Inkjet-printed RF Energy Harvesting and Wireless Power Trasmission Devices on Paper Substrate

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Abstract— **This paper presents an overview of the state-of-the-art inkjet-printed energy harvesting and wireless power transfer technology on paper substrate. RF energy harvesting devices utilizing a charge pump circuit or an active antenna based wireless power transmission device are presented. Inkjet printing technology on paper substrate and fabrication techniques, along with a variety of applications, are presented with particular focus on low-cost and eco-friendly wireless systems for wireless sensor networks.**

Keywords— inkjet printing; paper substrate; energy harvesting; wireless power transfer; charge pump

I. Introduction

Many kinds of energy harvesting technology is existing such as piezo-electric devices, solar cells, and RF power harvesting devices. Particularly, RF power harvesting for wireless sensor networks (WSN) has attracted lots of interest for a decade [1]. The life time of wireless sensor networks can be extended because RF power harvesting technology reduces battery usage which results in reducing the operation cost of wireless devices. Along with the RF power harvesting technology, wireless power transmission technology also emerged as promising technology for sustainable wireless network system [2]. The wireless power transmission technology has a broad application range from biomedical to WSN because it can overcome the limitations of low power electronics in terms of lifetime and space. The introduction of inkjet-printing technology on paper substrate improved the conventional RF energy harvesting/transmission technology in terms of cost, and fabrication efficiency [3]. The inkjet printing technology can achieve conductive traces which have a high conductivity in the order of 10^6 ~10^7 S/m, and it is an environmentally friendly additive process [4].

This paper presents the state-of-the-art inkjet-printed RF power harvesting and wireless power transmission devices on paper substrate involved in sustainable eco-friendly technology.

II. Inkjet Printing Technology on Paper Substrate

Inkjet printer has been introduced for the first time in 1970s. The invention of nano-particle-based inks enabled the use of this technology as a fabrication method. Recently, inkjet printing technology has evolved in a popular fabrication method in the microwave area. It has attracted a large interest from many researchers due to its many advantages [5-7]. It is an additive process which does not produce harmful by-products such as acids, which are typically used to wash away metals from the top of a substrate surface. The required amount of ink is deposited on a desired position which enables a cost effective fabrication. In addition, it is suitable for mass production on flexible substrates such as paper or PET. In this section, the properties of inkjet-printed silver nano-particles are presented as well as the properties of organic paper substrate.

A. Inkjet-printed Nano-silver Particle

Silver nano-particles ink is composed of silver nano-particles and solvent which keep the nano-particles in ink form. The average grain size of the silver nano-particles varies from 10 nm ~ 150 nm. Commercially available inkjet printers are able to achieve a high resolution up to 50 μm without any wet processes such as photolithography or electroplating. The mean diameter obtained from a 1 pL ink droplet are about 28 μm, while the resulting diameter from a 10 pL ink droplet is 45 μm.

A sintering process usually follows immediately after inkjet printing of a desired pattern. Sintering is required in order to increase the conductivity of the printed patterns because it burns off polymers and solvent which are mixed with the silver nano-particles. Silver nano-particles form agglomerations under high temperature, and those are percolation channel for electrons. Therefore, a higher conductivity can be achieved when nano-silver particles are sintered at a higher temperature. Fig. 1 shows inkjet-printed silver nano-particles on paper substrate and its surface when it is sintered at 120 ˚C for 2 hours. The printed silver nano-particles have formed a continuous metal sheet (left). The craters on the printed silver trace come from the impurities and gases which are released during the sintering process. The surface of the inkjet-printed silver nano-particles has been scanned using Veeco atomic force microscopy (AFM) to measure the roughness. The measured arithmetic average roughness (R_a) is 11.4 nm and root mean square roughness (R_q) is 14.4 nm.

Conductivity is an important design parameter for microwave circuits and devices. Simple straight lines were

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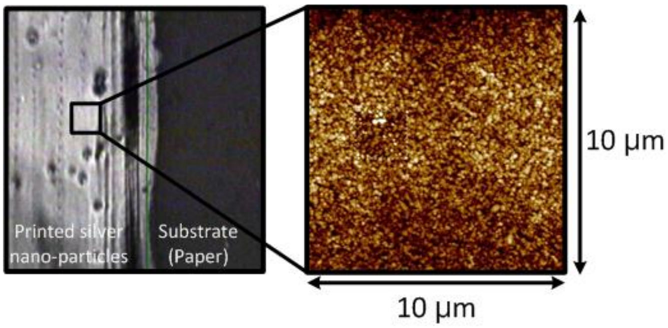


Fig 1. Inkjet-printed silver nano-particle on paper (left) and its surface (right) at 120 ˚C for 2 hours.

