A Novel Flexible Wearable Magnetic Energy Harvester utilizing Inkjet Masking Techniques

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***Abstract*—In this paper, a novel flexible ambient energy harvesting circuit for the magnetic field from an off-the-shelf 1W two-way talk radio is discussed. As a result, a maximum output power of 146.9 mW with the RF-DC conversion efficiency of 89.2 % and open voltage of 23.86 V is achieved with H-field energy harvester placed on the back of a hand.**

I. INTRODUCTION

Recently, wearable electronics and sensors are becoming more and more popular, but most of these wearable devices require recharging process with a cable. The next big step for the seamless operation of wearable devices will be brought by by integrating flexible wireless power transfer and energy harvesting systems to these wearable devices. Ambient RF waves are available in more locations than other ambient energy sources such as solar, heat and so on because of their general characteristics that they can penetrate obstacles. At the same time, however, the energy density is quite lower than other energy sources. Nevertheless, there are some 'hot-spots' where the RF energy density is very high. The two-way talk radio is one of the most commonly used short distance mobile communication devices. Since it does not require the use of any base station and directly transmits the signal to the other devices, it generates relatively high power RF signals compared to other cellular communication devices, especially in near field. In this paper, a novel flexible/wearable ambient energy harvesting circuit fabricated through inkjet printed making for the magnetic field from a 1W handheld radio, Motorola RDU2020, is discussed.

II. RF RECEIVER DESIGN AND CIRCUIT FABRICATION

In this research, the RF receiver and the energy harvesting circuit are expected to be placed on top of the back of a hand where there are less movements to stabilize the operation of the circuit. In order to be held by typical sizes of a palm, a 8 cm wide by 5 cm long rectangular is considered as the size limit of the receiver. Based on this restriction, an open-type helical coil with four loops for H-field, whose physical dimension is shown in Figure 2(a), is adopted as the receiver for this application. The receiver is soldered with the balun(ADT1-1WT) from Coilcraft Ink.

After the recent major improvements in performance, inkjet printing technology is becoming an attractive option for the fabrication of RF circuits up to millimeter-wave frequency range. It has been proven that inkjet printing technologies for the fabrication of conductive traces with silver nanoparticle-based inks provides people with an access to flexible and easy circuit patterning [1]. However, it is very difficult to integrate printed conductive traces with lumped circuit components for the wearable applications because of the limited flexibility of conductive epoxy which is typically utilized to realize the electrical interconnects between inkjet printed conductive traces and lumped circuit components in the energy harvesting circuit. Therefore, we chose to apply inkjet printing with polymer-based inks in order to facilitate durable flexible circuit traces for the wearable energy harvesting application. The polymer-based ink for inkjet printing is made of 35 $w\%$ SU-8 polymer from MicroChem. The printed polymer traces are used as the mask on the copper cladded liquid crystalline polymer (LCP) substrate provided by Rogers Corporation. The thickness of the substrate is 100 µm and dielectric constant is 2.9. Once the SU-8 masking layer is printed, the substrate is soft baked at 120 °C for 10 minutes. After the soft bake, the masking is exposed to 365 nm UV light for cross linking followed with the post bake at 120 °C for 5 minutes, yielding 4 to 6 µm thick SU-8 per layer [2]. For the masking, two layers of SU-8 are printed and then the uncovered copper layer is etched away with $FeCl_3$ solution.

III. RECEIVED POWER ESTIMATION AND RF-DC CONVERSION CIRCUIT DESIGN

Since the two-way talk radio and the harvester are expected to be placed within the near field of each other, it is very difficult to accurately estimate how much power is really available at the receiver through simulations. The fact that the harvester is designed for wearable applications and given the inevitable proximity effect of the human body make this estimation further complicated. Therefore, in this paper, the power available at the receiver port is analytically computed from 2-port S-parameter measurements with the vector network analyzer (ZVA8 from Rohde & Schwarz). The ambient energy harvesting system can be generally modeled as shown in Figure 1. In this figure, Z_S is source impedance and Z_L is the load impedance. If input and output power at port1 and 2 are described as a_1, b_1, a_2 and b_2 respectively, the arrangement of the transmitting antenna and of the receiver can be expressed as a S-parameter matrix. Once the power transferred to the load and the power generated from the source are defined as P_L and P_S respectively, the power transfer efficiency from

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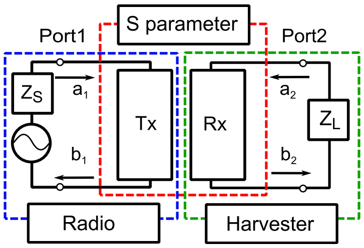


Fig. 1. System configuration with equivalent S parameter matrix.

the source to the load can be written as equation (1). If the reflection coefficient between source to port1 (Γ_{IN}) in equation (1) is substituted with equation (2), the efficiency can be expressed only as a function of the reflection coefficient between port2 to the load (Γ_L). Therefore, once the 2-port S-parameter matrix representing the channel between transmitter and receiver is obtained experimentally, the maximum power transfer efficiency can be analytically camputed by sweeping the value of $\Gamma_L = Ae^{j\theta}$ in the range of $|A| = 1$ and θ =0 to 360°. At the same time, the load impedance yielding the maximum transfer efficiency is obtained from equation (2).

