Low Cost Inkjet-printing Paper-Based Modules for RFID Sensing and Wireless Applications

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***Abstract*— A very low cost substrate, paper makes one of the best substrate candidates for applications of Radio Frequency Identification (RFID), wireless and ubiquitous sensing due to the fact that it is the lowest cost materials, is environmentally friendly and can be easily used for mass reel-to-reel processing while having good flexibility, minimal water absorption if treated with an appropriate coating and is suitable for fast printing processes such as direct write methodologies instead of the traditional metal etching techniques. In this paper, three modules are presented: a paper based wireless sensor module, a wifi antenna on paper via, and a paper based three dimensional RFID antennas. These modules prove paper and inkjet printing as a candidate for the first ultra low cost paper based wireless electronics.**

I. Introduction

The demand for low cost, robust, flexible, reliable, low-power consumption and durable wireless modules such as RFID-enabled sensor nodes is driven by several applications, such as logistics, Aero-ID, anti-counterfeiting, supply-chain monitoring, space, healthcare, pharmaceutical, military and is regarded as one of the most important methods for realizing ubiquitous ad-hoc networks.

Paper material is one of the candidates that could potentially cause a break through in the electronics world for its ultra low cost and environmental friendly characteristics. This could realize a truly “ubiquitous computing” network. From a manufacturing perspective, paper can go large reel to reel processing and so is a perfect candidate for bulk production especially when accompanied by a fast direct write methodology such as inkjet printing. This could be done since paper has a low surface profile and with the appropriate coating can host conductive paste on top of its surface which enables modules such as: antennas, IC, memory, batteries and/or sensors to be easily embedded in/on paper.

This paper presents three paper based modules. A three dimensional miniaturized RFID antenna, a wireless sensor module, and wifi antenna investigating the formation of via for the multi-layer build up.

II. Conductive Ink-Jet Printing on PAPER

Paper is an appropriate organic-based substrate for UHF and RF applications for several reasons. Its wide availability, the high demand and the mass production make it the cheapest material ever made. Reel-to-reel processing and being environmentally friendly along with the capability of fast printing processes such as direct write methodologies of conductors make it very attractive for manufacturing. In addition, paper can be made hydrophobic and/or fire-retardant by adding certain textiles to it.

While the electrical characterization of dielectric constant (ε_r) and loss tangent (tanδ) of paper over the frequency range 0.4 GHz to 2.4 GHz has been achieved by the authors [1], the dielectric characterization results have been incorporated in the design of the three modules presented in this paper.

Inkjet-printing is a direct-write technology by which the design pattern is transferred directly to the substrate, and there is no requirement of masks contrary to the traditional etching technique which is widely used [2]. In addition, unlike etching which is a subtractive method by removing unwanted metal from the substrate surface and which also uses chemicals such as the etchants throughout the fabrication process, inkjet-printing jets the single ink droplet from the nozzle to the desired position, therefore no waste is created, resulting in an economical fabrication solution. This aspect, together with the fact that the chemicals necessary for etching are eliminated, makes this approach environmentally friendly also.

Fig. 1 shows a photo taken by a fiducial camera of the Dimatix Material Printer DMP-2800 of an edge section (hence showing the substrate to the left of the ink) of a printed transmission line on paper. The total view width is 1.628 mm while the total height view is 1.221 mm with resolution of 2.54 microns.

Curing the conductive particles such as nano-silver (used in this paper) has to occur before any operation of the ink as a good conductor. Curing at temperature high temperatures is desirable; however, other methods such as UV or photonic curing may be used, which takes up only few seconds. The inkjet printing on-paper approach is very repeatable, allows for features down to 20µm and can be easily utilized for other passive structures, such as filters, baluns in single or multilayer (multi-sheet) configurations [2].

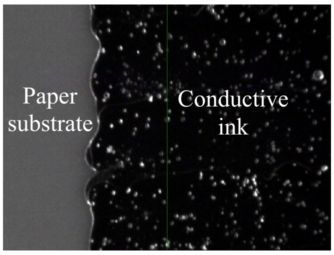

Fig. 1 Photograph of silver ink on paper with a resolution of 2.54 microns.

III. Antenna Modules On Paper

A. Three dimensional RFID Antenna

With the emerging applications of RFID such as tagging of large, lossy bodies such as cars, where most of the conventional planar RFID antennas suffer from multireflection/multipath effects; a three dimensional cubic antenna is designed in this section. The aim of this effort is to create an almost omnidirectional radiation pattern with a miniaturized cubic RFID antenna for the Real Time Locating of automotives as well as deployment of sensors creating a Wireless Sensing Network (WSN) where a three dimensional structure is desirable.

