Inkjet Printing of UWB Antennas on Paper Based Substrates

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***Abstract*— For the first time, we demonstrate the feasibility of realizing ultra-wideband antennas through ink-jetting of conductive inks on commercially available paper sheets (paper as an RF substrate). The characterization of the conductive ink as well as of the electrical properties of the paper substrate is reported for frequencies up to 10GHz. This work is one step further towards the development of low-cost environment-friendly conformal printed antennas/electronics for ad-hoc wireless sensor networks operating in rugged environments.**

I. Introduction

A Technology that has the potential as a means of short-range high-bandwidth communications utilizing very low power levels spreading the transmitted signal over a significantly large portion of the radio spectrum is Ultra-wideband (UWB) RF technologies, commonly between 3.1-10.5 GHz [1]. UWB applications have great variety. Some of the current and potential applications are listed below[2].

- ❖ Altimeter/Obstacle avoidance radars
- ❖ Collision voidance sensors
- ❖ Intrusion detection radars (through wall imaging)
- ❖ Industrial RF monitoring systems
- ❖ Wearable electronics for wireless body area network (WBAN)
- ❖ High speed WLANs and wireless personal area network (WPANs)

Interestingly, numerous recent applications of UWB radios target sensor data collection, precision localization, and tracking applications. Such applications necessitate the deployment of a large number of UWB antennas to meet system requirements. To this end, it is important to keep the cost per antenna as low as possible to maintain an adequate operational cost for such UWB systems. A quick look at the most common techniques for the fabrication of printed UWB antennas reveals that photolithography has been the most dominant technology. However, this method involves multiple steps including etching, masking, and electroplating, thus being a time consuming, labor intensive and expensive process. In addition, since the solvent used in the etching process is corrosive, the choice of substrates is limited. Moreover, the photolithography process generates high volumes of hazardous waste, which are environmentally detrimental. An alternative technique would be favored.

In addition to the technologies mentioned above, flexible electronics (also known as flex circuits) is a technology that not just has witnessed an increase in attention and investments in research and development, but also is becoming more essential in today's growing market in every day's mobile devices as well as in applications that demand flexibility, light weight, and space savings. Flex electronics also allow the screen printing and more recently the inkjet printing on substrates such as paper and Liquid Crystal Polymer (LCP). These are especially important in communication systems' design where a planar antenna that meets the specifications of a certain application is physically non-realizable, enforcing the utilization of a conformal antenna as a necessity.

In a similar scheme, the substrate material and integration techniques are becoming more of a critical materials research topic due to the ever growing demand for low cost, flexible and power-efficient broadband wireless electronics almost in a ubiquitous fashion. This demand may also be further enhanced by the need for inexpensive, reliable, and durable wireless automatic identification (i.e. RFIDs) and communication devices (i.e. mobile Wifi enabled systems).

II. Inkjet Printing Technology

Modern inkjet printers operate by propelling tiny droplets of liquid down to several pL [3,4]. This new technology of inkjet printing utilizing conductive paste or ink may rapidly fabricate prototype circuits without iterations in photolithographic mask design or traditional etching techniques that have been widely used in industry. Printing is completely controlled from the designer's computer and does not require a clean room environment. A droplet's volume is one of the parameters that determine the resolution of the printer, for e.g. a droplet of 10 pL gives ~ 25µm minimum thickness or gap size of printed traces/lines. In addition to that, the ink material, the substrate, the curing processes as well as the voltage waveform used on the jetting nozzles all play a role in the resolution, accuracy, and finally the success of the inkjet printing process. These have been studied in depth in this work.

The cartridge consists of a Piezo-driven jetting device with integrated reservoir and heater [3]. A detailed description of the Inkjet printer used in this work is shown in Fig. 1. The inkjet-printing is done in a horizontal bar-by-bar printing using a print-head or cartridge "DMC-11610" which has a drop volume of 10 pL nominal.

Inkjet Printing; unlike etching which is a subtractive method by removing unwanted metal from the substrate surface, jets the single ink droplet from the nozzle to the desired position, therefore, no waste is created, resulting in an economical fabrication solution. A microscopic picture is shown in Fig. 2 emphasizing a featured size of 50 µm. Silver nano-particle inks are usually selected in the inkjet-printing process to ensure a good metal conductivity. After the silver nano-particle droplet is driven through the nozzle, sintering process is found to be necessary to remove excess solvent and to remove material impurities from the depositions. Sintering process also provides the secondary benefit of increasing the bond of the deposition with the paper substrate [5]. The savings in fabrication/prototyping time that inkjet printing brings to RF/wireless circuits will be critical to the ever changing electronics market of today's, verifying its feasibility as an excellent prototyping and mass-production technology for next generation electronics especially in RFID, wireless sensors, handheld wireless devices (e.g.4G/4.5G cell phones), flex circuits, and even in thin-film batteries [6].

