A Flexible Hybrid Printed RF Energy Harvester Utilizing Catalyst-based Copper Printing Technologies for Far-Field RF Energy Harvesting Applications

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Abstract—In this paper, the design of a novel flexible RF energy harvester utilizing hybrid printed electronics technology is presented for the first time. The proposed RF energy harvester operates at UHF RFID band (868 MHz ~ 915 MHz) for far-field RF energy harvesting applications. A concept of hybrid printed electronics which takes advantage of both flexibility of low-cost printed electronics and high performances of ICs is introduced. The passive components of the RF energy harvester, such as the circuit layout and the antenna, are printed on a flexible low-cost polymer substrate utilizing a catalyst-based inkjet printing process for the fabrication of copper metallization layers. The surface-mount devices (SMDs) are soldered on the printed circuit board. The proposed approach demonstrates the feasibility of implementing low-cost flexible printed electronics for the Internet of Things (IoT) and stand-alone ("zero-power") wireless sensor platforms.

Index Terms—Catalyst-based inkjet printing, charge pump, hybrid printed electronics, printed copper, RF-DC converter, RF energy harvester, wireless power transfer.

I. Introduction

Energy harvesting is a critical technology for the first real-world implementations of scalable battery-less stand-alone wireless sensor platforms for quality of life and the Internet of Things (IoT) applications [1][2]. RF energy harvesting is becoming increasingly popular, especially for low-power wireless sensor platforms, among the many kinds of energy harvesting technologies, such as thermal or piezo-electric energy harvesting. The far-field RF energy harvesting technology features the advantages of power transfer capability to numerous wireless sensor platforms at the same time when they are deployed in difficult to access areas [2].

However, many issues should be overcome to implement a truly low-cost flexible RF energy harvester. Flexibility is important to realize the sensor platforms in rugged environments with a small form-factor without performance degradation when they are bent or conformed. An easy-to-scale cost-efficient and environmentally friendly fabrication process is also a critical factor since large numbers of sensor platforms would be required in practical IoT, M2M and smart-skin applications.

This paper introduces a flexible hybrid printed RF energy harvester utilizing catalyst-based copper printing technologies. It presents the system-level integration and design of a flexible hybrid printed RF platform for the first time. The inkjet-printed catalyst-based copper printing technology is utilized on a thin polymer substrate to minimize the fabrication cost and implement a flexible circuit on a low-cost thin polymer substrate [3]. This approach enables the effective soldering of surface-mount device (SMD) on inkjet-printed printed platforms and circuits, thus resulting in high performance low-cost hybrid flexible printed electronics in contrast to conventional silver nanoparticle-based inkjet printing technologies.

This paper is organized as follows. Section II presents the design of the flexible hybrid printed RF energy harvester. Section III shows wireless measurement results of the designed RF energy harvester prototype, while the last section closes with the conclusions.

II. RF Energy Harvester Design

The proposed RF energy harvester consists of 3 blocks as shown in Fig. 1: a receiving antenna, an RF-DC rectifying circuit, and a DC-DC converter. The hybrid printed electronics technology was chosen to implement a high performance low-cost flexible prototype, and a catalyst ink was inkjet-printed on a flexible polymer substrate in order to metalize the substrate with copper [3].

A. Antenna Design

A square loop antenna was designed using a finite element electromagnetic simulator, ANSYS HFSS v11.1. A loop type antenna was chosen in order to minimize the effects of the fabrication error of the printing process and optimize the form-factor of the proposed RF energy harvester. Typically, the resonant frequency of a loop antenna is determined by the length of its circumference which is minimally affected by the spreading effect of printed ink. It is also convenient to miniaturize the size of the RF energy harvester which consists of an antenna and RF-DC converter because the middle (interior) area of a loop antenna is a good place to implement the rest of the circuitry. The selected substrate material was a 100 μm thick polymer, Melinex 339 (DuPont Teijin Film, VA,