A non-uniform meander line structure that utilizes the folding of a half-wavelength dipole was used for the main radiating body. Meander line antennas for RFID applications have been discussed and developed in previous literature [3]. Since passive RFID Tags Integrated Circuits (ICs) are characterized by highly capacitive impedances, inductive coupling was used in this structure to create a good match in the reactive impedance section in order to supply conjugate matching. The structure is shown in Fig. 2 where the size of each side of the cube is 32mm. Miniaturization was achieved by utilizing all sides of the cube and by using two antenna each occupying three sides. The radiation of the top antenna that is connected to the IC causes the bottom rectangular loop to couple with the bottom antenna, which also causes radiation. The result of the coupling of these two independent three-dimensional meander line antennas causes the input impedance to be matched at two different resonant frequencies. By varying the length of the meander lines and their proximity to one another, the cube can be designed for a specific dual band use. The two antennas are symmetric with respect to a center cut plane or diagonal cut plane to the structure. The return Loss plot is shown in Fig. 3. The Impedance of the IC used was 73 – j113 Ohms.

Fabrication using ink-jet printing on paper, folded into a cube can realize a very small low cost cubic RFID tag.

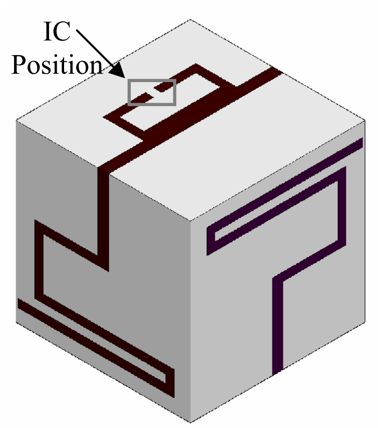

Fig. 2 Three dimensional RFID Antenna using meander line configuration.

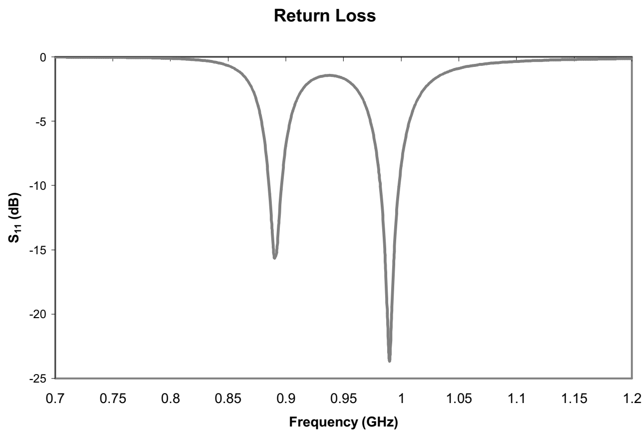

Fig. 3 S_{11} vs. frequency for the RFID Antenna of Fig.2.

B. Sensor Module

This section introduces the first wireless sensor module built and integrated completely on paper. In particular, a microcontroller paper-based enabled UHF wireless sensor prototype has been developed.

The wireless sensor module on the paper is shown in Fig 4. A transmission frequency of 904.4 MHz was generated by a crystal oscillator that was connected to the input of the PLL unit of the transmitter. The data transmission was to be carried out at the unlicensed UHF frequencies around 900 MHz. The entire wireless system including the antenna and the traces for the components mounting was printed on a 2-D paper module and operated remotely using a 3V Li-ion cell.

The antenna was designed to resonate at a center frequency of 904 MHz, where it would have an input impedance matched to the optimum output impedance of the power amplifier in the transmitter module. This aggregate impedance was determined after accounting for the shunt impedance introduced by the bias circuit and the series impedance introduced by the series coupling capacitor between the amplifier and the antenna terminals at 904 MHz.

The antenna shape chosen was a U-shaped tapered dipole [4] in order to reduce the overall size while, especially that the traces for the sensors components were enclosed within the U-shape of the antenna while establishing a wide bandwidth near the center frequency that covers the UHF RFID frequency band in the US. The overall dimensions of the module are 9.5 x 5 cm. The Return Loss or S11 measurements for the center frequency for the antenna terminals was recorded to be -15.05 dB for the simulated structure using the full wave EM simulator HFSS and -12.45 dB measured using the ZVA-8 VNA. The radiation pattern was also measured using Satimo's Stargate 64 Antenna Chamber measurement system and by using the NIST Calibrated SH8000 Horn Antenna as a calibration kit for the measured radiation pattern at 904 MHz, and is shown in figure 5.

