Inkjet-printed Sensors on Paper Substrate for Agricultural Applications

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***Abstract*—In this paper, recent progresses in inkjet-printed sensors on paper substrate is introduced. The advantages of inkjet-printing technology and paper substrate for agricultural applications are discussed. Inkjet-printed RFID-enabled sensor, inkjet-printed retro-directive dual band transponder and inkjet-printed sensor platform are presented as design examples.**

Keywords—Inkjet-printed sensors, inkjet-printed electronics, paper substrate, RFID-enabled sensor, retro-directive transponder, SenSprout

I. INTRODUCTION

Famine is one of the most serious problem in the world. There are many reasons for the world wide famine such as crop failure and population unbalance. Among them, damage from crop failure can be relieved by advanced agricultural technology [1]. Water monitoring and control like irrigation plays very important role on modern agriculture. Pervasive computing and wireless technology have brought brilliant agricultural advances but it is challenging to implement wireless system over vast agricultural areas such as cost and environmental issues [1, 2].

Introduction of inkjet printing technology has reduced the fabrication cost and enabled large scale produce due to inkjet-printing technology's advantages over other conventional fabrication methods [3]. Utilizing paper substrate has enhanced these advantages of inkjet printing technology because paper substrate is eco-friendly and extremely low-cost material. The inkjet-printed electronics on paper has great potential for agricultural applications due to these reasons.

This paper presents state-of-the-art results of inkjet-printed wireless sensors on paper such as capacitive, retro-directive, and sensor platform. Inkjet-printed wireless sensor systems for future agriculture applications are introduced in terms of environmentally friendly and sustainable technology.

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II. INKJET PRINTING AND PAPER SUBSTRATE

Inkjet printing technology has a lot of advantages in sensors especially for the agricultural applications. First of all, inkjet printing technology is environmentally friendly technology and cost effective method. It is because inkjet printing technology does not use any hazardous chemicals to wash away unwanted metals on the substrate surface. It drops nano-particle ink on the desired position so that there are no by-products because it is an additive fabrication method. The advantages of the inkjet printing technology such as fast fabrication and ease of mass produce also help to lower the cost of the inkjet-printed electronics. The electrical properties of inkjet-printed silver nano-particle were thoroughly studied in [4], and lots of microwave applications were proposed by utilizing the silver nano-particles [5-7]. The conductivity value of the inkjet-printed silver nano-particle is about 1.1×10^{7} S/m which is high enough to be utilized in microwave area.

Inkjet printing technology can print various electronics on many kinds of substrates so that it is possible to utilize an environmentally friendly substrate such as a paper. The paper substrate is a very attractive substrate for inkjet-printed electronics for agricultural applications. A paper is a low cost, renewable, and inkjet printable material. It is also one of the cheapest material in the world as well as decomposes completely in nature. Plus, there are many kinds of papers such as hydrophobic, porous, and almost transparent papers. The hydrophilic property of normal papers is very useful to implement sensors for humidity or rainfall because water is one of the most important factor in agriculture. The properties of paper for inkjet-printing were reported in many papers utilizing different characterization methods such as ring resonator or T-resonator methods [3, 4]. The reported dielectric constant (ε_r) of paper is about 3.0 and its loss tangent (tan δ) is about 0.05 ~

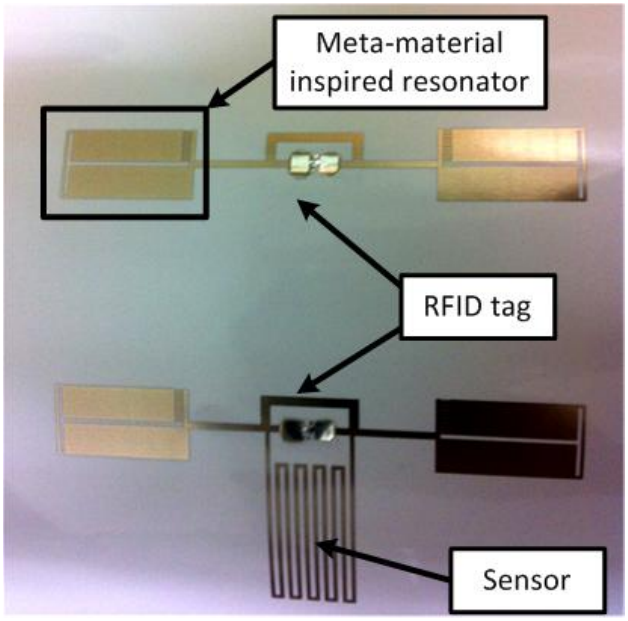


Fig 1. Inkjet-printed capacitive sensor [9].

