Energy-autonomous Bi-directional Wireless Power Transmission (WPT) and Energy Harvesting Circuit

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Abstract — This work demonstrates a novel 2.45-GHz bi-directional circuit that can operate as both a wireless power transmitter and energy harvester. The circuit is based on a class-F oscillator/rectifier and is energy-autonomous since it does not need an external bias supply for either power transmission or power reception. Bi-directionality is exploited in two steps: the system first operates in rectifying mode with harvested DC voltages for biasing the oscillator; followed by the transmitting mode where the harvested DC power is used to start up oscillations. Conversion efficiencies for both configurations are higher than 50% for output/input RF power in the 10dBm range. This component can be exploited as a “power relay node” for distributed battery-less energy autonomous microsystems.

Index Terms — wireless power transfer, energy harvesting, rectifier, autonomous circuit, battery-less.

I. INTRODUCTION

Next generation wireless systems are anticipated to consist of very large numbers of distributed low-power efficient nodes. Energy harvesting and wireless powering are seen as one of the key enabling technologies toward providing energy autonomy to an increasing number of devices [1]–[3]. In this context it is important to integrate energy harvesting and wireless power transfer capabilities, enabling each device to act on demand either as a wireless power provider or as a user.

A promising solution for medium power transfer (on the order of a few watts), is presented in [4], where it is demonstrated that class-F RF power amplifiers exhibit comparable efficiencies when operated as self-synchronous rectifiers. In [5], this concept is extended to a 2.14-GHz 85% efficient 10-W class-F⁻¹ rectifier and a Fourier expansion-based theory for various classes of harmonically-terminated rectifiers (C,F,F⁻¹) is developed. A reconfigurable class-E oscillator/rectifier in the UHF band is detailed in [6] for RF power in the mW range. In both operating states, high conversion efficiencies are obtained for specific gate and drain DC biases, a limiting factor for system operation.

In this paper, we demonstrate a solution for a 2.45-GHz class-F oscillator/rectifier which overcomes constraints on DC bias without degrading the performance of the two states. Fig.1 (a) shows a circuit schematic of the approach and in Fig.1 (b) a photograph of the implemented circuit is shown.

The two main contributions of the paper are: (1) implementation of self-biasing of the transistor for proper oscillator class-F operation; and (2) increased efficiency in the rectifier mode at low input power levels by means of a bias-assisting feedback loop.

In this way the circuit does not need a dedicated gate bias supply, and thus eliminates on-board batteries, enabling a completely energy-autonomous device with high efficiency in both transmit and power-receive modes.

Fig. 1. Modified, with bias-assisting feedback loop, oscillator/rectifier circuit: (a) Schematic of the circuit, (b) photo of the fabricated prototype.

In particular, when the system is operated in oscillator mode the self-biasing mechanism of the transistor [7] is exploited to provide the proper gate bias for class-F operation; when the system is operated in rectifier mode, we are able to increase the maximum obtainable DC power by introducing a bias-assisting loop, based on a Schottky diode (see Fig.1 (a)) to enhance the gate bias of the transistor.

The demonstrated oscillator/rectifier is envisioned as a fully autonomous circuit whose operation starts in rectifying mode, in order to harvest RF signals either from intentional or unintentional power transmission, and after storing the necessary energy, is switched to oscillator mode to wirelessly power devices located in its proximity.

The next sections describe the design of the oscillator/rectifier circuit and show preliminary experimental results which demonstrate the advantages of the approach.

II. OSCILLATOR/RECTIFIER DESIGN

In the circuit schematic of Fig. 1a, a JFET NE3509M04 transistor is used as the active device, having a negative threshold voltage of -0.5 V. The advantage of a negative threshold is two-fold: 1) the oscillation build-up is possible in the absence of a gate bias, that is, in a floating-gate condition; 2) the bias point for optimum oscillator/rectifier conversion efficiency can be reached, by exploiting the gate self-biasing mechanism of the transistor [7].

