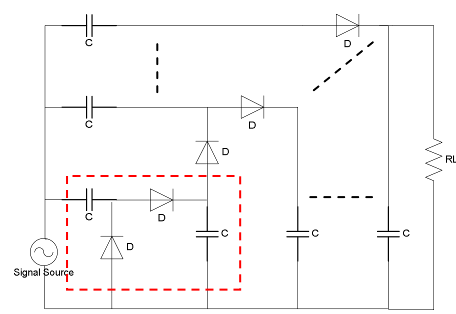

Fig. 2 N-level cascaded Voltage multiplier

II. Theoretical Analysis

In order to understand the mechanisms behind the RF to DC conversion a mathematical model description of the Schottky diode will be used. This model describes the relationship between the total current flowing through a Schottky diode and its applied voltage and it is given by:

$$I_D = I_s\left(e^{\frac{V_b}{nV_t}}-1\right) \tag{1}$$

Where I_s is the diode saturation current, V_b is the voltage across the Schottky barrier, n the ideality factor and V_t the thermal voltage. V_b is equal to an external applied voltage minus the voltage drop at the diode series resistance R_S Fig. 1.

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Figure 3 shows a typical measured I-V characteristic curve of the Schottky diode. This curve should follow the law expressed by (1). At low bias levels the voltage drop across R_S is insignificant so the diode behaviour is dominated by the Schottky barrier (quadratic region), while at higher bias levels the ohmic resistance R_S dominates (linear region).

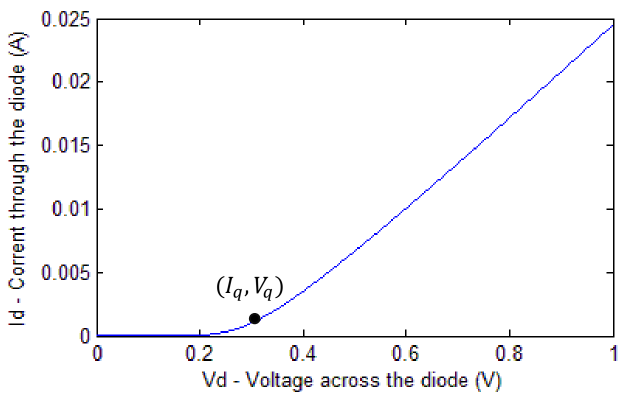

Fig. 3 Typical I-V characteristic for a Schottky diode

In order to better understand the nonlinear phenomena that will exists in the diode probe, when we excite it with a RF signal excitation, we will expand equation (1) in a simple polynomial series expansion around a quiescent operating point (I_q, V_q) truncated to order four, as was done previously in [4]. The fourth order was selected because it can be proved that it is the minimum enough for demonstrating the basic rectification operation. Hence, the current through the diode can be approximated by:

$$i_d = I_q + k_1(v_d - V_q) + k_2(v_d - V_q)^2$$
$$+k_3(v_d - V_q)^3 + k_4(v_d - V_q)^4 + \cdots \quad (2)$$

whereby $v_d = v_o - v_i$ (3)

The model coefficients $k_1, k_2, \ldots, k_N$ can be obtained from the successive derivatives of the diode current [5]:

$$k_1 = \frac{1}{1!}\frac{\partial I_d}{\partial V_d}\bigg|_{V_{d=V_q}} ;\ k_2 = \frac{1}{2!}\frac{\partial^2 I_d}{\partial V_d^2}\bigg|_{V_{d=V_q}} ; \ldots ; k_n = \frac{1}{n!}\frac{\partial^n I_d}{\partial V_d^n}\bigg|_{V_{d=V_q}}$$

(4)

To have a better understanding of the nonlinear mechanisms involved here and in order to evaluate the impact of the biasing point, we extracted the first four order polynomial coefficients from the diode I-V curve. These coefficients are shown in Fig. 4. For instance, if the diode was used for small power measurement purposes, the best operation point would be in its square law region , where the second order coefficient k_2 is dominant. On the other hand, if used for RF-DC conversion, a good operation region would be in between the maximum of k_2 and k_4. It should be notice that even though no DC biasing is externally imposed, the diode will be DC biased by a self-biasing mechanism. A validation of the extracted model of Fig.4 was done by coupling a small time-varying sinusoidal perturbation v_d to a DC quiescent point $V_q = 300\,mV$. As can be seen in Fig.5 the modelled current as predicted by (2) fits perfectly the measured diode current.