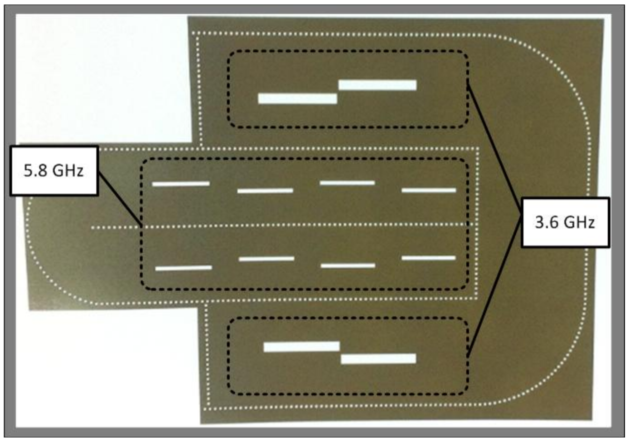
0.06. The relatively high loss of the paper is not a critical issue for RFID or planar structures which have low Q-factor because the thickness of the paper is very thin which results in small interaction between E-field and the paper substrate.

III. INKJET-PRINTED SENSORS FOR AGRICULTURAL APLICATIONS

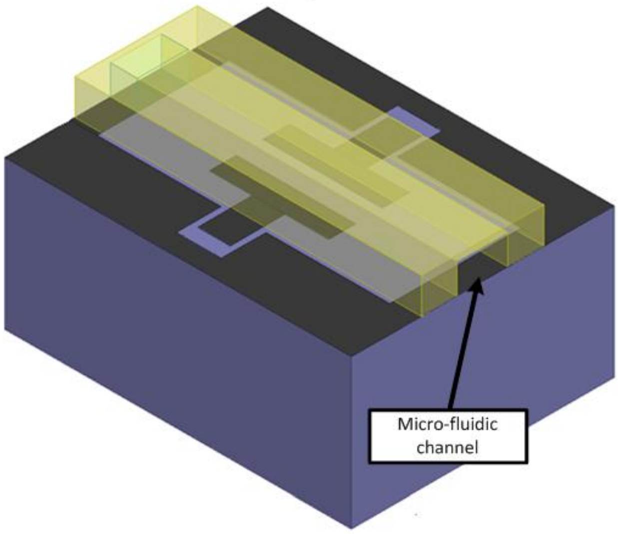
A. RFID-enabled Sensor

RFID-enable sensor has lots of advantages over conventional sensor system in terms of cost and implementation. Usually, the cost of RFID tag is very low and the system is relatively simple (reader and sensor tag). Therefore it is possible to realize the RFID-enabled sensor system over the vast agricultural field with low cost. RFID standards are also compatible with existing wireless sensor networks (WSN) which results in ease of implementation [8].

In [9], inkjet-printed RFID-enabled sensor for haptic and water level detection was introduced. It consists of two identical RFID tags for UHF band (915 MHz) but a sensor is integrated with one of the RFID tags. The sensor is a meandered line which has self-resonant frequency around 915 MHz. Once a material which has the different dielectric constant and loss tangent from the air meets the meandered line, the capacitance of the sensor changes which results in shifting of the resonant frequency of the tag. The two tags return their unique IDs at the same frequency when they are illuminated by a reader because their resonant frequencies are the same. However the resonant frequency of the antenna with the sensor (Fig 1) is shifted to the low frequency when the sensor is loaded by human finger or water. Using a tag without the sensor as a reference, the presence of the sensing target can be easily detected. In the same way, water level can be detected because the capacitance variation of the sensor affects on the resonant frequency of the RFID-enabled sensor. The meta-material inspired resonator cell is integrated to the tags in order to suppress the cross talk of the two tags.



