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Power Optimized Waveform for Wireless Power Transfer Systems : Simulations and Experiments

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Abstract—This paper focuses on the power optimization waveform, applied to the improvement of the efficiency and/or the maximum supply distance of far-field wireless power transfer systems. The emphasis is given to RF pulse modulation signal and multisine waveforms. The power conversion efficiency (PCE) of a RF-to-dc conversion circuits is strongly impacted by the threshold voltage of Schottky diodes at low RF power levels, and one of the objectives is to improve the efficiency under these conditions. An ultra-wide band rectifier, operating from 1.6 to 2.8 GHz, is used in this work. Significant improvement of the efficiency, compared to a CW signal, has been shown especially when the power level is small and the output load is large. Also, this work allowed evaluating the important parameters of the waveforms to be optimized.

Keywords—Power optimized waveform, ultra-wide band, RF-to-dc rectifier, Pulse modulation, Multisine, Power conversion efficiency.

I. INTRODUCTION

The massive deployment of wireless communicating sensors in the context of the Internet of Things (IoT) requires developing alternative solutions to the traditional battery power supply. These traditional solutions raise a few problems related to the limited lifetime, the environmental pollution they generate and the difficulty of recycling. Also, some sensors will be placed in areas that are difficult or impossible to reach. Replacing a battery is therefore not practical. An alternative solution to increase the battery life or replace it completely might accelerate the deployment of these sensors and open the way for much more applications. To address this issue, Wireless Power Transfer (WPT) is presented and considered as one of the most useful ways as it can remotely supply sensors and other electronics devices by converting electromagnetic waves into useful DC power, using rectenna circuits. There are several limitations that prevent high conversion efficiency. For low RF power levels, it is mainly due to the threshold voltage of the Schottky diode. The development of new Schottky diodes with lower threshold voltage than what is proposed today is one of the proposed solutions. Another solution, which interests several research groups in recent years, is to substitute the CW (Continuous Wave) waveform traditionally used in WPT by other waveforms with variable envelope. This allows to increase the non-linearities and therefore to improve the RF-to-dc conversion efficiency. Signals with high Peak-to-Average Power Ratio (PAPR) are widely used.

It was shown by authors in [1] that the output DC voltage of a single diode rectifier is often improved as the PAPR of the input signal increases. Several waveforms are used: CW, OFDM, white noise and chaotic signals. In [2], the efficiency gain of a single-diode rectifier was enhanced by up to 5 dB at -15 dBm when using multisine signal compared to CW. A voltage gain of approximately 7 dB is obtained at -11 dBm by using a 2-tone signal applied on a rectifier designed and optimized to operate at 5.8 GHz [3]. Furthermore, a voltage gain of 2.7 dB at -4 dBm input power is obtained when using a multistage rectifier optimized at 2.4 GHz [4]. In [5], multisine signal is used to improve the range and readability of RFID tags. In [6-7], RF pulse signal allows to improve the output DC voltage and efficiency of rectifiers operating at 2.4 GHz when the duty cycle and the load resistances vary. In [8], the authors demonstrate that with the 3-tone Tx waveforms, the IM3 carrier generated by the nonlinear tag can be enhanced by 4 dB. Under the same PAPR, the harvested DC power with the excited IM3 is noticeably higher than that obtained with the 2-tone waveform.

This paper focuses on the improvement of the performance of an ultra-wide band RF-to-dc conversion circuit operating from 1.6 to 2.8 GHz and using RF pulse modulation and multisine signals. ADS simulations and experimental measurements were performed to characterize the contribution of both waveforms to the conversion efficiency. Several numbers of subcarriers, ranging from 2 to 16, were considered in this paper. Also, the optimization of the duty cycle and the modulation frequency has been done in the case of the RF pulse modulation signal.