The oscillator design is performed with the switches of Fig. 1a in State 1. After oscillations reach steady state, the gate bias settles to a self-rectified value obtained through internal transistor feedback. The Colpitts-like feedback and matching network with harmonic termination are tuned to optimize class-F operation.

When the switches are in State 2 (Fig. 1 (a)), and again exploiting the transistor self-biasing, the same circuit can operate in a rectifying mode by connecting an appropriate DC load at the drain supply terminal and using the oscillator output RF port as the rectifier input port. Simultaneous optimization of both operating modes (oscillator and rectifier), with the dedicated bias assisting networks for the two operations, is performed by means of nonlinear harmonic balance (HB) technique with optimization goals on the DC-to-RF oscillator efficiency and on RF-to-DC rectifier conversion efficiency. In this way the oscillator and rectifier operations are enabled to coexist, embedded in the same linear network, without reciprocally affecting their optimum performances.

In order to enhance the RF-to-DC conversion efficiency of the rectifier at the lowest input RF power levels, a bias-assisting loop is added to the circuit to drive the gate self-biasing. This loop is designed in such a way that it does not affect the oscillator mode operation, while providing the biasing to the transistor gate. The bias-assisting loop is formed of a 15-dB coupled-line microstrip directional coupler, which drives a sample of the incoming RF signal at 2.45 GHz to a Schottky diode through a suitably optimized matching network. The coupler and the diode are connected by a stepped-impedance matching network, optimized for the

lowest incoming power levels. The two quarter-wave lines in the assisting loop play the role of RF blocks, thus ensuring isolation between the Class-F oscillator and bias-assisting loop.

The Schottky diode is arranged in shunt configuration providing a negative DC voltage at the transistor gate port. This allows the circuit to operate in rectifier mode with good RF-to-DC conversion efficiency for a wide range of input power levels, as demonstrated in the next session where an extensive system experimental characterization is discussed.

III. BIDIRECTIONAL CIRCUIT MEASURED PERFORMANCE

The fabricated prototype is shown in Fig.1 (b) with two testing ports for measuring the directional coupler insertion loss and the input matching of the bias-assisting loop. The circuit is measured in oscillator mode by biasing the transistor drain (switches in State 1). Fig. 2 shows the output power and DC-RF conversion efficiency of the oscillator as a function of drain supply voltage. It can be observed that the efficiency remains above 50% over most of the drain supply range. The oscillator mode has a maximum DC-RF conversion efficiency of 55.6% at 4.8 V drain bias voltage and an output power of 12 dBm (Fig. 2).

Fig. 2. Measured output power and DC-RF efficiency of the oscillator/rectifier circuit operating in oscillator mode, as a function of drain supply voltage.

Fig. 3 and Fig. 4 show the frequency spectrum and time domain waveform of the oscillator, respectively, for a drain bias of 4.8 V. The effect of the harmonic termination is evident from Fig. 3. The frequency spectrum was measured using an Agilent E4440A PSA spectrum analyzer with a resolution bandwidth of 3 MHz, and the time domain waveform was measured using an Agilent Infiniium DSO81004A oscilloscope. The oscillator has a phase noise of -115 dBc/Hz at 1 MHz from the carrier, measured using the Agilent E4440A PSA spectrum analyzer with span 3 MHz and resolution bandwidth of 1 KHz. The phase noise measurement has been carried out by biasing the prototype with a 4.8-V battery in order to eliminate supply noise.

Fig. 3. Measured output power spectrum of the oscillator/rectifier circuit in oscillator mode.

Fig. 4. Measured output voltage time domain waveform of the oscillator/rectifier circuit in oscillator mode.