(a)

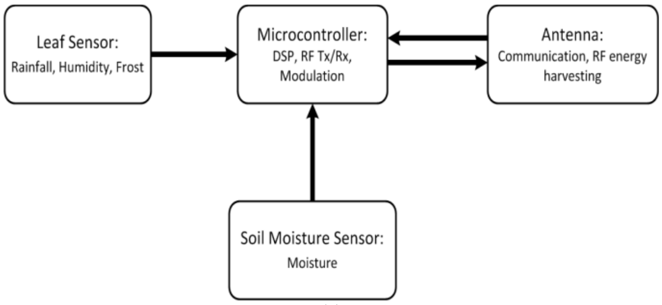


(b)

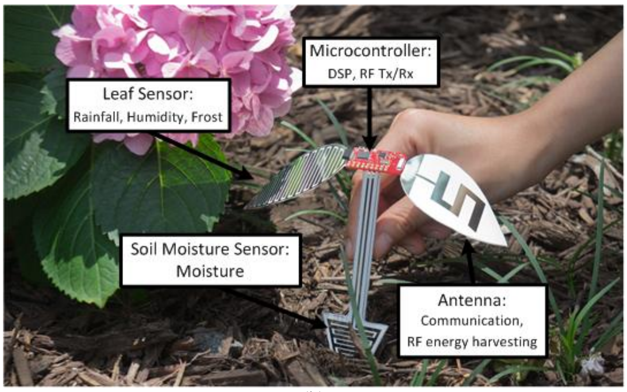
Fig 2. (a) Inkjet-printed dual-band SIW retro-directive array on paper and (b) proposed micro-fluidic sensor [12][13].

B. Retro-directive transponders for sensing

Retro-directive antenna arrays can re-transmit interrogation signal back to its source without any complicated computations [10]. The Van Atta topology is one of the most popular topology for the retro-directive antenna array topology due to its simple structure and passive implementation [11]. The concept of integrating micro-fluidic sensor and retro-directive antenna array was proposed in [12][13]. It is purely passive and has self-steering capability. Its self-steering capability leads to strong system performance because of its



(a)



(b)

Fig 3. Inkjet-printed sensor platform for agriculture application: SenSprout (a) block diagram, (b) proposed design [14].

wide readable angle of the passive transponder or the sensor. Especially, this property is very critical in RCS-based back-scattering communication applications such as passive wireless sensor system. For example, the back-scattered power level of most RCS-based passive wireless sensors depends on the illumination angle but the retro-directive antenna arrays can improve the performance of the sensor because the retro-directive antenna array can reflect almost the same power level to the interrogation direction over the broad angle. The proposed inkjet-printed dual-band substrate integrated waveguide (SIW) retro-directive array and micro-fluidic sensor are shown in Fig 2 [12]. It suggests that the potential applications for a chipless RFID-enabled sensor tag at two different frequencies for temperature or water quality sensing. The variation of RCS from micro-fluidic sensor can be read in broad range due to retro-directive transponder and dual-band property of the retro-directive transponder lead to the capability of sensing two targets at two different frequencies.

C. Inkjet-printed Sensor Platform:SenSprout

Recently, a low cost inkjet-printed sensor platform for agricultural application was proposed in [14]. The proposed sensor platform optimized to detect humidity of ambient environment, water content in the soil and the rain fall because the moisture monitoring is one of the most important factor in the agriculture. Its system level block diagram is shown in Fig 3(a). It consists of a leaf sensor, a soil moisture sensor, a microcontroller unit and an antenna. The capacitances of the leaf sensor and soil moisture sensor vary depending on the humidity and water contents of the soil or near environment of the sensor platform. The microcontroller detects the capacitance variations of the leaf sensor as well as the soil moisture sensor. The microcontroller processes the collected data from the sensor, and broadcasts the information through the antenna. The antenna and microcontroller also can be utilized to collect ambient power in order to reduce the battery usage or power up the microcontroller [15]. Unlike the conventional sensors, whole passive components are inkjet printed on environmentally friendly paper substrate. Plus, dense monitoring of soil moisture and rainfall over the vast agricultural field are possible due to the advantages of inkjet printing technology on paper such as low fabrication cost, and ease of mass produce. Fig 3(b) shows the implementation of the proposed sensor platform. The soil moisture sensor is buried in the ground to detect surface soil moisture. The leaf sensor, the microcontroller and the antenna are exposed to exterior environment. The exposed components can be chemically coated such as a silicon or a Parylene in order to protect and extend the lifetime of the sensor platform.

IV. CONCLUSION

This paper has presented the recent progresses of inkjet-printed sensors on paper substrate for agricultural applications. The RFID-enabled capacitive sensor for water level detection and haptic sensor application is presented. Furthermore, a concept of retro-directive SIW dual band transponder for sensor application and inkjet-printed sensor platform for agricultural application have been introduced. Inkjet-printed wireless sensors on paper substrate are very promising technology since it is low cost, eco-friendly, and sustainable wireless system.

