Inkjet-Printed Monopole Antenna and Voltage Doubler on Cardboard for RF Energy Harvesting

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***Abstract*—We outline the development of an RF energy harvester manufactured on regular packaging cardboard using the inkjet-printing technology. The harvester is composed of a planar monopole antenna, impedance matching network and a voltage doubler circuit. The paper summarizes the procedure of achieving highly conductive traces on rough and porous cardboard, describes the circuit and antenna design, and presents simulated and measured results.**

I. INTRODUCTION

Inkjet printing, based on contactless drop-on-demand deposition of metallic nanoparticle inks, enables additive manufacturing of conductive patterns on a wide variety of platforms. As the material choices in electronic devices have a huge impact on the environment, the use of renewable, environmental-friendly materials and additive manufacturing methods, such as inkjet-printing, is a growing trend. Great potential lies in the use of wood and paper as substrates for antennas and electronic circuits. Furthermore, in wireless devices which provide intermittent data transmissions instead of a continuous stream, ambient energy harvesting is an attractive approach to achieve battery-free devices. The life-time of such energy autonomous systems is not limited by the battery-life and smaller, cheaper and more unobtrusive devices are obtained. Importantly, the toxic materials contained in most batteries are also removed. Antennas and passive microwave structures, radio-frequency identification (RFID) tags and sensor tags as well as ambient RF energy harvesters are some of the demonstration of this technology [1-4].

In our previous work [5-6], we optimized the process parameters for of inkjet-printing fabricating of conductive patterns on regular packaging cardboard and presented a wide-band planar monopole antenna on cardboard for RF energy harvesting applications in the frequency range of 600-1500 MHz, which contains several strong RF signals, such as GSM and digital TV. In this work we focus on the 2.45 GHz range, where much smaller antenna is attainable and review the recent progress in the development of an inkjet-printed RF energy harvester on cardboard for this frequency [7].

II. INKJET-PRINTING PROCESS

We used Fujifilm Dimatix DMP-2831 material printer to deposit the conductive patterns on packaging cardboard with the thickness of 560 μm from Stora Enso. The conductor was formed by printing Harima NPS-JL silver nanoparticle ink 55.5wt% metal content. In order to create an antenna and RF circuit based on these unconventional materials, first the dielectric properties of the cardboard as well as the conductivity of printed conductor has to be known. These properties (ε_r = 1.78, tanδ = 0.025, σ = 20 MS/m at 2.4 GHz) have been measured in our previous work [5] where a two-transmission line method was employed in the RF characterization.

A challenge in achieving highly conductive patterns on cardboard is the porosity which leads to absorption of significant amounts of ink into the substrate. The negative impact of the ink absorption on the RF performance can be mitigated by depositing up to 20 layers of ink [8], but this comes at the cost of increased material consumption. In this work, we inkjet-printed a dielectric coating on the surface before depositing the conductive ink. The material used for coating was Primer [9], which we cured by using ultraviolet light (UV) exposure for 15 min followed by 1-hour thermal sintering in 150°C. Regarding the deposition of the conductor, we found that it was best to print it in cycles of two subsequent layers followed by 1-hour thermal sintering in 150°C. While in general sintering at a higher temperature may provide higher conductivity, in our application the temperature is limited by the cardboard substrate. Following results obtained in [5], we deposited the conductor in four printing cycles (total of eight printed layers), since more cycles did not improve the RF performance significantly. In this process we obtained thickness and conductivity of approximately 3 μm and 20 MS/m, respectively. In the circuit assembly, we used conductive epoxy (Circuit Works CW2400) to attach the lumped components to the printed conductors.

III. DESIGN AND TESTING OF THE HARVESTER

Referring to Fig. 1, the energy harvester we have investigated is composed of an antenna, an impedance matching circuit and a voltage doubler. The doubler consists of two capacitors and zero-bias Schottky detector diodes (Avago Technologies HSMS-2820), which convert the input RF-signal to output DC-voltage. The charge is built up in the input capacitor C_1 during negative half of the input cycle is transferred to C_2 output capacitor during positive half. This leads to the output DC-voltage which is approximately double the input rms voltage.

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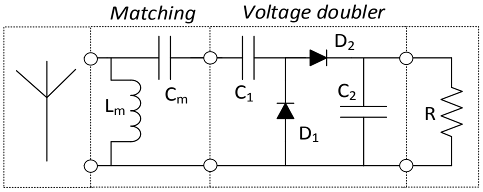


Figure 2. Circuit block diagram of the energy harvester.

An impedance matching circuit between the antenna and the voltage doubler is needed to transfer the maximum available RF power from the antenna to the doubler and consequently to maximize the output DC-voltage. Due to the non-linear voltage-current relationship of the diodes, the input impedance of the voltage doubler varies with the input power. Hence, various input power levels must considered in the optimization of the matching circuit. We used the PSPICE model of the diodes in Agilent ADS circuit simulator to optimize the matching. As shown in Fig. 2, we achieved less than 10% impedance mismatch power loss (S_{11} < 10 dB) for the input power range −5…5 dBm at 2.4 GHz. for output power from –15 dBm to 5 dBm. Figure 3 presents the measured output DC-voltage. In this test we used a signal generator as a source to maintain a stable and accurate input.