II. BROADBAND RECTIFIER DESCRIPTION

The ultra-wide band rectifying circuit that was used in this paper operates from 1.6 to 2.8 GHz (GSM, UMTS, Wi-Fi and LTE2600/4G frequency bands) [9]. It is designed and optimized using Harmonic Balance and Momentum simulations under Advanced Design System (ADS) software of Keysight Technologies. It is made of an input HF filter, a DC low pass filter, an output load, and 2 Schottky diodes. The voltage doubler topology was used to provide higher output DC voltage compared to single-mounted diode rectifier. The input matching network is designed and optimized as a microstrip non-uniform transmission line (NUTL). This allows for a wide frequency range of operation. A S-shaped geometry was chosen to make the

structure more compact. The Schottky diode SMS7630-079 LF from Skyworks is chosen for its low threshold voltage requirement for small input power levels.

Figure 1 shows the generic layout and the fabricated prototype of the ultra-wide band rectifier. The optimum output load of the rectifier is 3 k Ω for an RF power level of about -15 dBm. The prototype is printed on a 1.6-mm thick FR-4 substrate ($\epsilon_r = 4.3$ and $\tan\delta = 0.02$).

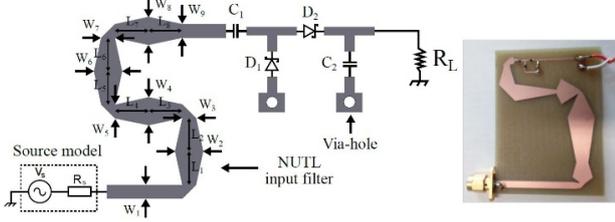


Fig.1. Generic circuit layout of the UWB rectifier with the picture of the fabricated prototype.

III. NUMERICAL SIMULATION AND WAVEFORM DESCRIPTION

For the multisine waveform, Harmonic Balance (HB) simulations were performed. The number of subcarriers varies between 2 and 16 in this work. For the RF pulse modulation signal, the numerical simulation is performed under the ADS software and using envelope analysis method. For the RF pulse modulation waveform, the envelope of the signal is first generated, using a Matlab code that had been developed, for different duty cycle values ranging from 1 to 99%. Several modulation frequencies were also used: 100 kHz, 1 MHz and finally 10 MHz. The data files are then imported into ADS and an envelope analysis simulation is performed to characterize the DC output of the circuit as a function of the duty cycle and as a function of the modulation frequency, for different RF power levels and load values. To optimize the computation time and the convergence to the steady state, the envelope parameters such as the sampling frequency and the number of periods are optimized. The sampling frequency needs to be sufficiently high to obtain sufficient non-zero samples at the lowest duty cycle value being considered (1% in this work). The number of periods of the modulated signal needs also to be high enough to reach the steady state for the largest load value being considered (100 k Ω in this work).

Multisine signals are usually used in WPT in order to achieve higher DC output. It is generated by the following equation:

$$v(t) = \sum_{k=1}^N A_k \sin \left[\left(\omega - \frac{\Delta\omega}{2}(N-1) + \Delta\omega(k-1) \right) t + \varphi_k \right]$$

Where A_k , φ_k and N are the amplitude, the phase and the number of subcarriers.

Figure 2 depicts an example of 4-tone signal plotted in time and frequency domains. The PAPR of multisine signal is increased by 3 dB when the number of subcarriers is doubled. The PAPR is calculated as follows:

$$PAPR = 10 \log_{10} \left(\frac{\max|x^2(t)|}{\langle x^2(t) \rangle} \right)$$

Where $x(t)$ is the time domain signal ; $\langle x(t) \rangle$ is the average of $x(t)$.

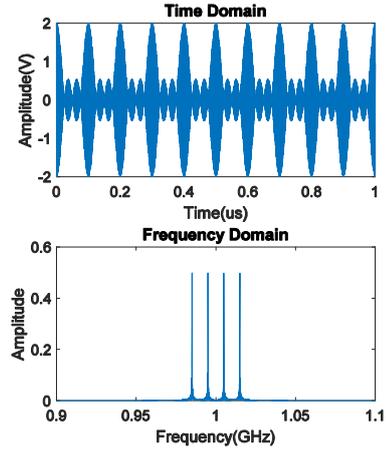


Fig.2. 4-tone signal in time and frequency domains.

The pulse modulation RF signal consists of a carrier signal with a frequency f_c modulated by a square signal of frequency f_m with a duty cycle β . In one period of the modulated signal, the time during which the pulse is turned on is called T_{on} . The duty cycle is then calculated by the following formula:

$$\beta(\%) = 100 \frac{T_{on}}{T_m}$$

Where T_m is the period of the modulated signal.

