2.4 GHz Inkjet-Printed RF Energy Harvester on Bulk Cardboard Substrate

Zahra Khonsari*, Toni Björninen*, Manos M. Tentzeris†, Lauri Sydänheimo* and Leena Ukkonen*

*Department of Electronics and Communication Engineering, Tampere University of Technology, Tampere, Finland

†School of Electrical and Computer Engineering, Georgia Institute of Technology, Atlanta, GA, USA

***Abstract* — An experimental investigation on the inkjet-printed power harvester for 2.4GHz and review of RF characterization of substrate and printed conductors are presented in this paper. A one stage discrete rectifier based on a voltage doubler structure and a planar monopole antenna are fabricated on cardboard using inkjet printing. The performance of the whole system is examined by measuring the output voltage of the RF power harvester. By the utilization of the proposed idea, the fabrication of low-cost environmentally-friendly battery-less wireless modules is conceivable.**

***Index Terms* — Inkjet printing, additive manufacturing, cardboard substrate, energy harvester, planar monopole.**

I. Introduction

Inkjet printing enables additive manufacturing of conductive patterns on a wide variety of platforms based on contactless drop-on-demand deposition of metallic nanoparticle inks. As the material choices in electronic devices have a huge impact on the environment, lately, the use of renewable, environmental-friendly materials, and additive manufacturing methods, such as inkjet-printing, has been a growing trend. In the field of wireless systems, antennas [1-2], radio-frequency identification (RFID) tags [3], sensors [4], and ambient energy harvesting [5] have been some of the focus areas in this endeavor.

Previously we have analyzed the impact of conductor thickness on the performance of inkjet-printed RFID tags [6] and presented methods to optimize the cost-performance ratio of inkjet-printed RFID tags by using narrow-line antennas [7] and selective ink deposition [8]. We have also demonstrated the application of inkjet printing technology in the fabrication of IC-enabled [9] and chipless RFID sensors [10] and printed antennas directly on renewable materials, with rough and porous surfaces [11].

In this article, we will present the inkjet printing fabrication of an energy harvesting circuit and a planar monopole antenna and review the RF characterization of substrates and printed conductors for optimizing the print outcome on a given platform.

II. The Inkjet-Printing Procedure and Power Harvesting Circuit

Inkjet-printing technology is utilized in this study for the fabrication of the circuits. For this purpose, Fujifilm Dimatix DMP-2831 material printer, Stora Enso packaging thin cardboard, and NPS-JL silver nanoparticle ink with 55.5wt% metal content are used as the printer, substrate and conductor, respectively. In order to design an RF/Microwave circuit, the electrical properties of the substrate and conductor need to be known. We have used a transmission line method detailed in [2] to characterize the cardboard substrate. The method relies on the measurement of two-port S-parameters of a set of transmission lines with known relative length differences and conductivity. The dielectric properties of the substrate are then extract from the measured S-parameters by utilizing numerical models and the length differences. As a second step, a set of transmission lines are inkjet printed on the same substrate. With a similar procedure, the conductivity of the printed conductor can be approximated based on the measured S-parameters, length differences, and known dielectric properties of the substrate. To achieve highly conductive traces, we first deposited five layers of Primer dielectric to make the fibrous substrate ink-proof and smoother. Then, 8 layers of silver ink were printed in 4 cycles. In each cycle, 2 layers were printed

Table 1
Properties of Cardboard and Printed Conductor.

Measured Parameter	Value at 2.45 GHz
Relative permittivity of cardboard	1.78
Loss tangent of cardboard	0.025
Thickness of cardboard	560 um
Conductivity of the printed conductor	2×10^7 S/m
Thickness of the printed conductor	3 um

with 635 dpi resolution and sintered at 150 °C for one hour. The obtained properties of the cardboard and printed conductor are summarized in Table 1.

In any wireless portable device, usage of battery limits its size and lifetime. As increasing the lifetime of the battery is still infeasible, ambient energy harvesting is considered a promising solution in the designing battery-less circuits. The ambient sources for power harvesting can be light, temperature, motion and radio signals, for instance. In urban areas, ambient RF energy is generally available at all hours both indoors and outdoors. Hence RF energy harvesting is one the most popular type of power harvesting. Some of the strongest ambient RF sources include WiFi, AM/FM radio, television broadcasting and mobile networks [13].

In general, an RF energy harvester consists of an antenna, a matching circuit, a rectifier and a charging control unit [12]. In diode-based rectifiers, the input RF signal is converted to DC signal based on the input-output characteristic of the diode. Fig. 1 illustrates the schematic of a voltage doubler, which is utilized in this study. The voltage doubler is designed in two parts where in each a schottky diode and capacitor perform the rectification. The voltage stored in C_1 during negative half of the input cycle is transferred to C_2 during positive half. Hence, the output DC voltage is approximately double the input rms voltage. We used zero-bias schottky surface mount HSMS-2820 which are appropriate for input power levels above –20 dBm at frequencies below 4 GHz [14]. The design frequency of the rectifier was 2.4 GHz.