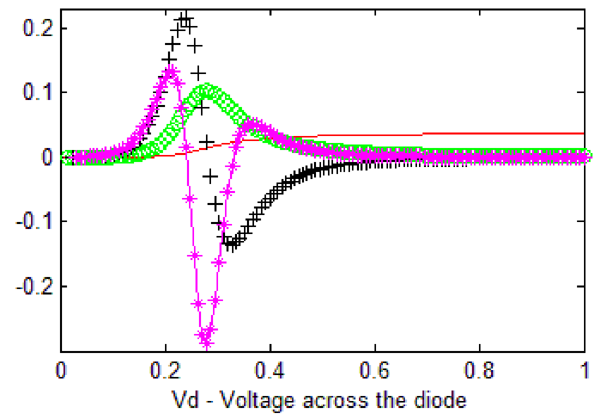

Fig. 4 Coefficients dependence on diode voltage V_d . solid red: k1 (A/V); o green: k2 (A/V^2); + black: k3 (A/V^3); * magenta: k4 (A/V^4);

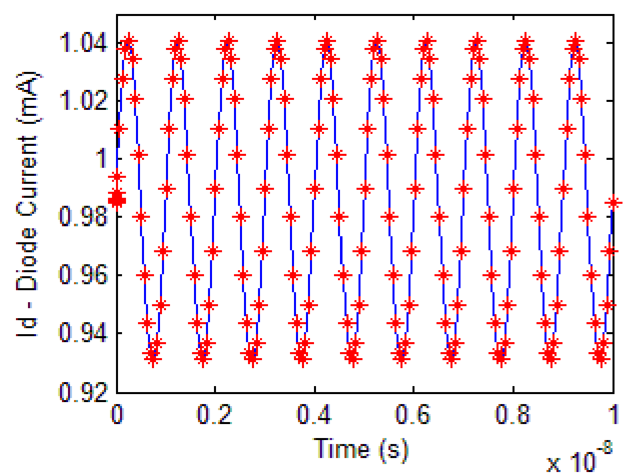

Fig. 5 Diode current over time (solid blue) and modeled current (red stars) as computed by (2) and (4)

The presented basic and simple system will now be excited using a single tone excitation, and a multisine signal. From now on V_d and I_d will be represented by generic signals $x(t)$ and $y(t)$ respectively. In order to account mainly for the components that will fall on DC, equation (2) will be simplified to consider exclusively the even order terms, since the odd order ones do not have a DC impact [5] :

$$y(t) = k_2 x(t)^2 + k_4 x(t)^4 \quad (5)$$

If we consider (5) and a single input tone at ω_1 with amplitude B and phase φ_1:

$$x(t) = Bcos(\omega_1 t + \varphi 1) \quad (6)$$

the diode output will be:

$$y(t) = \frac{B^2 k_2}{2} + \frac{3B^4 k_4}{8} + \frac{B^2 k_2}{2} cos(2\omega_1 t + 2\varphi_1) +$$
$$B^4 k_4 \cos(2\omega_1 t + 2\varphi_1) + B^4 k_4 \cos(4\omega_1 t + 4\varphi_1) \quad (7)$$

After pass this signal through a low-pass filter the components of $y(t)$ at $2\omega_1$ and $4\omega_1$ will be eliminated and the

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remaining terms will be exclusively the DC component $\frac{B^2 k_2}{2} + \frac{3B^4 k_4}{8}$. In the square law region, k_2 dominates and DC can be approximated by $\frac{B^2 k_2}{2}$. This gives us information about power since it is proportional to the input power. This relationship is the key rule of power measurements made with diodes, if it is guaranteed that the diode is operating in its square law region.

However, when a multisine signal is used as the diode excitation, a very different result will be obtained. In order to clearly understand this effect, consider a 4-tone evenly spaced multisine signal at the input, with amplitudes $A_1 = A_2 = A_3 = A_4 = A = \frac{B}{2}$, phases $\varphi_1, \varphi_2, \varphi_3$ and φ_4 , and frequencies ω_1, $\omega_2 = \omega_1 + \Delta w$; $\omega_3 = \omega_1 + 2\Delta\omega$; $\omega_4 = \omega_1 + 3\Delta\omega$,where $\Delta\omega$ is the frequency spacing between the carriers:

$$x(t) = A cos(\omega_1 t + \varphi_1) + A cos(\omega_2 t + \varphi_2) + A cos(\omega_3 t + \varphi_3) + A cos(\omega_4 t + \varphi_4) \quad (8)$$

Considering (5) and (8) we performed a symbolic computation and after filtering out both the RF and baseband signals, the following expression was obtained for the pure DC value at the diode output:

$$\begin{aligned} y_{DC}(\varphi_1, \varphi_2, \varphi_3, \varphi_4) &= \frac{4A^2 k_2}{2} + \frac{21A^4 k_4}{2} \\ &+ \frac{3A^4 k_4}{2} \cos(2\varphi_3 - \varphi_2 - \varphi_4) \\ &+ \frac{3A^4 k_4}{2} \cos(-2\varphi_2 + \varphi_1 + \varphi_3) \\ &+ 3A^4 k_4 \cos(\varphi_1 - \varphi_2 - \varphi_3 + \varphi_4) \end{aligned} \quad (9)$$