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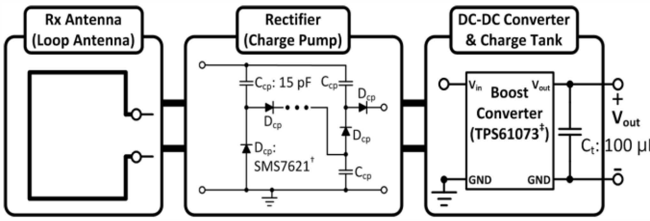

†http://www.skyworksinc.com/uploads/documents/Surface_Mount_Schottky_Diodes_200041X.pdf
‡http://www.ti.com/product/tps61073

Fig. 1. Block diagram of the proposed RF energy harvester topology.

USA, [4]), with a dielectric constant (ε_r) of 2.4. The designed square loop antenna resonates around 880 MHz and it is fed by a 2:1 balun which converts an unbalanced 50 Ω microstrip line to a 100 Ω balanced differential line as shown in Fig. 2(a). The bandwidth of the designed antenna is about 80 MHz (850 MHz ~ 930 MHz) covering most UHF RFID bands. The measured and simulated reflection coefficient values (S_{11}) are shown in Fig. 3 and they agree very well. The flexibility of the antenna was demonstrated by wrapping it around cylinders of various radii (Fig. 3). The antenna performance metrics, such as the bandwidth, still meet the system requirements as the antenna covers most UHF RFID bands when wrapped around cylinders with radii of R = 45 mm and 20 mm. The antenna maintains a typical radiation patterns of a loop antenna (bi-directional radiation pattern) and an estimated average realized antenna gain value is 2.5 dBi over its operation bandwidth.

B. RF-DC Converter Design

The proposed RF-DC converter consists of a rectifying circuit and a DC-DC converter (Fig. 1). The designed RF-DC converter prototype was also implemented on the same low-cost flexible polymer substrate utilizing the hybrid printed electronics technology as shown in Fig. 2(b). In this work, the Dickson charge pump was chosen, that utilizes diodes instead of switches to charge and discharge capacitors (C_{cp}). Unlike other types of charge pumps, such as the bootstrap charge pump, switch control signals are not required which is important for a passive (or autonomous) operation. A 5-stage charge pump was chosen to achieve maximum output voltage (V_{out}) with high conversion efficiency as typically a 3~5-stage charge pump yields the maximum efficiency in single-tone RF input power levels (mW level) [5]. The RF-DC charge pump circuit was designed and optimized to have the best efficiency at 900 MHz for an input power level of 0 dBm using the harmonic balance simulator of the Agilent Advanced Design System (ADS). A low-power microcontroller usually requires 200 µW, which can be achieved with only 20 % RF-DC conversion efficiency at 0 dBm. It is important to select capacitors (C_{cp}) which feature a higher self resonant frequency (SRF) than the operation frequency, and the capacitor value should be carefully chosen for an efficient RF-DC conversion since it is a critical factor for the charging/discharging time [6]. The capacitors cannot be fully charged during the half cycle of

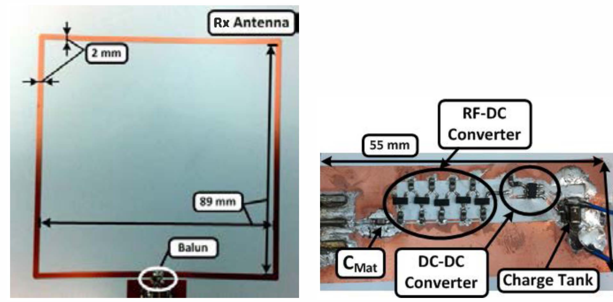

Fig. 2. Hybrid printed flexible RF energy harvester on a low-cost polymer: (a) square loop antenna, (b) RF-DC converter.