REFERENCES

[1] T. Wark, P. Corke, P. Sikka, L. Klingbeil, G. Ying, C. Crossman, P. Valencia, D. Swain, and G. Bishop-Hurley, "Transforming Agriculture through Pervasive Wireless Sensor Networks," *Pervasive Comput.*, vol. 6, no. 2, pp. 50-57, 2007.

[2] C. Bauckhage, K. Kersting, and A. Schmidt, "Agriculture's Technological Makeover," *Pervasive Comput.*, vol. 11, no. 2, pp. 4-7, 2012.

[3] L. Yang, A. Rida, R. Vyas, and M.M. Tentzeris, "RFID Tag and RF Structures on a Paper Substrate Using Inkjet-Printing Technology," *IEEE Trans. Microw. Theory Tech.*, vol. 55, no. 12, pp. 2894-2901, 2007.

[4] B. S. Cook, and A. Shamim, "Inkjet printing of novel wideband and high gain antennas on low-cost paper substrate," *IEEE Trans. Antennas Propag*, vol. 60,no. 9, pp. 4148–4156, 2012.

[5] M. M. Tentzeris, R. Vyas, V. Lakafosis, T. Le, A. Rida, and S. Kim, "Conformal 2D/3D Wireless Modules Utilizing Inkjet Printing and Nanotechnology", *Microwave J.*, vol. 33, no. 2, 2012.

[6] S. Kim, A. Georgiadis, A. Collado, and M. M. Tentzeris, "A Inkjet-Printed Solar-Powered Wireless Beacon on Paper for Identification and

Wireless Power Transmission Applications", *IEEE Trans. Microw. Theory Tech.*, vol. 60, no. 12, pp. 4178–4186, 2012.
[7] J. Virtanen, L. Ukkonen, T. Bjorninen, A. Z. Elsherbeni, and L. Sydänheimo, "Inkjet-Printed Humidity Sensor for Passive UHF RFID Systems," *IEEE Trans. Instrum. Meas.*, vol. 60, no. 8, pp. 2768–2777, 2011.
[8] H. Liu, M. Bolic, A. Nayak, and I. Stojmenovic, "Taxonomy and Challenges of the Integration of RFID and Wireless Sensor Networks," *IEEE Netw.*, vol. 22, no. 6, pp. 26–35, 2008.
[9] S. Kim, Y. Kawahara, A. Georgiadis, A. Collado, and M.M. Tentzeris, " Low-Cost Inkjet-Printed Fully Passive RFID Tags Using Metamaterial-inspired Antennas for Capacitive Sensing Applications," in *IEEE MTT-S IMS*, *2013,* 2-7 Jun. 2013.
[10] R. Y. Miyamoto and T. Itoh, "Retrodirective arrays for wireless communications," *IEEE Microw. Mag.*, vol. 3, no. 1, pp. 71–79, Mar. 2002.
[11] L. C. Van Atta, “Electromagnetic reflector,” U.S. Patent 2 908 002, Oct. 1959.
[12] S. Kim, B. Cook, J. Cooper, A. Traille, A. Georgiadis, H. Aubert, and M. M. Tentzeris, "Inkjet-printed Substrate Integrated Waveguide (SIW) Passive Dual-band Retro-directive Array on Paper substrate for Chipless RFID Tag and Sensor Applications," in *IEEE MTT-S IMS*, 2013, 2-7 Jun.
[13] S. Bouaziz, F. Chebila, A. Traille, P. Pons, H. Aubert, and M.M. Tentzeris, "Novel Microfluidic Structures for Wireless Passive Temperature Telemetry Medical Systems Using Radar Interrogation Techniques in Ka-Band," *IEEE Antennas Wireless Propag. Lett.*, vol. 11, pp. 1706-1709, 2012.
[14] Y. Kawahara, H. Lee, and M. M. Tentzeris, "SenSprout: inkjet-printed soil moisture and leaf wetness sensor," in *Proc. UbiComp*, 2012, 5-8 Sep.
[15] H. Nishimoto, Y. Kawahara, and T. Asami, "Prototype implementation of ambient RF energy harvesting wireless sensor networks," in *Proc. IEEE Sensors*, 2010, pp. 1282-1287, 1-4 Nov.