Ambient Energy Harvesting from a Two-way Talk Radio for Flexible Wearable Devices utilizing Inkjet Printing Masking

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Abstract—**In this paper, the design, on a flexible LCP substrate, and fabrication process of a wearable circuit harvesting the ambient energy emitted from a two-way radio is discussed in detail.The circuit is fabricated through the combination of circuit traces made with masking utilizing inkjet printing technology and lumped circuit components. The input power for the RF-DC conversion circuit is analytically computed from the measured S-parameters of the Tx-Rx propagation channel. A maximum output power of 43.2mW with the RF-DC conversion efficiency of 82.5% and open- circuit voltage of 17.87 V is achieved with an E-field energy harvester placed 7cm away from an off-the-shelf 1W two-way talk radio.**

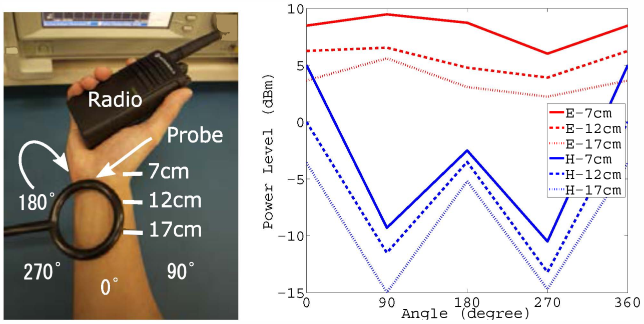
Index Terms—**Inkjet printing, Energy harvesting, Flexible, Wearable**

I. INTRODUCTION

In the last couple of decades, energy harvesting from ambient RF signals has attracted the interest of the research community following the explosive increase of the use of RF waves for communication and broadcasting. There are plenty of different kinds of RF sources which can possibly be used as the power source for low-power consumption electronics and wearable sensors, especially in urban environments, such as VHF radio, UHF TV signals and Wi-Fi signals [1],[2]. A typical characteristic of microwaves is their capability to penetrate opaque walls, making them available in more locations than other ambient energy sources such as solar and vibration, although the energy density of RF signals is usually lower than other sources [3]. However, there are some 'hotspots' where RF energy density is quite high. The two-way talk radio is a commonly used device for short distance communication. Since it does not use any base station and directly sends the signal to the other mobile devices, it generates relatively high RF power compared to other mobile communication electronics, especially in near field. In this research, a novel near-field energy harvesting circuit on a flexible substrate that can be fabricated with inkjet printing technology for wearable device applications (Internet of Things, Wireless Body Area Networks, etc.) is introduced.

II. RF POWER MEASUREMENT

Since most people turn on the Walkie-Talkie with their hands, it is assumed that a sufficiently high amount of power out of the near field of the radio can be harvested by placing a harvester on a wrist. In order to orient the design of the wearable energy harvesting circuit, the intensity of electric and magnetic field around the wrist were measured with ETS-Lundgren E-field and H-field probe which are connected to the real-time spectrum analyzer, RSA3408A, from Tektronix. A Motorola RDU2020 two-way talk radio (1 W) was used as a power source and the radio was held with a right hand. The operation frequency of this radio was 464 MHz. The measurement setup and the measured E- and H-field values at 7 to 17 cm away from the radio at various angular positions are shown in Figure 1 (a) and (b) respectively. It can be concluded from these measurements that the electrical field is stronger than the magnetic field around the wrist. However, due to the typical near-field E-field distribution of a monopole antenna, the optimum E-field receiver needs to be placed parallel to the 2-way radio antenna which is difficult because of typical motions and changes in the relative positions of the radio in the arrangement of the radio and the wrist. On the other hand, the power level of magnetic field at 0° position is relatively higher than any other angle, and it is easier to mount a larger structure which can possibly increase the received power from the H-field. Based on this assumption, receiver circuits for both electrical field and magnetic field were designed for proof-of-concept purposes.



(a) (b)

Fig. 1: (a) Measurement configuration. (b) Measured power level at each angle and distance.