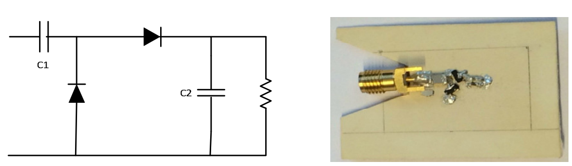

Fig. 1. The schematic of voltage doubler and fabricated rectifier using inkjet-printed technology.

III. Matching Network

The maximum available power will be transferred to the rectifier by antenna when the impedance of rectifier is equal to the conjugate impedance of antenna z^*_{ant} . Hence a matching network is required to transfer the impedance of rectifier to z^*_{ant} .

The input impedance of rectifier which is shown in Fig.3 is measured by Agilent PNA E8358A Vector Network Analyzer (VNA) for output power from –10dBm to 5dBm. Then the matching network is designed and added to the circuit. From the Fig. 2, it can be seen that the circuit is matched for these input power levels.

The experimental results of output voltage versus input power levels are represented in Fig. 3 for the rectifier with and without matching circuit. For an output signal of 5 dBm from the signal generator, the circuit produces 1.21 V across 10 kΩ.

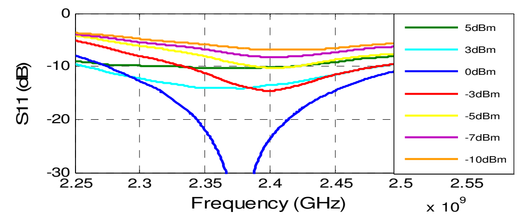

Fig. 2. The input return loss of fabricated rectifier for different input power (dBm).

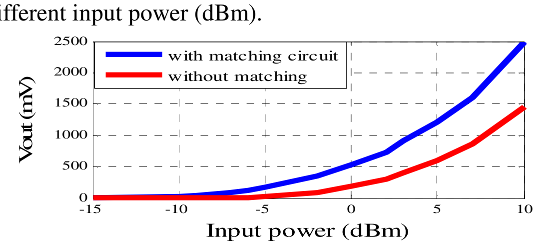

Fig. 3. The measurement results for the output of rectifier before/after adding matching circuit.

IV. Planar Monopole Antenna

A planar monopole antenna is designed and fabricated on cardboard by inkjet-printing technique. The proposed antenna is appropriate for power harvesting as power source since its radiation pattern is omnidirectional in the H plane and the radiation pattern does not change with frequency. The antenna is fabricated with the same procedure discussed in the Section II.

The simulation and measurement results of the radiation patterns of the antenna and maximum realized gain are represented in Fig. 4 and Fig. 5, respectively. The maximum realized gain of the antenna varies between 2.2 dBi to 2.7 dBi in the desired frequency range. In addition, the measured efficiency of antenna is between 75% to 81% and the measured input return loss of antenna in desired frequency range is less than -13dB.The antenna is simulated using the 3-D full wave electromagnetics simulator Ansys HFSS based on finite element method, and the input matching is measured by two port VNA between 2.35 GHz and 2.45 GHz, and the antenna parameters are obtained by the near-field measurement equipment Satimo Starlab. By comparing the simulation and experimental results, it can be deduced that the antenna performance is appropriate for energy harvesting at 2.4 GHz.

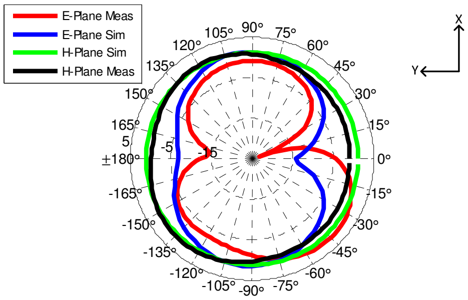

Fig. 4. The simulation and measurement results of the radiation patterns of proposed antenna at 2.4GHz.

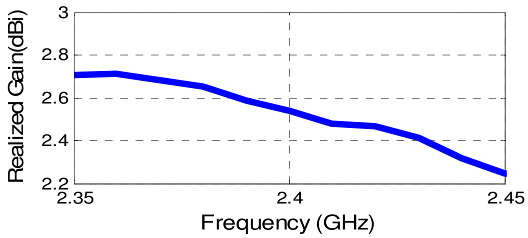

Fig. 5. The measurement result of maximum Realized gain of proposed antenna.

V. Performance Validation of RF Energy Harvesting System

The printed circuit and antenna for RF energy harvesting system is shown in Fig. 6. The overall system was tested by using a patch antenna [2] as power source and various power levels were tested. The experimental results showed a very good correlation with the simulations of Fig.3 and they will be presented at the conference together with results for the powering up of low-power wireless modules using the inkjet printed harvester.

VII. Conclusions

An inkjet-printed RF power harvester at 2.4 GHz has been proposed here to power up low power devices. The simulation and measurements for both the rectifier and for the antenna shows appropriate agreement and suitable output voltage particularly for high input power levels.

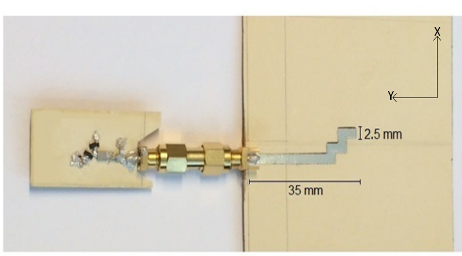

Fig. 6. The fabricated RF energy harvester.

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