Expand Horizons of Microfluidic Systems: An Inkjet Printed Flexible Energy Autonomous Micropump System for Wearable and IoT Microfluidic Applications

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***Abstract*—A novel inkjet printed flexible energy autonomous micropump system is proposed to provide actuation forces and open new applications for microfluidic such as smart skin and IoT. The broadband energy harvester is proposed to harvest near-field two-way talk radio at 464.5 MHz and far-field UHF RFID reader from 850 MHz to 950 MHz simultaneously. The near-field energy harvesting can support high power at certain time to overcome IC cold start and the far-field energy harvesting can harvest power all the time to maintain the function. The proposed broadband rectifier can be operated from 300 MHz to over 1200 MHz which equals to over 120 % fractional bandwidth. The RF-DC conversion efficiency is about 50 % while 20 dBm input power is used and the load impedance is 125 Ω. The duty cycle for the charging and discharging of the far-field energy harvesting is 13 %. The proof-of-concept system is built and the micropump is driven successfully by both near-field and far-field energy harvesting.**

***Index Terms*—Energy harvesting, Micropump, Inkjet printing, Microfluidic, Flexible.**

I. INTRODUCTION

Microfluidics have been a significant technique for advanced RF components over the last decade. Non-conductive fluidics are used to adjust the permittivity and achieve reconfigurable RF components such as resonators, filters, antennas, sensors, and frequency selective surfaces (FSS) [1]–[3]. In the mean time, conductive fluidics are suitable for switches and flexible circuits [4]. For all microfluidic applications, actuation forces are required to move fluidics inside micro-channels. Typical ways of moving fluidics includes manually pressing fluidics into the channels using syringes [5], using pumps [6], and using electrochemically controlled capillarity [7]. However, all methods require a certain power or voltage to drive the system which significantly limits their applications.

In order to expand the usage of microfluidics techniques to modern applications such as Internet of Things (IoT) and smart skins, it is crucial to provide a battery-less actuation force to reduce the maintenance cost. The energy harvesting techniues combining with a cheap and small micropump which is capable of driving all types of liquids inside micro-channels is an appropriate solution to expand the horizon of the microfluidic applications since it have been proven that the energy harvesting techniques are suitable to support green and constant energy for low-power electronics [8]. For energy harvesting techniques, there are many different types of ambient energy sources such as solar, RF, heat, and vibration that can be utilized in energy harvesting systems. Among all ambient energy sources, RF sources are particularly popular since they can be accessed all day while their ability of bypassing or penetrating walls makes them ubiquitously available. There are two types of RF energy harvesting approaches. The first one is to harvest far-field RF energy such as TV and communication signals [9]. This type of energy can be accessed all the time but it typically has relatively low energy density [10]. The other type of RF energy harvesting technique is to harvest RF energy from nearby "hot spots" such as hand-held and wearable devices where RF energy is fairly high. With a wearable and flexible energy harvester, this type of energy can generate very high dc voltage and power [11]. However, it might be accessible only small amount of time when those hand-held and wearable devices are transmitting power.

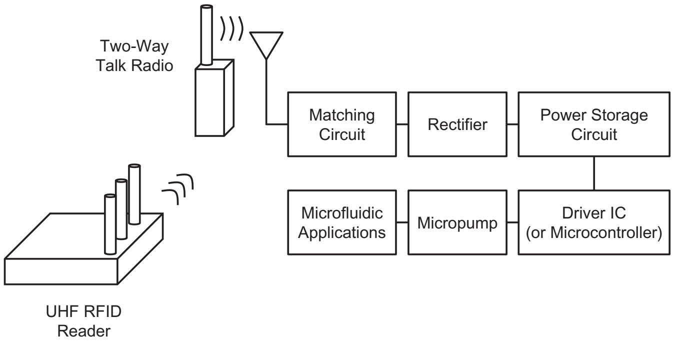
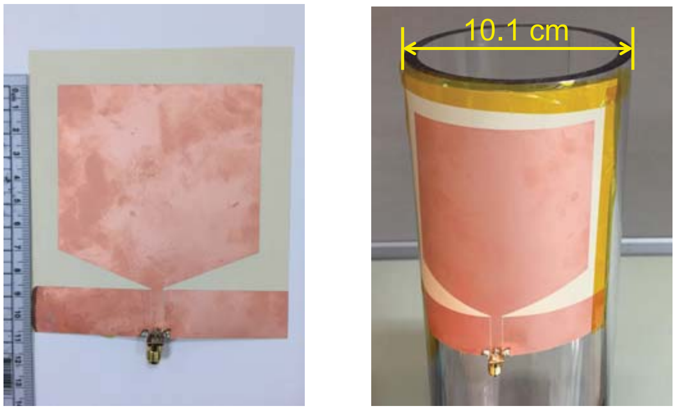