III. RECEIVER DESIGN

Referring to the typical size of a wrist, a width of 5 cm, a length of 8 cm and a circumference of 15 cm were adopted as the size constraints of the receiver. Based on the near-field

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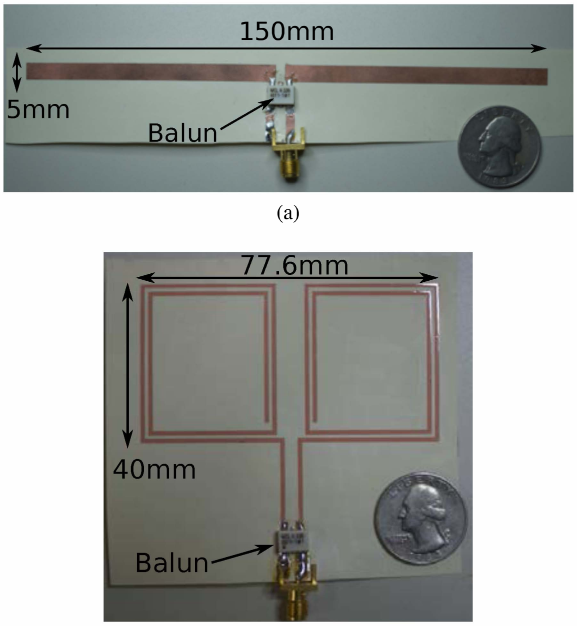


(a)

(b)

Fig. 2: (a) Receiver for E-field. (b) Receiver for H-field.

power measurements and the above wrist-dependent restrictions, receiver circuits for both electrical field and H-field were designed. A dipole antenna for E-field and open-type helical coil with four loops for magnetic field were adopted at the wearable harvesting receiver. Both were soldered with the balun (ADT1-1WT) from Coilcraft Ink. The dimension of the E-and the H-field receivers are shown in Figure 2.

IV. CIRCUIT FABRICATION

Due to recent substantial improvements in fabrication processes and performance up to the millimeter-wave frequency range, inkjet printing technology has become increasingly attractive for RF circuit fabrication. Inkjet printing technologies with silver nanoparticle-based inks have proven to be a very efficient solution for low-loss RF circuit patterning [4]. However, it is quite challenging to fabricate durable flexible circuits with printed traces and lumped circuit components because of the limited flexibility of the conductive epoxy, that is commonly utilized as the electrical interconnect between inkjet printed conductive patterns. In order to create durable flexible circuits for wearable energy harvesting applications, the masking through the use of an inkjet printed polymer was adopted. The polymer ink is made of 35 $w\%$ SU-8 polymer from MicroChem, and was used as a mask on copper-cladded liquid crystalline polymer (LCP) substrate from Rogers Corporation. The thickness and dielectric constant of the substrate are $100\,\mu\mathrm{m}$ and 2.9 respectively. Once the SU-8 ink was printed, the substrate was soft baked at $120\,^{\circ}\mathrm{C}$ for 10 minutes before the masking was exposed to $365\,\mathrm{nm}$ UV light for cross linking. After the UV light exposure, the substrate was heated at $120\,^{\circ}\mathrm{C}$ for 5 minutes, yielding 4 to $6\,\mu\mathrm{m}$ thick SU-8 per layer [5]. Two layers of SU-8 were printed and then the uncovered copper metallization was etched with $FeCl_3$. The etching time varied from 30 to 90 minutes depending on the temperature, size of substrate, thickness of metal layer and freshness of the $FeCl_3$ solution. The resolution of the conductive patterning is effectively equal to the resolution of inkjet printing, making it possible to fabricate circuit traces width and spacing of less than $400\,\mu\mathrm{m}$, which is sufficiently good for many commonly used packaged IC's. Figure 3 shows the printed conductive traces for a $3\,\mathrm{mm}$ by $3\,\mathrm{mm}$ TDFN8 package that have been fabricated with the above additive fabrication approach.

