Additive Manufacturing Technologies for Near- and Far-field Energy Harvesting Applications

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***Abstract* — This paper reviews the fabrication and design of two different types of energy harvesting systems, that utilize ambient energy to power up connected wireless modules. A 3D/inkjet-printed origami-style (morphing) cube with orthogonally-placed patch antennas is presented which enhances the nodes diversity reception capabilities. The cube changes its shape upon heating upto 60°C. In contrast, the presented near-field energy harvester utilizes the ambient RF energy of a handheld two-way radio to convert the RF signal with an efficiency of 82.5%. For proof-of-concept purposes, an E-field energy harvesting receiver is fabricated on a flexible LCP substrate with inkjet printing technology featuring an open-circuit voltage of 17.87V for an output power of 43.2 mW for the E-field energy harvester placed 7 cm away from a 1W Walkie-Talkie transmitter**

***Index Terms* — Additive manufacturing techniques, energy harvesting, origami, inkjet printing, 3D printing, morphing RF**

I. Introduction

The recent advancements in additive manufacturing technologies (AMT), such as 3D printing and inkjet printing, have allowed the fabrication of low-cost, flexible and environment friendly electronic and communication systems. Some of the key advantages of using AMT include low setup cost, little or no material waste, repeatability and scalability, which facilitate the prototype to industrial scale transition compared to the conventional wafer-by-wafer production [1]. Due to the aforementioned advantages, significant research has been done in AMT during the past decade ranging for material characterization to the design of wearable tags, sensors, printed flexible displays and portable devices [2],[3].

Among numerous key application areas, AMT can be extensively used in the design of sensors, wireless power transfer and energy harvesting systems.

This paper reviews two AMT based ambient energy harvesting systems which use a combination of 3D and inkjet printing technologies. In section II, an origami-based morphing far-field energy harvesting 3D/inkjet-printed cube is introduced [4]. The cube has orthogonally-placed patch antennas on it which effectively increase the energy harvesting capability and overall efficiency of the system. The cube changes its shape by heating the hinges of the cube around 60°C for couple of minutes. In section III, a wearable energy-harvesting system is introduced which exploits the high electric and magnetic field in the surroundings (mostly near-field) of communication devices such as handheld radios to power up the connected electronics [5]. For proof-of-concept, a simple LED is used to demonstrate the amount of the received power. This is particularly useful for applications like wireless sensor networks and Wireless Body Area Networks which should preferably be self-sufficient in power and can capable to use the ambient energy to recharge their batteries or supercapacitors.

II. AMT Based Morphing/Reconfigurable Cube for Far-field Energy Harvesting

A 3D/inkjet-printed, origami-based, cube prototype with multi-directional RF harvesting capability at 2.4GHz is shown in Fig. 1. The cube is formed by six 4.2×4.2 cm squares and connecting hinges into a cross sign configuration. The squares and hinges are printed with VeroWhitePlus RGD835 and Grey60 RGD8530-DM material respectively using a 3D-printer. For the proof-of-concept two (2.68×3.65 cm) patch antennas are placed on orthogonal planes to increase antenna diversity, thus improving the system efficiency in case of multiple sources.

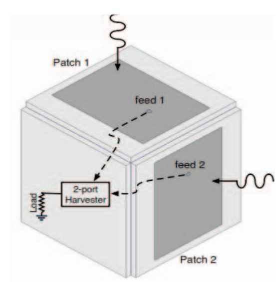


Fig. 1. Origami-based 3D printed cube with two patch antennas placed on orthogonal axis and an enclosed 2-port harvester

In room temperature, both materials are rigid. However, upon heating the hinges to temperatures around 60°-70° C for about 2-3 minutes, they become flexible and the whole structure folds on itself to become a cube-like structure as shown in Fig. 2. Upon cooling the structure takes a cuboid

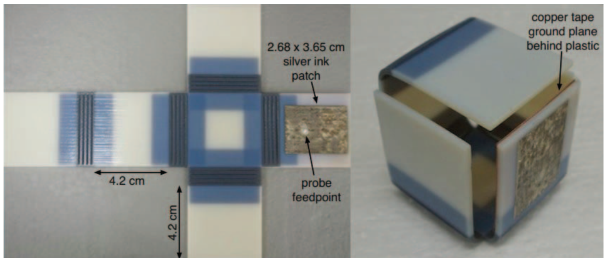


Fig. 2. Shape change of the cube before (left) and after (right) heating, shaping and cooling. Thickness of each square is 2mm

shape while the hinges become rigid and provide a good mechanical support to the sides.