Fig. 1. Block diagram of the proposed energy-autonomous microfluidic system.

In this paper, a novel micropump system solely powered by energy harvesting techniques which harvests near-field and far-field RF energy sources simultaneously is proposed. A broadband energy harvester which is composed of a broadband antenna and a broadband rectifier is proposed to simultaneously harvest the far-field UHF RFID reader signals within the range of 850 to 950 MHz and near-field two-way talk radio waves at 464.5 MHz. By combining the two sources, the system would have both advantages from the near-field and far-field energy harvesting. The high power and dc from near-field energy harvesting can be achieved to overcome the cold-



(a) (b)

Fig. 2. Broadband antenna in (a) flat and (b) folded conditions.

start of the driving IC chip for the micropump immediately while the consistent accessed far-field energy can be used to charge the energy storage device continuously to maintain function of the micropump system. The proposed autonomous micropump system can provide large actuation forces which can be applied to any type of microfluidic applications.

II. SYSTEM ARCHITECTURE

The block diagram of the proposed energy autonomous micropump system is shown in Fig. 1. As shown in Fig. 1, the energy sources are a UHF RFID reader (850 MHz-950 MHz) with EIRP equals to 4 W (36 dBm) and a two-way talk radio (464.5 MHz) with output power around 35 dBm at near range. A broadband antenna is used to receive power from both sources while a broadband matching circuit is used to match the antenna with the rectifier within these frequencies. The rectifier would convert the RF signal to DC power and use it to charge a supercapacitor which serves as the power storage circuit. Once the voltage is high enough, the supercapacitor can be used to power up the driving IC or a micro-controller unit to generate driving signals for the micropump. A small and cheap micropump which is operated based on a piezoelectric diaphragm is used to support the actuation force for the microfluidic applications.

III. BROADBAND ENERGY HARVESTER DESIGN

A. Inkjet Printed Flexible Broadband Antenna Design

A broadband monopole antenna as shown in Fig. 2 is used for the collection of energy from multiple ambient sources. As shown in Fig. 2(b), good flexibility can be observed by curving the broadband antenna along a cylinder with a diameter equals to 10.1 cm. The measured S_{11} of the antenna in the flat and the curved configurations are shown in Fig. 3. As demonstrated in Fig. 3, for the flat condition, the measured S_{11} is smaller than -10 dB from 700 MHz to over 1.2 GHz. There is a frequency shift due to folding and the S_{11} is kept smaller than -9 dB from 850 MHz to over 1.2 GHz. The UHF RFID band can be covered by this broadband antenna under both conditions. The near-field coupling between the 464.5 MHz two-way radio and the antenna is still good enough as discussed in Section IV.