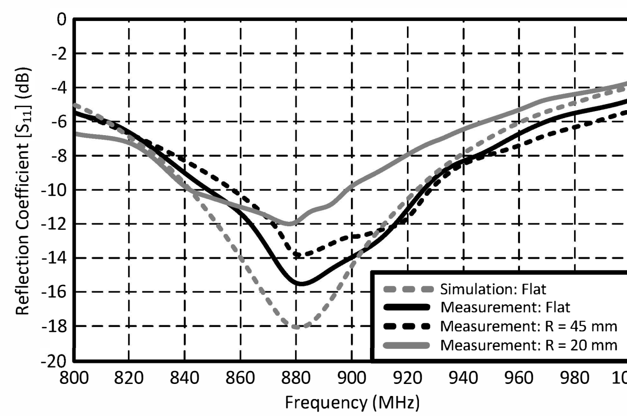

Fig. 3. Measured reflection coefficient values (S_{11}) of the flexible square loop antenna.

the input signal if their values are too large, while only a small fraction of input power can be delivered to next stage when the capacitance is too small. The drop down voltage of the diode is also an important design parameter since it lowers significantly the output voltage [6].

The DC-DC converter with a charge tank (C_t) is connected to the charge pump in order to store the rectified RF power. The DC-DC boost converter generates 3.0 V when the input DC voltage is higher than 0.9 V‡ featuring the capability to achieve relatively high output voltages at low input power levels (increased sensitivity).

The measured reflection coefficient values (S_{11}) of the designed RF-DC converter (the combination of the charge pump, the DC-DC converter, and the charge tank) is shown in Fig. 4. A LC matching network was designed to match the output impedance of the antenna (50 Ω) and the input impedance of the RF-DC converter. The load-pull method was used to define the input power dependant input impedance of the RF-DC converter. The bandwidth of the designed RF-DC converter (800 MHz ~ 1150 MHz) covers effectively most of the desired UHF RFID frequency bands even when bent around cylinders of variable curvature radii (R = 27 mm & 38 mm) for a power level of 0 dBm. The matching is improved as the input power is increasing. The measured open-circuit output voltage is shown in Fig. 5 as a function of the input RF

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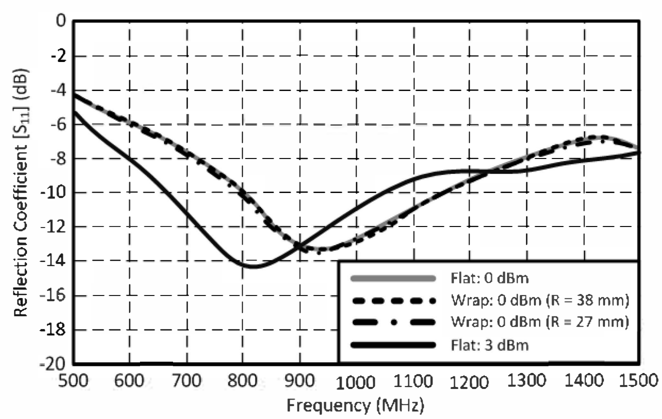

Fig. 4. Measured reflection coefficient values (S_{11}) of the designed RF-DC converter.

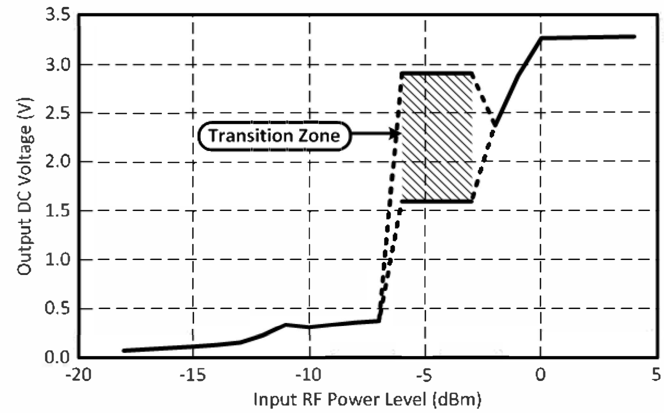

Fig. 5. Measured output DC voltage depending on input RF power level: flat and bent circuit at 900 MHz.