The quadratic part of (9) is consistent with the single-tone case, since it states that the input power is four times greater than the one tone case if A=B, or it is equal if A=B/2. However, we have here an additional contribution of a phase-dependent part. This make us believe that by choosing convenient phases in the multisine excitation, the DC can be maximized. Actually, the more obvious choice is to align all the tones in phase ($\varphi_1 = \varphi_2 = \varphi_3 = \varphi_4 = 0°$). These results can be expanded to more sines and thus to any N-tones multisine signal, and it can also be proved that the greater the number of tones in the multisine, the greater the rectified DC voltage, which could be useful in energy harvesting system to increase the RF-DC conversion efficiency.

III. Simulation Results

A simple diode detector (Fig.6) was used to validate the previous developed theory. The Agilent HSMS2850 Zero bias Schottky diode was used in the simulations. Two different simulations were conducted, the first one with a single tone input signal and the second with N-tone input signal with constant frequency separation between the tones and zero phase between them. In both cases the total input power is the same in order to facilitate the comparison. For simulation we used $\omega_1 = 5.8\ GHz$ and $\Delta\omega = \frac{5\ MHz}{N-1}$, N-number of tones, N>1.

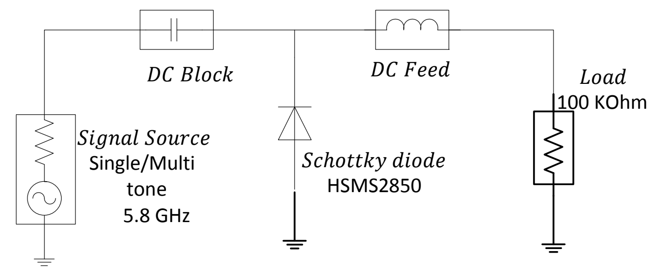

Fig. 6 Simple diode detector used in the simulations

Fig.7 shows the output DC voltage as function of the RF input power for 1 tone, 2 tones, 4 tones and 8 tones. As can be seen the simulation results corroborate our previous mathematical proof. As we increase the number of tones in the signal, the DC output voltage increases, with a constant input RF power.

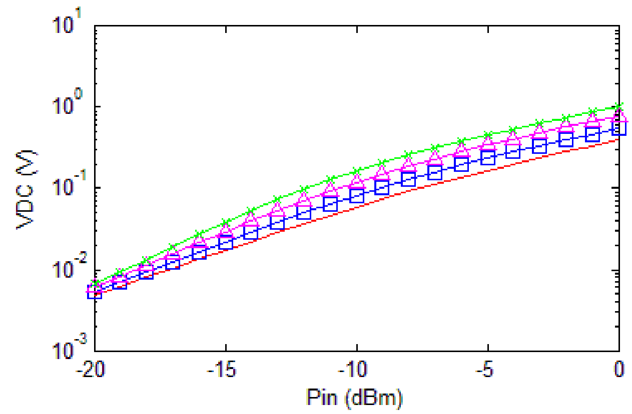

Fig. 7 DC voltage (V) as function of average input power (dBm) for: 1 tone (solid red), 2 tones (blue squares), 4 tones (magenta triangles) and 8 tones (green crosses).

In order to better analyze the results we defined a power gain figure G_p which defines the power gain obtained with N-tone signal regarding to the one-tone case. Since the DC load resistance is the same in both cases, P_G can be defined only as function of the voltages. It is defined in (10) and the results are shown in Fig.8. For the 8-tones case the gain can be as high as 9dB regarding to the one tone case.

$$G_p = 10\log\left(\frac{P_{DC_{NTone}}}{P_{DC1Tone}}\right) = 10\log\left(\frac{V_{DCNTone}^2}{V_{DC1Tone}^2}\right) \quad (10)$$

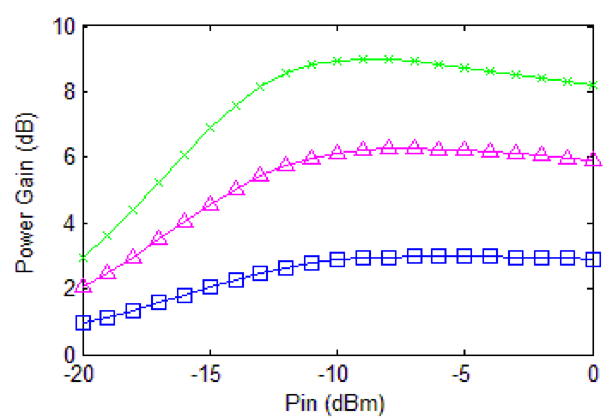

Fig. 8 Power gain as function of input power (dBm) for: 2 tones (blue squares), 4 tones (magenta triangles) and 8 tones (green crosses)