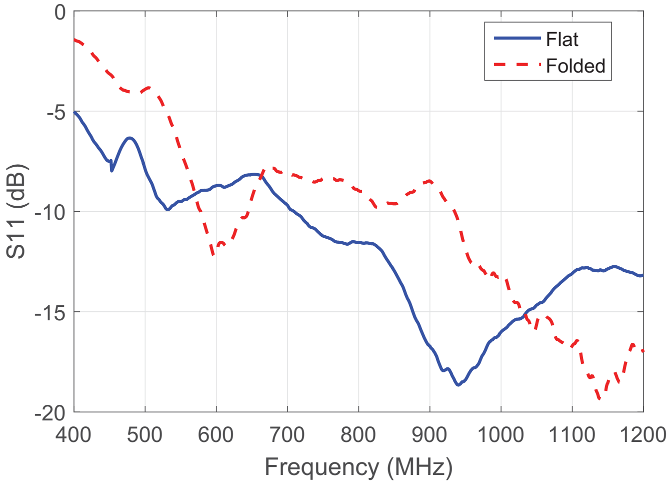


Fig. 3. Measured S_{11} in flat and folded condition.

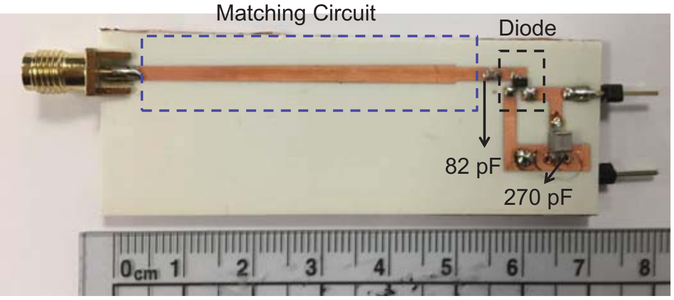


Fig. 4. Proposed broadband rectifier.

B. Broadband Rectifier Design

A broadband rectifier which covers frequencies from 300 MHz to over 1.2 GHz is proposed as shown in Fig. 4. A tapered line is used to achieve broadband impedance matching. The voltage doubler topology is adapted for the rectification. The voltage doubler is composed of an 82 pF capacitor, a HSMS 282C diode package for rectification, and a 270 pF capacitor to eliminate higher-order harmonics. The load of the proposed rectifier is the driving IC of the micropump which has a resistance equal to $125\,\Omega$. The measured S_{11} values for different input power levels are shown in Fig. 5. The measured S_{11} are all smaller than -9 dB for different input power levels and a very broadband performance can be proved. The measured output power levels while using different input power levels at different frequencies are shown in Fig. 6. The simulated results using harmonic balance provided by Advanced Design System (ADS) are also included for comparison and a good agreements can be observed. As depicted in Fig. 6, flat responses at different frequencies can be observed which serve as a strong proof of the broadband performance of the proposed broadband rectifier. There is a minor decrease around 1000 MHz due to the higher S_{11} values around that frequency. The RF-DC conversion efficiency is

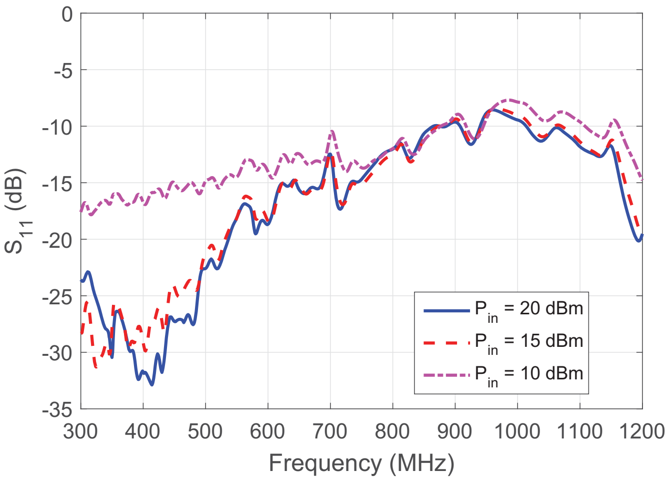


Fig. 5. Measured S_{11} of the proposed broadband rectifier.