power level. The designed RF-DC converter successfully generates a voltage above 2.9 V with an acceptable efficiency (> 20 %) for input power levels higher than -7 dBm. The output voltage of the DC-DC converter varies between 1.6 V ~ 2.9 V (transition zone) when the input RF power to the rectifier is in the range of -7 dBm ~ -3 dBm. In this power range, the DC-DC converter circuitry is not able to provide a regulated output voltage of 3.0 V. For input power levels below -7 dBm the rectifier output voltage does not reach the required value of 0.9 V necessary to start-up the DC-DC converter circuitry. In this case, the input resistance of the DC-DC converter which represents a load of the rectifier has a large value. When the RF input power becomes -7 dBm, the DC output voltage of the rectifier reaches more than 0.9 V and the DC-DC converter begins to operate, and its input resistance is reduced. This may have an immediate effect in the rectifier performance including its input impedance, output voltage and rectifier efficiency which results in an operating point which the regulator is unable to properly regulate its output voltage. However, if the RF input power is increased above -3 dBm, proper operation of the DC-DC converter is observed.

C. Hybrid Printed Electronics

Hybrid printed electronics is a hybrid approach combining printing and surface mounting technologies to implement low-cost flexible electronics while fully taking advantage of the high performance of surface-mount components, such as analog and digital ICs. The fabrication process of the hybrid printed electronics consists of two steps: 1) print conductive layers and 2) mount electronic devices and components (IC chips, capacitors, inductors, etc.). There are numerous methods to print conductive layers, like the inkjet printing of conductive nanoparticles, but the inkjet printing-based electroless electroplating using a catalyst ink was chosen [3], since it enables the catalyst-based electroless electroplating technology enables soldering while maintaining the advantages of printing technology, such as cost efficiency and flexibility. The electronic components, such as IC chips, capacitors, are mounted and soldered on the deposited copper layer utilizing a low-temperature solder paste that needs to melt at a lower temperature than the melting point of the glass transition temperature of the substrate in order to minimally deteriorate the printed patterns and the substrate. A lead-free paste consisting of $Bi_{58}Sn_{42}$ was chosen for a solder paste since it has a low melting temperature of 140 °C while the melting point of the substrate (Melinex 339) is 250 °C. The fabricated hybrid printed RF-DC converter is shown in Fig. 2.

III. PERFORMANCE EVALUATION

The designed antenna and the combined topology performance was successfully demonstrated through wireless measurements. The RF energy harvester was interrogated by a linearly polarized log-periodic antenna at 900 MHz with a transmitted power of 20 dBm, and the output voltage (voltage across the charge tank (C_t)) was measured. The transmitting (Tx) antenna had a gain value of 3.2 dBi at 900 MHz and the distance between the RF energy harvester and the Tx antenna was 1.0 m ($3\cdot\lambda_0$). The measured output voltage was 2.9 V for a received (Rx) power level by the square loop antenna of -7 dBm resulting in a power density of 1 $\mu W/cm^2$ (conversion efficiency: 20 %). The implemented harvester featured a similar performance over the frequency range of 800 MHz ~ 1.15 GHz since more than 90 % of input power can be delivered to the RF-DC converter (Fig. 4). Plus, similar measurement results (open circuit output voltage, Rx RF power level, and power density) were obtained when the designed RF energy harvester was wrapped on a cylinder of R = 150 mm. The RF-DC conversion efficiency values of the reported RF energy harvesters were about 20 % ~ 40 % at 900 MHz when the input power level was -7 dBm ~ 0 dBm but their output voltage were lower than 2.9 V and non-flexible circuits [2][7].

IV. CONCLUSIONS

The design of a novel flexible hybrid printed low-cost RF energy harvester has been demonstrated fully taking advantage of the main flex-independent benefits of catalyst-based copper printing technologies: cost efficiency, flexibility, solder-ability and functionality. The performance of the designed far-field RF energy harvester has been verified through wireless experiments demonstrating output voltages above 2.9 V for input power levels above 0 dBm from 0.8 GHz ~ 1.15 GHz. The proposed RF energy harvester could find numerous applications, such as stand-alone sensor platforms for Internet of Things (IoT) applications.

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