The discrete passive components, the temperature sensor, and a Li-ion cell for "stand-alone" (autonomous) operation were assembled on paper. The first step involved holding the components in place on the printed silver pads with the use of a very small amount of adhesive between the component terminals and the printed silver pads. Once in place, conductive silver epoxy was them applied on the terminals of the components to establish a conductive path between the terminals and printed silver pads as shown in Fig 6.

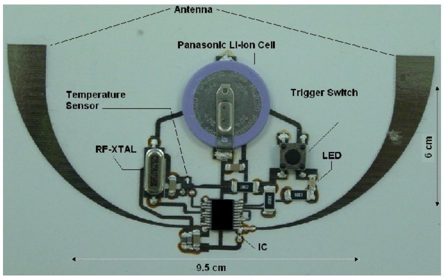

Fig. 4 Wireless Sensor transmitter prototype on paper substrate using silver inkjet printing technology.

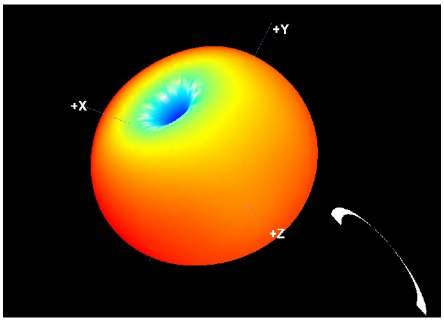

Fig. 5 Measured radiation pattern of U-shaped antenna including all metal traces of the module.

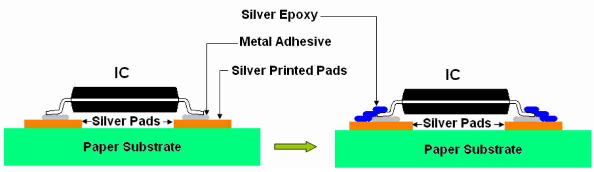

Fig 6. Assembly process for components on inkjet printed silver pads on paper substrates.

C. PIFA wifi Antenna with metalized via

A simple structure "the planar inverted F antenna" (PIFA) is designed in this section to demonstrate multi-layer packaging with paper as a dielectric and using filled vias a z-interconnects (shorting element of the PIFA structure). PIFA has a wide usage in portable wireless devices because of its low profile, small size, and embedded structure [5].

The basic PIFA is a grounded patch antenna ~λ/4 patch length instead of the conventional λ/2, and consists of a ground plane, a top plate resonance element, a feed wire feeding the resonating top plate, and a shorting element that is connecting the ground and the resonating patch. The PIFA configuration is shown in Fig. 7. The location of VIA and feeding point is shown in Fig 8 shows where the antenna was fed by a typical 50 Ohms SMA connector on the back side of the Antenna.

Metalized vias are necessary for layer to layer registration in the vertical direction. A carbon dioxide laser having a wave-length of 10.6 micrometer was selected for via construction. Since, CO_2 laser beam is not easily absorbed by metal, the beam can be stopped at the metal layer (ground plane) underneath the laminated paper substrate, therefore making an easy route for the via filling process. The theoretical limit of the CO_2 laser used in this study is about 250 micrometer. Hence, the via hole had to be larger than 0.25 mm. Moreover, the thickness of the multi-layer paper thickness was on the order of 0.75 mm, therefore, the via opening was adjusted to 1 mm in diameter. Multiple (3 to 4) passes of the focused laser beam were required to drill through the paper layers. The debris inside the via hole and around the via wall were removed mechanically followed by rinsing with isopropyl alcohol. Reactive ion etching will be implemented in future for the via clearing process.

After the via was drilled, flexible, high temperature, electrically conductive adhesive was used to fill the via hole. This conductive adhesive was supplied by Creative Materials (package 102-32 and is ISO 9001 certified). The curing temperature of 90 °C for three hours was used to enhance the conductivity of the conductive material.

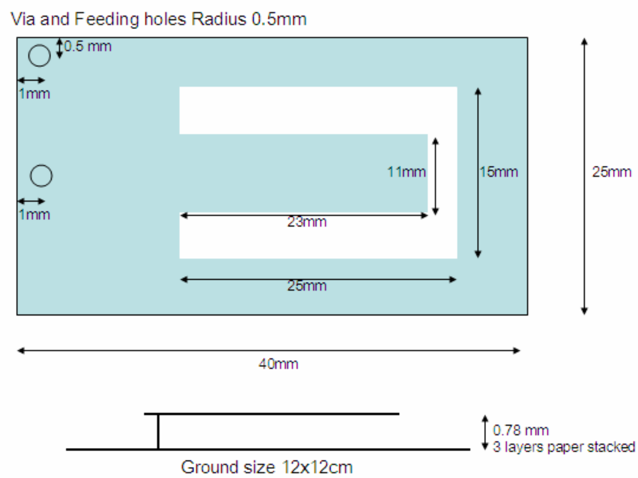

Fig 7. PIFA Antenna configuration showing dimensions (top) and cross section (bottom) of the design.