The patch antennas were inkjet printed on the glossy side of the squares to exploit its better surface smoothness using a supporting layer of reactive silver ink and twenty layers of silver acetate with heat drying after each layer deposition. The ground plane was constructed using copper tape at the bottom surface. The DC resistance between the two cross edges of the patch was measured to be 0.2Ω. The two patch antennas were fed by a coaxial cable through SMA connectors and connected to a harvester. The schematic of the harvester along with its fabricated prototype on 20 mil Rogers RO4003C with ε_r=3.55 and tanδ=0.002 is shown in Fig. 3. The measured return loss and coupling for the two-port harvester is shown in Fig. 4 which demonstrates the strong isolation of the two ports.

III. Inkjet-printed Wearable Near-field Energy Harvesting System

Two wearable near-field energy harvester prototypes consisting of an inkjet-printed dipole and a loop antennas for systems like two-way Walkie-Talkie radios are shown in Fig. 5. A balun (ADT1-1WT) is used to match the antennas to a 50Ω coaxial line. Experiments show that even though E-field is much stronger than H-field around the radio, it is difficult to design an optimum E-field receiver which is perfectly parallel (aligned) to the monopole antenna of the handset radio. Therefore, an H-field receiver is also presented which exploits the relatively higher magnetic field at 0º position. The

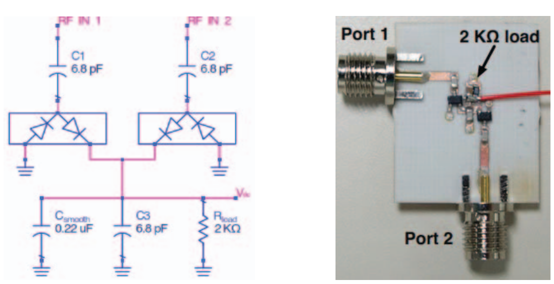


Fig. 3. Two-port energy harvester schematic (left) and fabricated prototype (right)

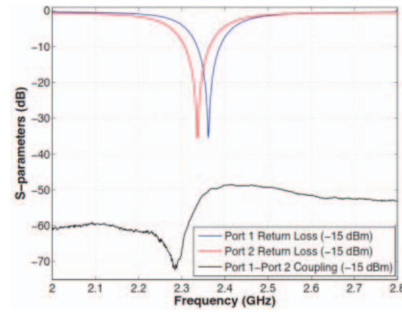
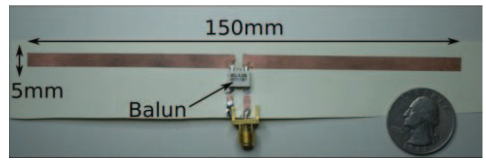
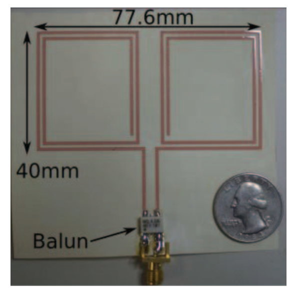


Fig. 4 Measured return loss & coupling of the two-port harvester



(a)



(b)

Fig. 5. Inkjet-printed energy harvesting receiver for (a) E-field using a dipole antenna, (b) H-field using loop antenna

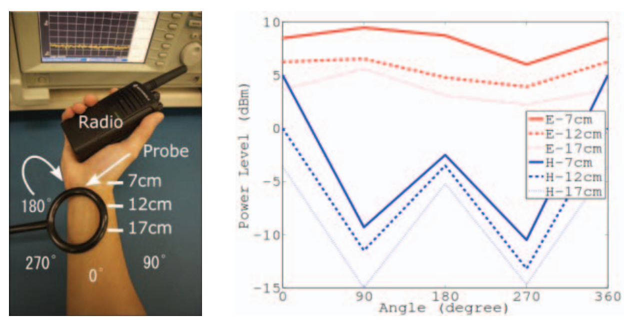


Fig. 6. Power measurement setup (left) and distribution around the handheld radio (right)

distribution of E and H-field around the handheld radio (Motorola RDU2020 - operating at 464MHz) and its measurement setup (ETS-Lundgren probe and real-time spectrum analyzer, RSA3408A) is shown in Fig. 6.