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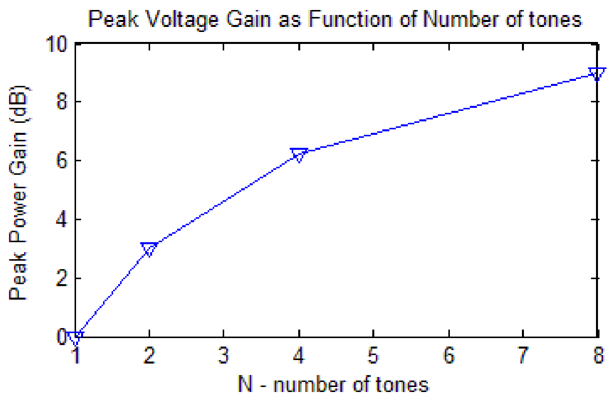

Fig. 9 Peak Power gain (dB) as function of number of tones

IV. Experimental Results

In order to prove that the theoretical assumptions are correct we built a simple RF to DC converter as in Fig. 12, the used diode was the Agilent HSMS2850 and the circuit was optimized to work at 2.4GHz band. Fig.10 shows the measured output DC voltage as function of RF input power for 1 tone, 2 tones, 4 tones and 16 tones.

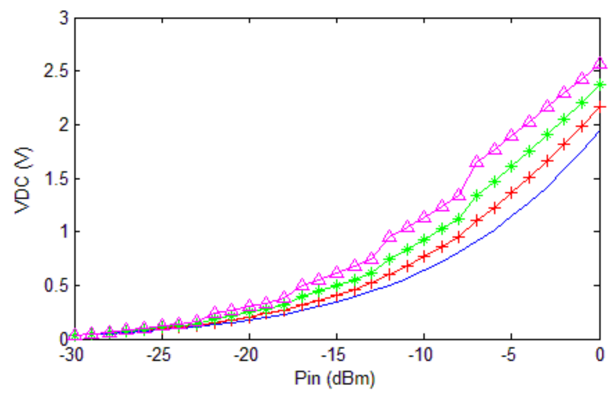

Fig. 10 Measured DC voltage (V) as function of input power (dBm) for: 1 tone (solid blue), 2 tones (red crosses), 4 tones (green stars) and 16 tones (magenta triangles).

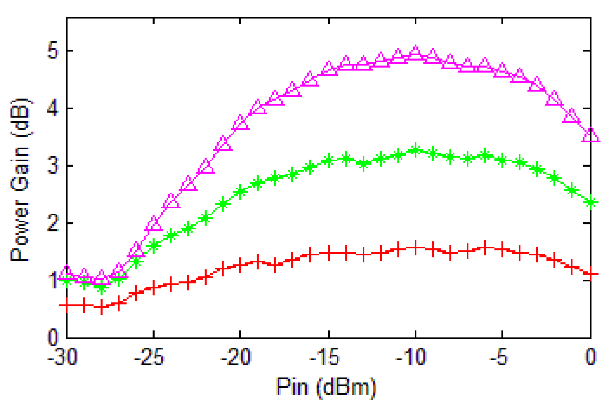

Fig. 11 Measured Power Gain (dB) as function of input power (dBm) for: 2 tones (red crosses), 4 tones (green stars) and 16 tones (magenta triangles)

In Fig.11 we can observe a maximum power gain of 5 dB for 16 tones input signal. These measured results validate the initial guess and promises novel types of harvesting systems using mutisine signal excitations to provide increased RF-DC conversion efficiency.

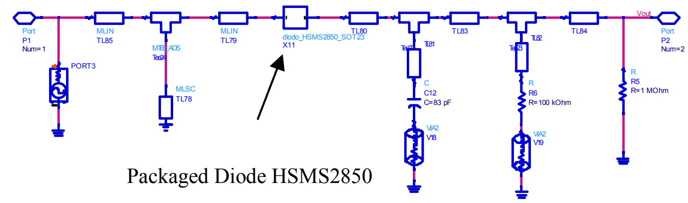

Fig.12 Diode detector used in measurements

V. Conclusions And Future work

In this paper it was shown that the use of multisine signals as the excitation in an energy harvesting system can be beneficial if the objective is to maximize the obtained DC Power and RF-DC conversion efficiency. The paper proves that using the same average power the results with a single tone excitation and with a mutisine excitation can be significantly different, with significant DC power gain in the multisine case.

More work is needed in order to carefully analyze the impact of several signal parameters in the RF-DC conversion efficiency of diode detectors such as the signal bandwidth, the uniformity/non-uniformity of tones spacing in the multisine, and more important, the phase arrangement and amplitude statistics of the excitation signal.

Acknowledgements

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