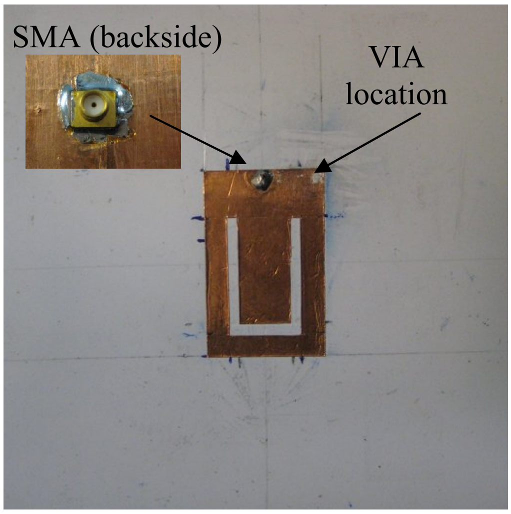

Fig 8. Photograph of PIFA showing dimensions, feeding, and VIA location.

The simulated results for Return Loss are shown in Fig. 9 for the PIFA with and without the shorting via. The dual resonance of the PIFA as shown has resonances around 0.7 GHz and 2.4 GHz for the final structure. Measurement results were achieved using ZVA-8 VNA and are shown in Fig. 10 for the structure with VIA. These results show a good agreement with a slight shift in resonance frequency that could be due to several reasons. It is to be noted that the structure was formed by cutting copper tape by hand to the required dimensions and so significant inaccuracy might have occurred and caused this frequency shifting. Hence, measurement results show proof of concept of formation of via holes in paper substrate.

Upon successful realization of vias, integration of 3D paper-on-paper package with embedded RFIDs, sensors, and batteries for application in tracking, sensing, and bio-medical arena can be made possible.

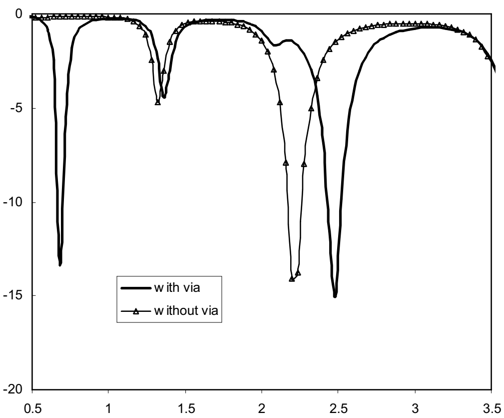

Fig 9. Simulation S parameters vs. frequency for PIFA Antenna.

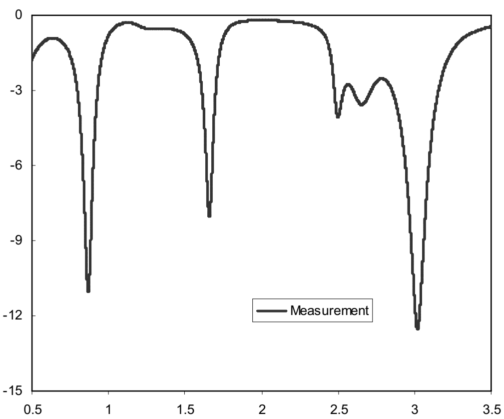

Fig 9. Measurement S parameters vs. frequency for PIFA Antenna with VIA.

IV. Conclusions

Paper is an excellent candidate as a substrate for the mass production of RF electronics for its low cost and industrial ability to be processed in large reel-to-reel, capability of direct write methodologies, such as inkjet-printing, to be used in replacement of relatively expensive wet-etching techniques. Such a fast process can be used to print electronics on the surface of paper substrate or even embedded in a multilayer fashion. Last, but not least, paper is one of the most environmentally-friendly materials. The three modules presented in this paper: a three dimensional RFID antenna that could be inkjet printed and folded on paper, a wireless sensor module on paper, and a multilayer PIFA with VIA set a foundation for a new generation "green" RF electronics and modules while being ultra-cheap to meet the ever growing demand of the wireless market.

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