TABLE 1. CONDUCTIVITY OF PRINTED NANO-SILVER PARTICLES [5]

Layers	Conductivity (S/m)
1	0.55×10^{6}
3	1.16×10^{6}
5	2.16×10^{6}

TABLE 2. RELATIVE PERMITTIVITY AND LOSS TANGENT OF PAPER [5]

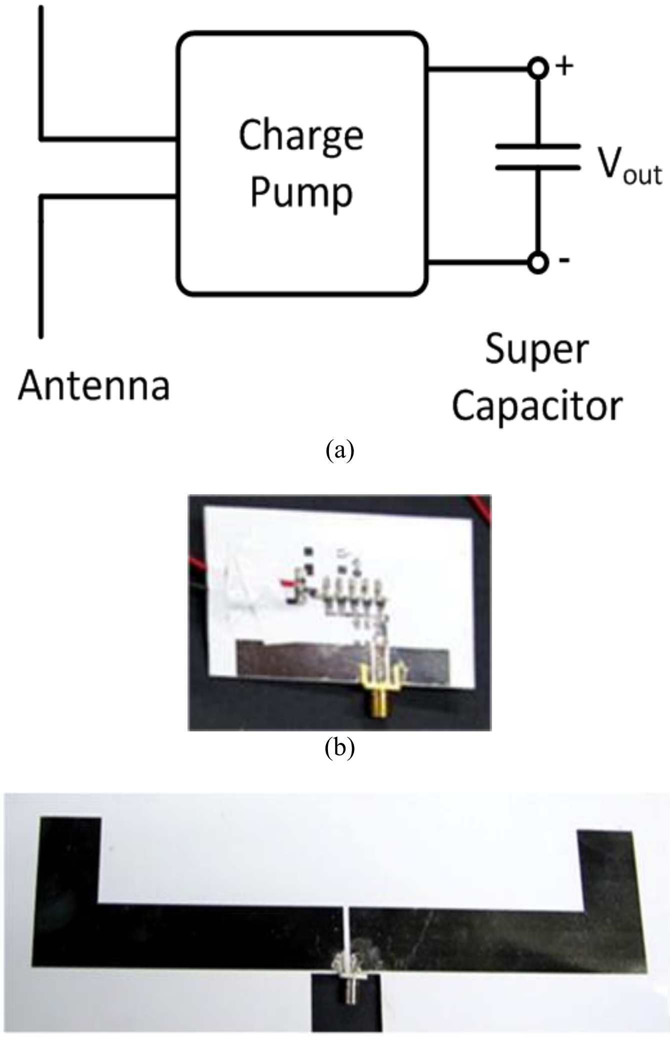
Frequency (GHz)	Relative Permittivity (ε_r)	Loss tangent (tan δ)
1	3.2	0.053
3	3.0	0.057
5	2.9	0.059
7	2.85	0.062
9	2.8	0.065

printed on glass substrate with different printed layers and the sample lines are sintered in thermal oven at 120 ˚C for 1 h [5]. The measured conductivity was in the order of 10^6 and conductivity is increasing as the printed layer increases (Table 1). This is because the particle density is increasing as the printed layers are increasing. A Cascade four points probing station was utilized to measure conductivity.

Mechanical properties of the inkjet-printed silver nano-particles are also reported in [8]. The reported average pull-off strength of the inkjet-printed is about 51 N. The adhesion strength between the printed trace and substrate is a function of moisture content of the substrate. The adhesion strength decreases when the substrate absorbs moisture.

B. Paper Substrate

Paper substrate in microwave applications has been proposed in many previous works [4,5]. Its electrical properties such as relative permittivity (ε_r) and loss tangent (tan δ) have been investigated utilizing ring resonators and T-resonators, and many applications such as antenna [9], RFID tag [10] and sensor [11] have been demonstrated. Paper has many



(a)

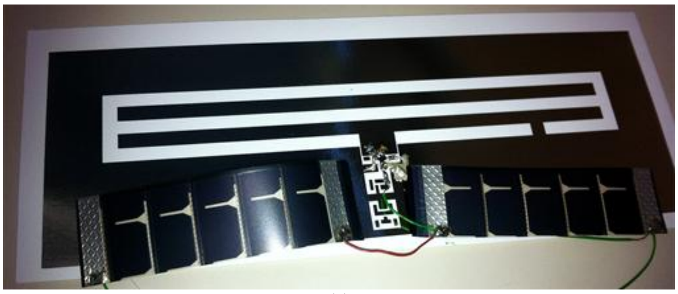
(b)

(c)