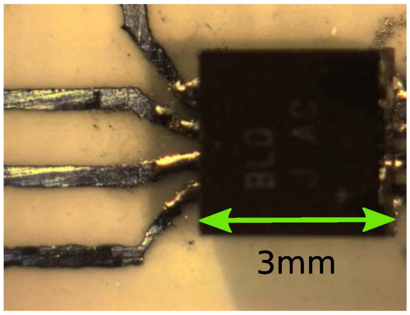


Fig. 3: Circuit traces for a TDFN8 IC package fabricated with inkjet printing masking.

V. INPUT POWER ESTIMATION AND RF-DC CONVERSION CIRCUIT DESIGN

Since the transmitter and the receiver circuits are placed in the near field, it is very difficult to estimate accurately how much power is actually transferred to the receiver through simulations. The requirement that the proposed receiver had to be wearable, as well as the detrimental proximity effect of the human body, further complicated this estimation. Therefore, in this paper, the power transferred to the receiver port was computed from 2-port S-parameter measurements with the vector network analyzer (ZVA8 from Rohde & Schwarz). The energy harvesting system can be generally modeled as shown in Figure 4. In this figure, Z_S is source impedance and Z_L is the load impedance. If input and output power at port1 and port2 are defined as a_1, b_1, a_2 and b_2 respectively, the topology of the transmitter antenna and of the harvesting receiver can be expressed as a S-parameter matrix. Once the power transferred to the load and the power from the source, defined as P_L and P_S respectively, the power transfer efficiency from the source to the load can be expressed as shown in equation (1). If the reflection coefficient from 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 from port2 to the load (Γ_L). Therefore, once the 2-port S-parameter matrix for the Tx-Rx propagation channel is calculated experimentally, the maximum power transfer efficiency can be analytically computed by sweeping the value of $\Gamma_L = Ae^{j\theta}$ in the range of $|A| = 1$ and $\theta =$0 to 360°. At the same time, the load impedance value yielding the maximum efficiency can be computed from equation (2).

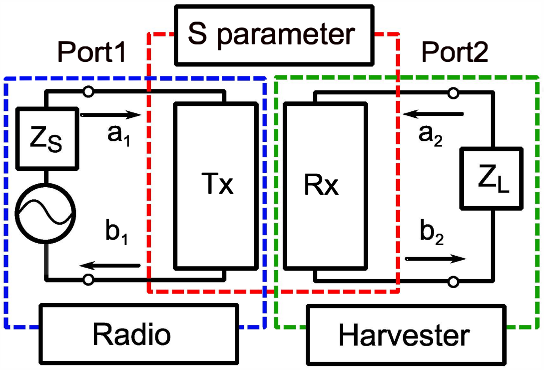


Fig. 4: System configuration with equivalent S parameter matrix.

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

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

In this research, the harvester circuit is expected to be placed on the human body. However, because of the regulation issue for human subject research, a bottle of water was adopted as the substitute material of the human forearm for the preliminary measurements. As a proof of concept, and without loss of generality, a spindle-shape $20\,\mathrm{cm}$ tall water bottle, which has the smallest diameter of $17.5\,\mathrm{cm}$ at the middle and the largest diameter of $23\,\mathrm{cm}$ at the top and bottom, was used. In order to mimic the two-way talk radio, a monopole antenna, ANT-433-CW-QW from Linx Technologies Inc, which has similar properties as the one on the 2-way talk radio, was placed at the bottom of the water bottle and was used for the S-parameter measurements. The wearable harvesting receiver was wrapped $7\,\mathrm{cm}$ from the bottom of the bottle in a configuration equivalent to the handheld 2-way radio and the ”$7\,\mathrm{cm}$” position of the harvester in Figure 1. The measured S-parameters for the transmitting monopole and for the E- and H-field receivers are plotted in Figure 5 for this specific configuration. Using this data in Equations (1) and (2), the maximum potential power transfer efficiency was determined to be $5.23\,\%$ and $3.71\,\%$ for the E-field and the H-field receivers, respectively. Therefore, the E-field receiver was chosen for the preliminary wearable harvester design. The maximum possible transferred power from the $1\,\mathrm{W}$ transmitter, $52.3\,\mathrm{mW}$, and the load impedance at the maximum power transfer condition, 28.4 - $j1.99$, were determined from Equation (1) and (2) respectively. In order to maximize the output voltage with the minimum possible circuit size, a single-stage Dickson voltage doubler with one Schottky diode chip, Avago HSMS282C, was used as the rectifier. The circuit was initially designed with ADS and the matching circuit was tweaked during measurements. The configuration of the rectifier prototype is shown in Figure 6.