A planar monopole antenna was chosen for energy harvesting due to its favorable properties for the application: omnidirectional radiation pattern, single-ended input and inkjet-printing-compatible structure. ANSYS HFSS was used to design the antenna. It is a modified planar monopole with a 50-Ω microstrip line feed (width: 2.5 mm) with an equal width for the monopole. The stepped structure of the monopole (Fig. 4) provided the height of 35 mm (0.28λ at 2.4 GHz). The performance of the antenna is summarized in Fig. 4. Moreover, the measured radiation efficiency of antenna varies from 75% up to 81% within the considered frequencies.

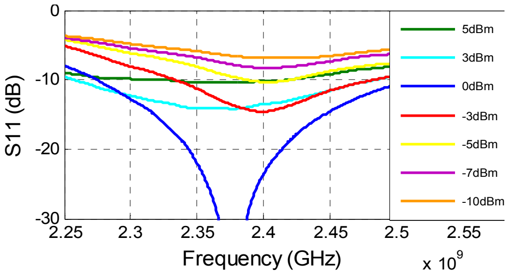


Figure 2. Measured input reflection coefficient of the voltage doubler.

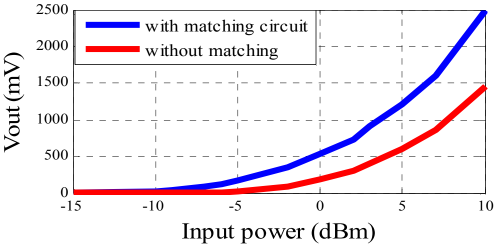
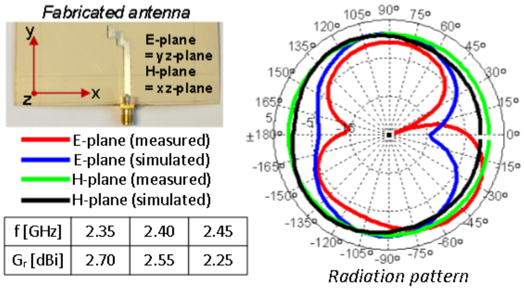


Figure 3. Measured output-DC voltage of the rectifier.



f [GHz]	2.35	2.40	2.45
G_r [dBi]	2.70	2.55	2.25

Figure 1. Measured antenna performance.

IV. CONCLUSION

Ambient RF energy harvesting is a compelling approach to replace batteries while the use of environmental-friendly materials and additive manufacturing methods are a growing trend. In this article, we summarized an RF energy harvester manufactured on regular packaging cardboard using the inkjet-printing technology. The measured DC-outputs were 0.3 V, 0.5 V, and 1.0 V from the input RF signals of −5 dBm, −0.1 dBm, and 3.5 dBm, respectively. In addition to running ultra-low-power circuits, this can be used to accumulate charge in a supercapacitor serving as temporary energy storage. The ink-printed monopole on cardboard achieved high performance, with radiation efficiency above 75%. Future work includes improving the RF-to-DC conversion at low inputs and using co-planar transmission line technology replace the capacitors and inductors and to achieve fully single-side structure

REFERENCES

[1] B. Cook, A. Shamim, "Utilizing wideband AMC structures for high gain inkjet-printed antennas on lossy paper substrate," *IEEE Antennas Wireless Propag. Lett.*, vol. 12, pp. 76-79, Jan. 2013.

[2] S. Pranonsatit, D. Worasawate, P. Sritanavut, "Affordable ink-jet printed antennas for RFID applications," *IEEE Trans. Compon. Packag. Manuf. Technol.*, vol. 2, no. 5, May 2012, pp. 878-883.

[3] Y. Amin, Q. Chen, H. Tenhunen, L.-R. Zheng, "Performance-optimized quadrate bowtie RFID antennas for cost-effective and eco-friendly industrial applications," *Progress in Electromagnetics Research*, vol. 126, pp. 49-64, 2012.

[4] S. Kim, R. Vyas, A. Georgiadis, A. Collado, M. M. Tentzeris, "Inkjet-printed RF energy harvesting and wireless power trasmission devices on paper substrate," in Digest of EuMC, Oct. 2013, pp. 983-986.

[5] H. Saghlatoon, L. Sydänheimo, L. Ukkonen, M. M. Tentzeris, "Optimization of inkjet printing of patch antennas on low-cost fibrous substrates," *IEEE Antennas Wireless Propag. Lett.*, vol. 13, pp. 915-918, May 2014.

[6] H. Saghlatoon, Björninen, Toni, L. Sydänheimo, L. Ukkonen, M. M. Tentzeris, "Inkjet-printed wideband planar monopole antenna on cardboard for RF energy harvesting applications," published online ahead of print in *IEEE Antennas Wireless Propag. Lett.*, Oct. 2014.

[7] Z. Khonsari, T. Björninen, L. Sydänheimo, L. Ukkonen, M. M. Tentzeris, "2.4GHz Inkjet-printed RF energy harvester on bulk cardboard substrate," in Digest of IEEE RWS, Jan. 2015 (to appear).

[8] J. Virtanen, L. Virkki, L. Ukkonen and L. Sydänheimo, "Inkjet-printed UHF RFID tags on renewable materials," *Advances in Internet of Things*, vol. 2, no. 4, pp. 79-85, Oct. 2012.

[9] A. Denneulin, J. Bras, A. Blayo, C. Neuman, "Substrate pre-treatment of flexible material for printed electronics with carbon nanotube based Ink," *Appl. Surf. Sci.*, vol. 257, no. 8, pp. 3645□3651, Feb. 2011.