An example of RF pulse modulation signal with a duty cycle of 5%, a carrier frequency of 2.45 GHz and a modulation frequency of 1 MHz is depicted in figure 3. The peak power increases as the duty cycle decreases. For all simulations and measurements, the comparisons were done considering that the average power is constant.

IV. EXPERIMENTAL RESULTS AND DISCUSSION

After the simulation phase, experiments were performed. Measurements as a function of RF power level, for two different loads (3 and 100 k Ω), were carried out. The RF pulse modulation waveform, with optimized duty cycle and modulation frequency, is used. The results are presented in figures 4 and 5. The carrier frequency is fixed to 2.4 GHz and the RF power ranges from -30 to 0 dBm. For each load value, the voltage and efficiency obtained for optimized waveform and 1-tone signal are compared and the voltage gain is characterized. For each power level, the duty cycle is ranged from 1 to 99% and the maximum DC voltage is chosen. The impact of the modulation frequency is smaller. Indeed, three modulation frequencies were used (0.1, 1 and 10 MHz) and the difference between them is small. For 3 k Ω and small RF power levels from -30 to -12 dBm, the optimized waveform gives more DC voltage compared to 1-tone signal. On the other hand, there is no improvement in the power range from -12 to 0 dBm.

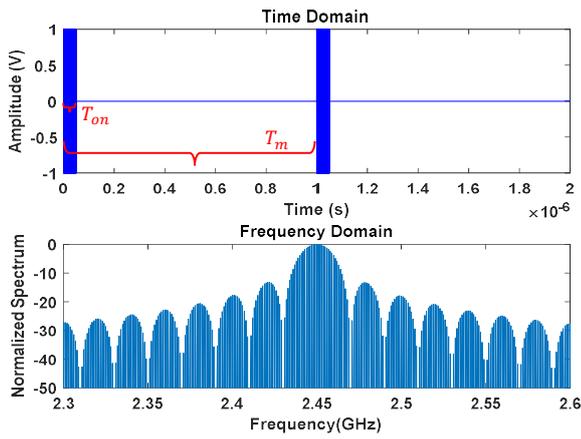


Fig.3. Pulse modulation RF signal with $f_m = 1$ MHz, $f_c = 2.45$ GHz and $\beta = 5\%$ (time and frequency domains).

The measured maximum gain is 4 dB at -30 dBm and then it decreases to 0 dB from about -12 dBm. Moreover, the results at 100k Ω are significantly improved. The voltage gain, with respect to a CW signal, is higher than 4 dB over the considered power range, with a maximum of 10.4 dB obtained at -20 dB.

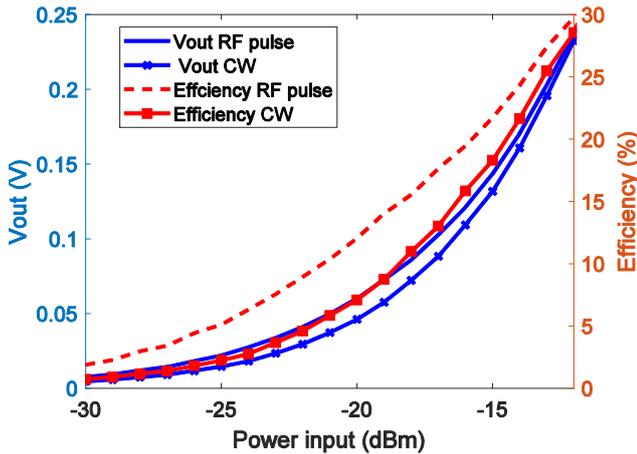


Fig.4. Output DC voltage and efficiency of RF pulse and CW signals versus RF power level ($R_L = 3$ k Ω).

For multisine signals, the measurement results are presented in the figures 5 and 6.