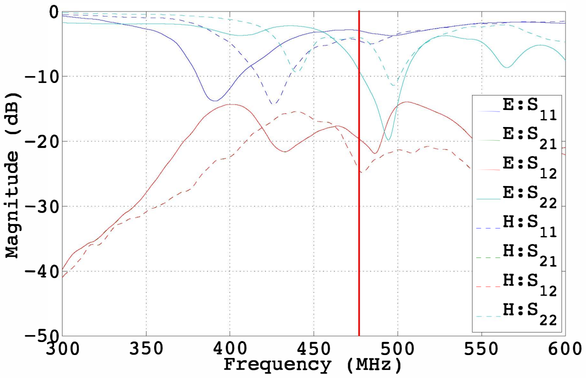


Fig. 5: Measured S parameter for E- and H-field receivers.

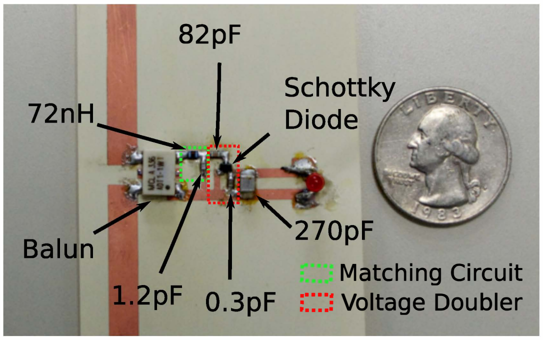


Fig. 6: RF-DC conversion circuit topology for wearable E-filed energy harvester.

VI. MEASUREMENT RESULTS

The output voltage measurements were initially conducted with an RDU2020 handheld radio by arranging the harvester and the radio on the side of the water bottle in a configuration similar to the one on the human arm holding the radio. The output voltage was measured by changing the load resistance of the circuit in the range of 100 to $6800\,\Omega$. The comparison between the simulated and the measured conversion efficiency values as a function of the load resistance is depicted in Figure 7, assuming the input power to be $52.3\,\mathrm{mW}$. The maximum RF-DC conversion efficiency of $82.5\,\%$ was achieved for the $1772\,\Omega$ load resistance. The operation test was conducted by replacing the load resistance with a LED and wrapping the prototype on the wrist. As a result, the LED was successfully turned on utilizing only the harvested energy from the handheld radio under the typical radio operation condition. The measurement of the open-circuit voltage and the verified on-arm successful operation of the wearable harvester are shown respectively in Figure 8 (a) and (b). In order to specify the effects of the energy harvesting circuit for the communication with the handheld radio, the received power, which represents the quality of communication, was measured in the anechoic chamber with the following three different conditions at 1 and $2\,\mathrm{m}$ separation between the transmitter and receiving antenna; (i) the prototype on the water bottle is placed at the proximity of the radio as is Figure 8, (ii) only the water