To characterize the circuit in rectifier mode, the drain bias is disconnected and an input RF signal at 2.45 GHz is fed into the RF port (switches in State 2). The input power levels are varied from -12 dBm up to 18 dBm and the output DC voltage is measured across the output load R_L . Fig. 5 shows the measured output voltage as a function of input power. Fig. 6 shows the measured RF-DC conversion efficiency as a function of input power. The DC-load was optimized, over input power between -10 and 10 dBm, as a design variable of the entire system in rectifying mode and resulted to be equal to 620 Ohm. This value gives the best average efficiency over the range of input power levels. The plots show that the circuit is able to operate with efficiency higher than 45% starting from as low as -4 dBm of input power. This performance is preserved over a 22 dB range in input power. The circuit is able to operate even at lower input power levels but with reduced efficiency (20% efficiency for -10 dBm input power). It is noteworthy that the efficiencies predicted by non-linear simulation of the modified oscillator/rectifier were higher of about 15% than the measured ones. These differences are probably due to the limited accuracy of the devices models used inside the simulator.

To validate that the bias-assisting loop indeed improves the performance, the loop is disconnected from the circuit and the measurements in the rectifier mode are repeated. The measured results without the bias-assisting loop are shown in Fig. 5 and Fig. 6 in solid line. Note that the circuit operates as a rectifier over a significantly reduced input power range in

this case, approximately from 5 dBm to 18 dBm. Additionally, the oscillator/rectifier circuit without the bias-assisting loop exhibits hysteretic behavior versus input power when operating in the rectifier mode. If the input power is increased (grey arrows), the rectifier begins operating only for input power levels above 8.7 dBm. However if the input power is decreased (black arrows) the rectifier operates down to 4.9 dBm.

Fig. 5. Measured output DC voltage for the oscillator/rectifier circuit operating in rectifier mode. The DC load impedance is 620 Ω and the input frequency is 2.45 GHz.

Fig. 6. Measured RF-DC conversion efficiency for the oscillator/rectifier circuit operating in rectifier mode. The DC load impedance is 620 Ω and the input frequency is 2.45 GHz.

This further limits the input power ranges for which the circuit could rectify, since operating in the hysteresis zone between 4.9 dBm and 8.7 dBm is undesirable. This means that rectifier operation without the bias-assisting loop is guaranteed only above 8.7 dBm.

Fig. 7 shows the measured gate DC bias voltage versus the input power level for the modified oscillator/rectifier circuit (dashed line). The measured transistor gate voltage without

the loop is also shown in Fig. 7 (solid line) for the operating zone with no hysteresis. A comparison of the two plots again confirms the key role of the bias-assisting loop in enhancing the system performance. Indeed, in rectifying mode, the minimum voltage required to start gate self-biasing is reached with input power levels as low as -12 dBm; while without the loop this operation can be safely started only if a 8.7 dBm input power is available. The minimum voltage is the absolute value of the device threshold voltage, which is 0.5V for the transistor used in this work.

Fig. 7. Gate voltage versus input power levels for the oscillator/rectifier circuit with and without the bias-assisting loop.

IV. CONCLUSION

This paper presents the design of an efficient 2.45 GHz oscillator/rectifier circuit exploiting floating gate biasing. In oscillator mode, this biasing reduces power consumption and allows more than 50% efficiency over a range of output power levels and drain supplies. In rectifier mode, a bias-assisting loop is introduced to increase the range of input powers (from 10 dB to 22 dB) over which the circuit can efficiently rectify with 45% conversion efficiency. The measured results confirm that bidirectional operation for harvesting and WPT within the same device is not only possible, but can be designed to be efficient at low RF power levels, in this case down to -10 dBm.

ACKNOWLEDGEMENTS

The authors would like to acknowledge EU COST Action IC1301 "Wireless Power Transmission for Sustainable Electronics (WIPE)", that supported a 1-month Short Term Scientific Mission (STSM) of Mr. Massimo del Prete at CTTC.

The work of A. Georgiadis and A. Collado was supported by the Generalitat de Catalunya under grant 2014 SGR 1551 and by the Spanish Ministry of Economy and Competitiveness and FEDER funds through the project TEC2012-39143.

The work of A. Costanzo, M. Del Prete and D. Masotti was partly funded by the Italian Ministry of the Instruction, University and Research (MIUR), within the framework of the national project GRETA.

Z. Popovic acknowledges funding by the Hudson Moore Jr. Chair endowment at the University of Colorado, Boulder.

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