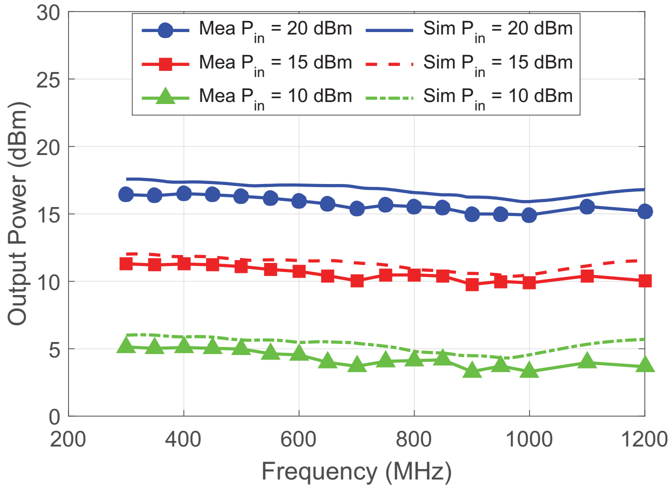


Fig. 6. Measured and simulated output DC power of the proposed rectifier.

about 50 %, 45 %, and 35 % while the input power levels of 20 dBm, 15 dBm, and 10 dBm, respectively.

IV. SYSTEM PERFORMANCE EVALUATION

For the near-field energy harvesting, the measured coupling between the two-way talk radio and the final output power at the output of the rectifier at different distances is 21.5 dBm, 16.3 dBm, and 14.6 dBm while the distance is 5 cm, 10 cm, and 15 cm, respectively. The micropump-driving IC can be driven at the power level of at least 14 dBm which means the maximum range is about 15 cm. For the far-field energy harvesting from UHF RFID reader, to follow FCC regulations, 4 W EIRP is used. The received power by the broadband antenna at 900 MHz and 45 cm away is around 13 dBm. It takes 77 s to fully charge a 47 mF supercapacitor to 3.5 V and the micropump can be operated for 10 s before the voltage drops below the driving point. Thus, the duty cycle is about 13 %. The measurement setup for the entire system is shown in Fig. 7.

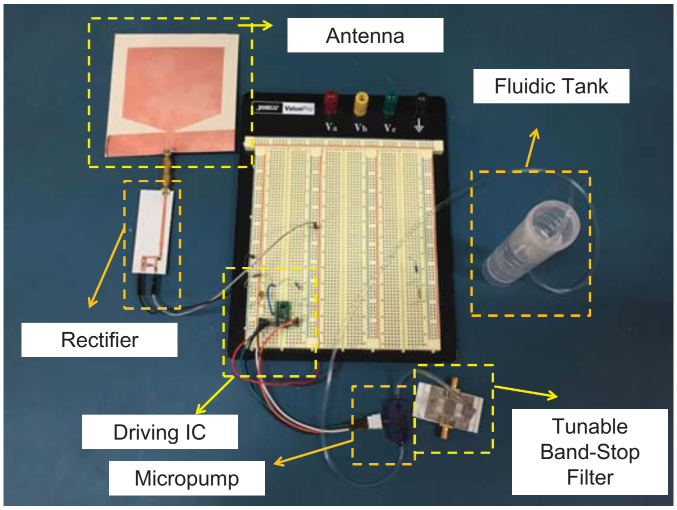


Fig. 7. The measurement setup of the proposed energy autonomous microfluidic system.

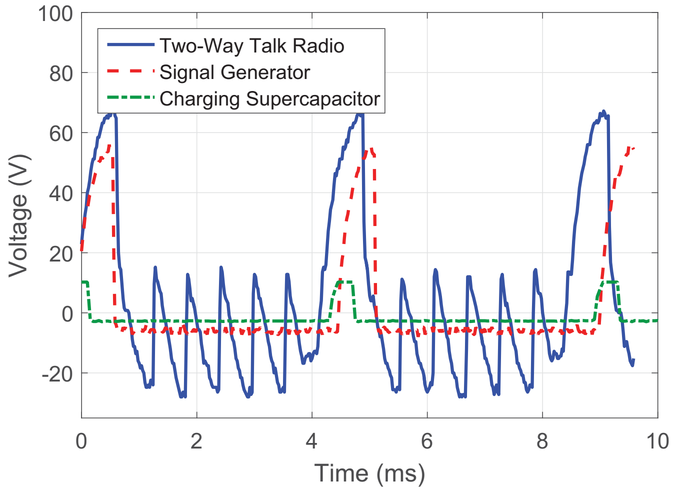


Fig. 8. Output voltage at the output pin of the driver IC.