In order to fabricate a durable and flexible energy harvesting receiver with interconnected conductive traces and lumped components, a 35 *wt%* SU-8 polymer ink from MicroChem was used to mask a 100µm thick copper cladded liquid crystalline polymer (LCP) substrate with ε_r=2.9. After printing, the substrate was soft baked for 10 minutes at 120ºC and cross linked by exposure to 365nm

UV light. Then the substrate was heated again at 120°C for 5 minutes to yield a 4-6μm thick SU-8 layer [6]. Finally, the unwanted copper was etched using the standard $FeCl_3$ solution.

The input power was estimated using standard microwave circuit theory equations given below.

$$\mu = \frac{P_L}{P_S} = \frac{(1-|\Gamma_L|^2)S_{21}^2}{(1-|\Gamma_{IN}|^2)|1-\Gamma_L S_{22}|^2} \qquad (1)$$

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

where μ is the power transfer efficiency (ratio between the power to the load and supplied power by the source). In order to model the effect of a human hand, a spindle-shaped water bottle was used. ANT-433-CW-QW monopole antenna (from Linx Technologies Inc.) was used to mimic the two-way radio and was placed under the bottle to obtain the S-parameters given in equations (1) and (2). While the receiver was placed at a 7 cm position as shown in Fig. 6, the measured S-parameters are shown in Fig. 7. The maximum power efficiency for the E- and H-field receivers (using equations 1 and 2) was measured to be 5.23% and 3.71%, respectively. Due to the higher power efficiency of E-field receiver, it was chosen for the main harvester design. The maximum transferred power and load impedance from a 1W transmitted power of the walkie-talkie were found out to be 52.3 mW and 28.4–j1.99, respectively. The rectifier was designed using a single-stage Dickson voltage doubler with on Schottky diode (Avago HSMS282C) to obtain the maximum output voltage while keeping the circuit size to a minimum as shown in Fig. 8.

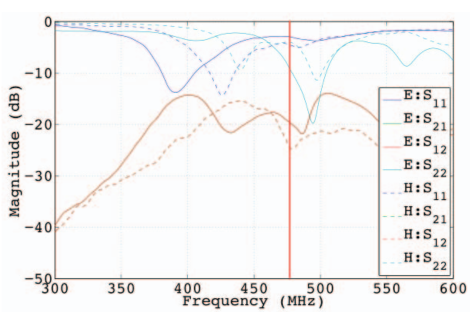


Fig. 7. Measured S parameters for E- and H-field harvesters

The maximum RF-DC conversion efficiency of 82.5% was calculated for an input power of 52.3mW and a load resistance of 1772Ω.

VII. Conclusion

In this paper, the design and fabrication process of the two near-field and far-field energy harvesting systems is presented using additive manufacturing technologies like 3D printing and inkjet-printing. The origami-based cube presents a first of its kind hybrid printing technique with multi-directional energy harvesting capability. On the other hand the proposed near-field energy harvesting system features a relatively high RF-DC conversion efficiency of 82.5% and an open voltage of 17.87V resulting in an output power of 43.2mW for the E-field energy harvester verifying its potential applicability in wearable RF applications.

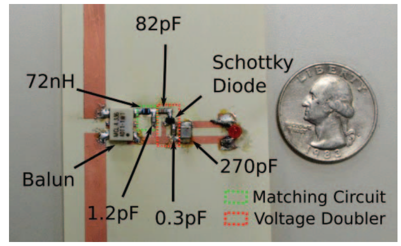


Fig. 8 RF-DC conversion circuit for E-field harvester

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