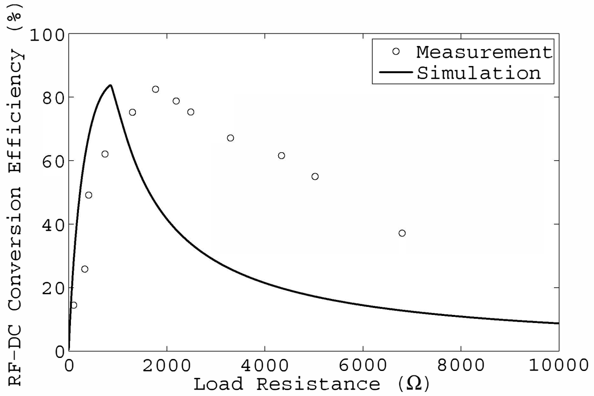
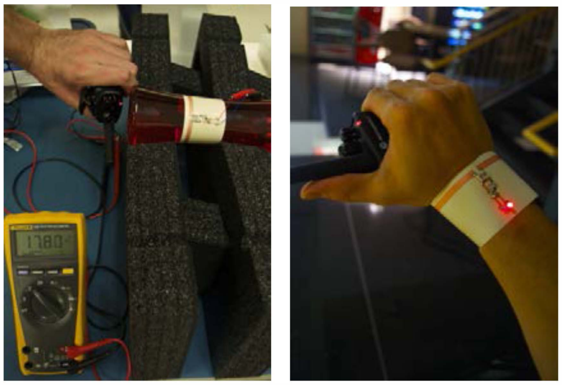


Fig. 7: RF-DC conversion efficiency from ADS simulation and measurement with respect to load resistance.



(a) (b)

Fig. 8: (a) Preliminary open voltage measurement with an on-bottle setup. (b) Operation verification of the wearable harvester on a wrist.

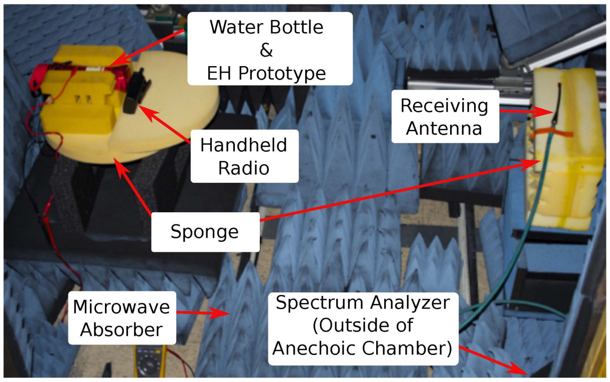


Fig. 9: Received power measurement in anechoic chamber.

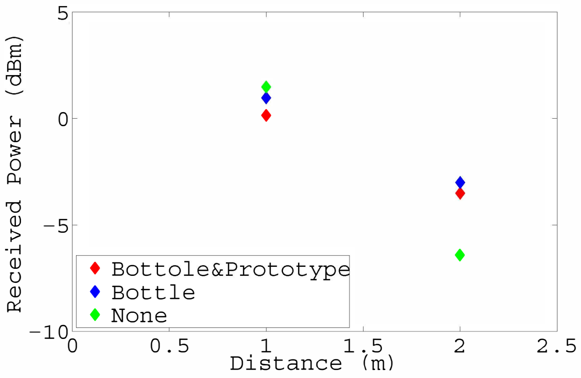


Fig. 10: Effect of harvester prototype for received power.

bottle is placed near the radio and (iii) both water bottle and the prototype are removed from the proximity of the radio. The measurement setup is shown in Figure 9. The receiving antenna is the monopole antenna, ANT-433-CW-QW. The measurement results are depicted in Figure 10. From the measurement, it can be said that difference in the received power between the case (i) and the case (ii) at two different separation distances in the far field were quite small. This result implies that the degradation of the communication performances of the radio by the energy harvesting circuit on is limited.

VII. CONCLUSION

In this paper, the design and fabrication process, on flexible substrates, of a near-field ambient energy harvesting circuit for wearable device applications is discussed. The circuit was fabricated through the combination of conductive traces realized with inkjet printing masking technology and lumped circuit components. The input power for the RF-DC conversion circuit was analytically estimated from the measured S-parameters, and the maximum RF-DC conversion efficiency of $82.5\,\%$ and open load voltage of $17.87\,\mathrm{V}$ were achieved with an E-field energy harvester yielding $43.2\,\mathrm{mW}$ of output power. This system can be implemented to power up microcontrollers/sensors for wearable biomonitoring, WBAN and Internet of Things applications.

VIII. ACKNOWLEDGMENT

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