Figure 5 depicts the output DC voltage and voltage gain of multisine and 1-tone signals against the output load, ranging from 1 to 100 k Ω . The frequency is fixed at 2.2 GHz and the input RF power at -15 dBm. The DC voltage is close to that of 1-tone signal at small load values from 1 to 3 k Ω . The voltage gain is increased when the number of sub-carriers as well as the load value increases. The highest gain obtained is 6.5 dB at 100 k Ω for 16-tone signal.

In figure 6, the output DC voltage and the voltage gain of multisine and 1-tone signal over the frequency range from 1.6 to 2.8 GHz for the load value of 100 k Ω are presented. The input RF power is set to -15 dBm. The DC voltage and the voltage gain increase with the number of sub-carriers. The voltage gain is relatively constant over the frequency

range of interest with the highest gain of 7 dB for 16-tone signal. The highest voltage gains are 5 dB, 3 dB and 1.5 dB for 8-tone, 4-tone and 2-tone signal, respectively.

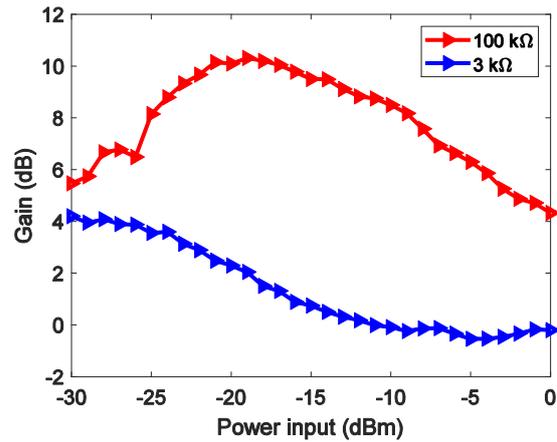


Fig.5. Voltage/efficiency gain of RF pulse signal against RF power level, for different loads (3 and 100 k Ω).

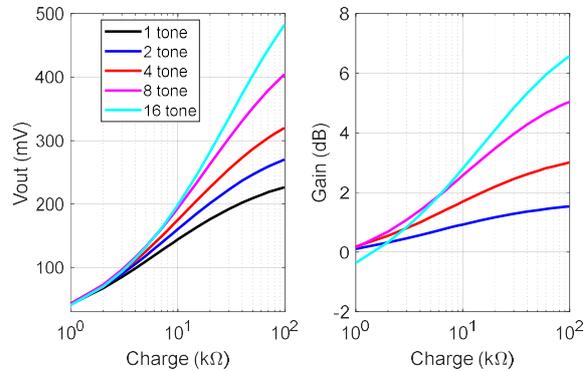


Fig.6. Measured output voltage and voltage gain against output load at 2.2 GHz

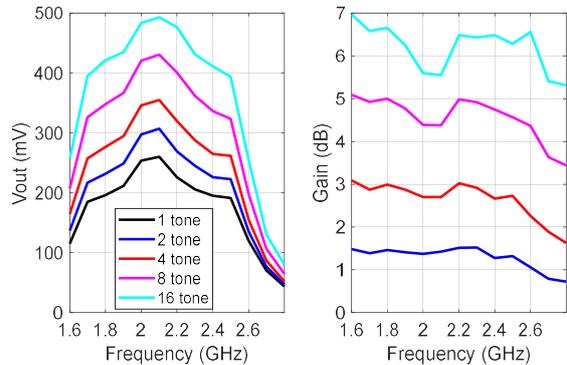


Fig.7. Measured output voltage and voltage gain against frequency ($R_L = 100$ k Ω).

V. CONCLUSION

This paper addresses the issue of improving the performance of wireless power transfer (WPT) systems by optimizing the transmitted waveform. Two waveforms are considered in this work: multisine and RF pulse modulation signals. An ultra-wide band RF-to-dc conversion circuit operating from 1.6 to 2.8 GHz was used in this work to show the potential of both waveforms. Through measurement results, it is shown that the improvement of the output voltage (and efficiency) is more important for low power

levels and high load values. A maximum voltage gain of 10.4 dB was measured with pulse modulation signal at -20 dBm and a load of 100 k Ω . This means a voltage improvement of 330%. The maximum gain measured in the case of multisine signal is about 7 dB at -15 dBm and with the same 100-k Ω load. This means an improvement of 220% in terms of DC output voltage.

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