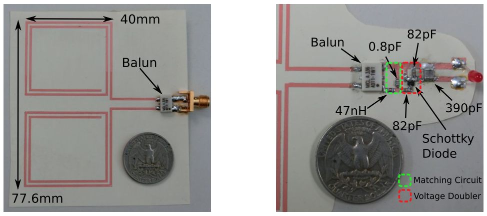
$$\mu = \frac{P_L}{P_S} = \frac{b_2 b_2^* - a_2 a_2^*}{a_1 a_1^* - b_1 b_1^*} = \frac{(1-|\Gamma_L|^2)S_{21}^2}{(1-|\Gamma_{IN}|^2)|1-\Gamma_L S_{22}|^2} \quad (1)$$

$$\Gamma_{IN} = S_{11} + \frac{\Gamma_L S_{21} S_{12}}{1-\Gamma_L S_{22}} \qquad Z_L = Z_0 \frac{1+\Gamma_L}{1-\Gamma_L} \quad (2)$$

In this research, a spindle-shape 20 cm tall water bottle which has the smallest diameter of 17.5 cm at the middle and the largest diameter of 23 cm at the top and bottom is used as a mimic of human arm for proof-of-concept purposes because of the regulation issue for human subject research. In order to imitate the two-way talk radio, a monopole antenna, ANT-433-CW-QW from Linx Technologies Inc, which has similar properties with the one in typically used handheld radios was placed at the bottom of the water bottle and S-parameters are measured. Using these data in equations (1)-(2), the maximum potential power transfer efficiency of the H-field receiver is 16.47 %. The maximum possible transferred power from the 1 W transmitter and the load impedance at the maximum power transfer condition are determined as 164.7 mW and 23.86 - j25.87 from equation (1)-(2) respectively. Based on these numbers, RF-DC conversion circuit and matching circuit are designed on Agilent Advanced Design System (ADS). In order to maximize the output voltage from the rectifier with the minimum possible physical circuit dimention, single stage Dickson charge pump voltage doubler with a single Schottky diode chip, Avago HSMS282C, was adopted. The fabricated protopype is shown in Figure 2(b).

IV. MEASUREMENT RESULT

The output voltage was measured by arranging the harvester and the handheld radio on the side of the water bottle imitating the configuration of the radio and the harvester under the operation. The output voltage was measured for numerous load resistance values ranging from 100 to 6800 Ω. The measured conversion efficiency values with respect to the load resistance is depicted in Figure 3, assuming the input power to be 164.7 mW. The maximum RF-DC conversion efficiency of 89.2 % was achieved with the 2996 Ω load resistance. The operation verification was conducted by connecting a LED as a load and placing the prototype on the back of a hand. As a result, the LED was successfully turned on using only the harvested energy from the handheld radio. The open voltage measurement setup and the operation test are shown respectively in Figure 4 (a) and (b).



(a) (b)

Fig. 2. (a) Receiver for H-field. (b) Energy harvesting circuit configuration.

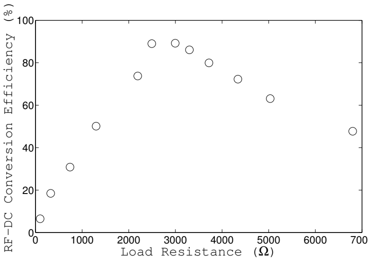
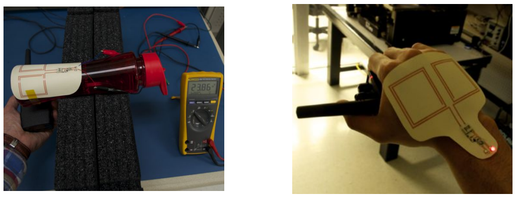


Fig. 3. Measured RF-DC conversion efficiency with varied load resistance.



(a) (b)

Fig. 4. (a) On-bottle open voltage measurement setup. (b) Energy harvesting circuit operation verification on the back of a hand.

V. CONCLUSION

In this paper, the design and fabrication process of a flexible wearable ambient energy harvester for a consumer two-way talk radio utilizing inkjet printing masking is discussed. The received power and optimal load are analytically computed from the measured S-parameters. As a result, a maximum output power of 146.9mW with the RF-DC conversion efficiency of 89.2 % and open voltage of 23.86 V is achieved with H-field energy harvester placed on the back of a hand.

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