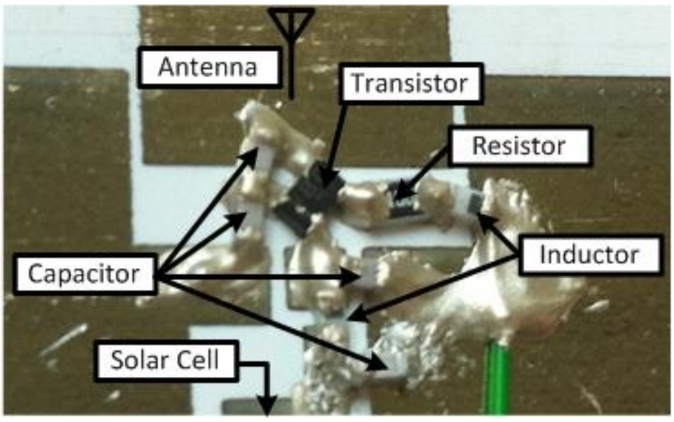
Fig 2. (a) Block diagram of inkjet-printed RF power scavenging device, (b) fabricated charge pump on paper (c) and inkjet-printed UHF band antenna for RF power scavenging [12].

advantages over other substrates. A cellulous-based paper is a cheap, biocompatible and environmentally friendly material. These properties can be fully explored when combined with inkjet printing technology.

The electrical properties of paper substrate are presented in Table 2 [5]. The relative permittivity (ε_r) of 0.23 mm thick (10 mil) photopaper is about 3.0 within the frequency band of 1 GHz to 9 GHz, and the loss tangent (tan δ) is about 0.059 through the same frequency range. The loss (tan δ) of paper is high compared to other flexible substrate such as PET (0.005), LCP (0.0025), and polyimide (0.002). This property may limit the number of applications of paper substrate because it is very challenging to implement high-Q microwave structures, such as resonator-based structures. However, the high loss of paper is not a critical design parameter for other designs on thin substrates such as RFID tags. This is because the interaction of the electrical field (E-field) with the thin paper substrate is weak and therefore parameters such as roughness and



(a)



(b)

Fig 3. (a) Inkjet-printed beacon oscillator and (b) fabricated oscillator circuit on paper[13]

conductivity of metal become the critical factor for implement microwave circuits.

III. Inkjet-printed RF Power Harvester and Wireless Power Transfer (WPT) Circuits on Paper

A. Inkjet-Printed Ambient Wireless Power Harvesting Circuits

An electromagnetic power harvesting circuit was implemented and presented in [12]. It aims to scavenge ambient RF power present at different frequencies corresponding to several wireless communication systems, and use it to supply power to a wireless sensor node. There are many power harvesting devices which utilize many frequency bands. The proposed design in [12] has utilized the UHF frequency band at 470 ~ 570 MHz. This frequency band has many advantages including high power density in free space as well as low attenuation because of its long wavelength in free space (520 mm ~ 640 mm).

The required voltage to power up most of existing microcontrollers and transceivers is in the range of 1.8 V ~ 3.6 V. A charge pump circuit was used to charge a low leakage super capacitor (Fig. 2(a)). The charged capacitor supplies power to microcontroller and transceiver like a battery. Super capacitors are superior to batteries when considering the trade-off between number of recharge cycles, leakage, and cost. A power management unit (PMU) was additionally introduced to regulate voltage across the super capacitor in order to prevent an uncontrolled charge-discharge. The PMU maintains a sufficient voltage across the super capacitor for the continuous operation of the wireless electronic devices.

The fabricated power scavenging device and inkjet-printed antenna for UHF band is shown in Fig. 2(b)(c). The charge pump consists of Schottky diodes which have a low forward voltage drop and fast switching speed. The proposed circuit produces an open circuit voltage of 1.8 V which is sufficiently high enough to turn-on the utilized microcontroller and transceiver. The open circuit voltage of the antenna should be higher than forward voltage drop of the diode in order to operate charge pump circuit [3].

B. Inkjet-printed Solar-powered Wireless Power Transmission Beacon Oscillator

The proposed design is presented in Fig. 3(a). It consists of antenna, oscillator circuit and power supply. Amorphous silicon (a-Si) solar cells are utilized as a power source, and a voltage regulator circuit is integrated with the solar cells for stable power supply. The oscillator circuit generates an RF signal at 800 MHz, and the generated RF power is broadcasted through the slot antenna. The oscillator circuit shown in Fig. 3(b) consumes 7.2 mW. The operating frequency of the device can be scaled up or down to other desired frequency band depending on the application. The oscillator generates stable oscillation frequency around 800 MHz with phase noise of about -130 dBc/Hz at 1MHz away from carrier frequency.

This work demonstrated the potential for conformal low cost inkjet printing technology for efficient wireless power transmission topologies. The next step of this work is to improve efficiency of the oscillator circuit as well as design a high gain antenna in order to achieve high DC-to-RF conversion efficiency.

IV. Conclusion

This paper has presented the recent progress of inkjet-printed electronics for power harvesting and wireless power transmission applications. An RF power scavenging device utilizing a charge pump circuit on paper substrate able to provide a 1.8 V supply voltage when a RF power of 35 µW is available in free space was demonstrated. Furthermore, a solar powered beacon oscillator for wireless power transfer was also presented. Inkjet-printed RF power harvesting/transmission technology is a very promising technology in terms of low cost, eco-friendly, sustainable wireless system.

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