The voltage at the output of the driving IC is measured and shown in Fig. 8. As shown in Fig. 8, three different conditions are measured. The first one is is the use of the energy from the two-way radio to turn on the driving IC immediately. The second one is to use a signal generator to generate a 19 dBm 464.5 Mz signal and directly feed to the proposed broadband rectifier. The final one is to harvest UHF signals to charge supercapacitor and use that to drive the IC. Since the micropump is based on piezoelectric principles, the resulting voltage change can be used to induce the vibration while the amplitude of the voltage difference can be used to control the amplitude of the vibration and thus, control the amplitude of the actuated force. As shown in Fig. 8, since the two-way talk radio can support high energy density, the IC can be turned on immediately with an output voltage of 67.2 V at the output end of the driving IC. The result is similar to that using a signal generator with 19 dBm input power and the output voltage is 56 V. The noise in the two-way talk radio measurement

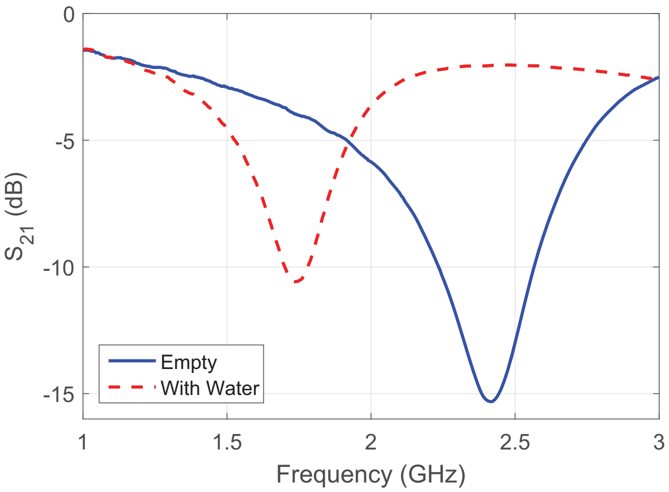


Fig. 9. Measured S_{21} of a liquid-tunable band-stop filter.

is due to the coupling between the two-way talk radio and the probing cable of the oscilloscope. Moreover, the output voltage is 10.2 V while using the UHF-charged supercapacitor. Although the voltage is smaller compared to that using two-way talk radio, the driving IC is still successfully turned on. Furthermore, the time duration of the voltage spikes shown in Fig. 8 is determined by the driving IC. The band-stop filter in the setup shown in Fig. 7 is tunable due to the embedded microfluidic channel. The measured S_{21} values are shown in Fig. 9 and the stop band can be changed by pumping water into the microchannel using the proposed micropump system. It takes less than 1 s to fill the channel with $6\,\mu\mathrm{L}$ water. Besides, the moving speed of the fluidic using the proposed micropump system is measured and the result is $37.8\,\mu\mathrm{L}\cdot\mathrm{s}^{-1}$. Thus, it takes only 0.16 s to finish the transition which is a much shorter time than the autonomous micropump operation time provided by the harvested energy.

V. CONCLUSION

A novel inkjet printed flexible energy autonomous micropump system utilizing RF energy harvesting techniques is proposed. A broadband energy harvester is presented to simultaneously harvest near-field two-way talk radio and far-field UHF RFID reader energy to provide both high power at a certain amount of time to overcome the cold-start of the IC and a constant power all the time to sustain a duty-cycle operation. The proposed rectifier can be operated from 300 MHz to over 1200 MHz which is 120 % fractional bandwidth. The RF-DC efficiency is 50 % for an input power of 20 dBm. The full system is constructed and the micropump is proven to be able to provide enough actuation force for microfluidic applications. This energy autonomous micropump system can be used to expand the the horizons of microfluidics to novel applications, such as smart skins and IoT.

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