After the printing process takes place, it is essential to cure the prototype in order to increase the conductivity of the silver ink. Curing is simply done by heating the fabricated antenna, so that the printed silver ink nano-particles melt and a good percolation channel is created for electrons to flow. The curing is performed in a high precision industrial oven, at a constant temperature of 100°C for 10 hours. The curing must be performed immediately after the printing, because the silver ink begins to oxidize which may result into permanent poor conductivity and efficiency of the antenna trace. It has to be noted that the maximum temperature that paper substrate can endure is 150°C. The conductivity of the printed conductive ink was studied through the use of the Signatone Four Point Probe (www.signatone.com). To ensure good conductivity, three layers of ink were printed, and then treated in a thermal oven as described earlier. The resulting ink thickness was measured using the Wyko profilometer (www.veeco.com). The resulting thickness was around 3 µm with a consistent measured conductivity in the range 9×10^6 [S/m] – 1.1×10^7 [S/m]. In addition, DC characterization was performed in order to test the silver epoxy and the integration of SMD devices. Fig. 3 shows a photograph of the test setup showing a 1.6Ω DC Resistance measurement by the multimeter for the trace shown with a 1Ω SMD Resistor assembled in the center of the trace using silver epoxy. This proves that such connections using epoxy can be made with losses that are tolerable.

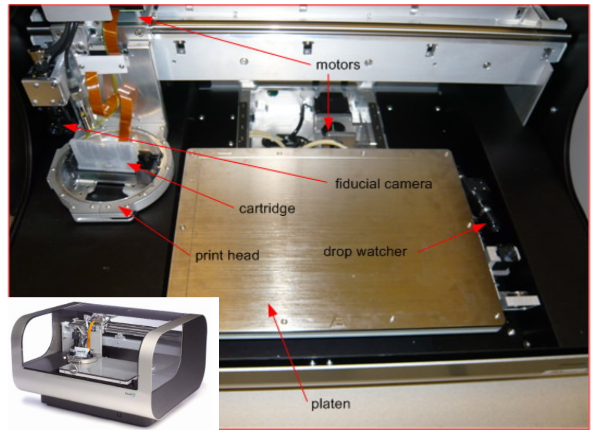

Fig 1. Details of Material Printer DMP 2800 [3].

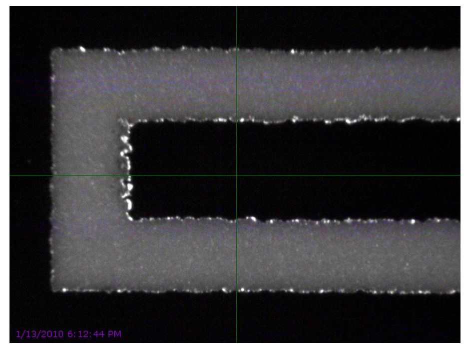

Fig 2. Realized feature size of 50 microns.

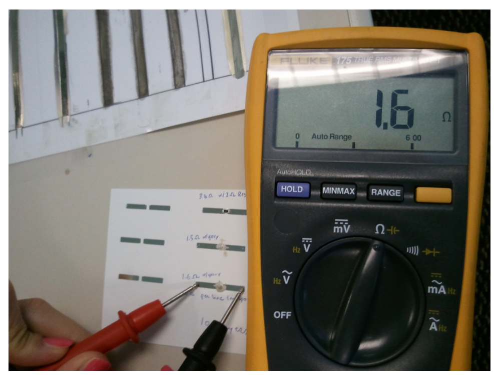

Fig 3. DC characterization for inkjet printed traces with epoxy and SMD 1Ω Resistor.

III. PAPER AS AN RF SUBSTRATE

There are many aspects of paper that make it an excellent candidate for an extremely low-cost substrate for RF applications and especially applications where mass deployment is required such as RFID and wireless sensor networks (WSN). Paper; an organic-based substrate, is widely available; the high demand and the mass production of paper make it the cheapest material ever made. From a manufacturing point of view, paper is well suited for reel-to-reel processing, thus mass fabricating RFID inlays on paper (to name an example) becomes more feasible. Paper also has low surface profile and, with appropriate coating, it is suitable for fast printing processes such as direct write methodologies instead of the traditional metal etching techniques. A fast process, like inkjet printing, which is discussed in the previous section, can be used efficiently to print electronics on/in paper substrates. Last, but not least, paper is one of the most environmentally friendly materials and the proposed approach could potentially set the foundation for the first generation of truly "green" RF electronics and modules.

RF characterization of paper becomes a critical step for the qualification of the paper material for a wide range of frequency domain applications. The knowledge of the dielectric properties such as dielectric constant (ε_r) and loss tangent (tanδ) become necessary for the design of any high frequency structure such as RFID antennas on the paper substrate and more importantly if it is to be embedded inside the substrate. Precise methods for high-frequency dielectric characterization for this frequency range are Transmission Line and Resonant Techniques. In an extensive literature review, dielectric properties of paper beyond few hundred megahertz were not available. A parallel plate capacitor characterization technique has been utilized in [7] in order to characterize paper up till 400MHz. Besides the inaccuracy of such a technique, a different characterization method needed to be considered in order to step up in the frequency till 10GHz.

The dielectric properties of paper have been studied by the authors in [8] with frequencies up till 2 GHz using the resonance technique ring resonators [9]. In this work the properties of the benchmarking paper substrates were studied in the UWB frequency range through the use of the split-post dielectric resonator technique [10] and were performed by the Electromagnetics Division at the National Institute of Standards and Technology (NIST), Boulder, CO, USA. Several cavities covering the band from 1GHz to 10GHz were utilized. Each blank paper sample was cured first in a thermal oven for 2 hours at 120 degrees to mimic the curing process of the printed ink. The results for the extracted relative permittivity of the 10mil thick cured paper are shown in Fig. 4. The measured dielectric loss tangent or tanδ values were bounded between 0.06 and 0.07 for the whole frequency range.

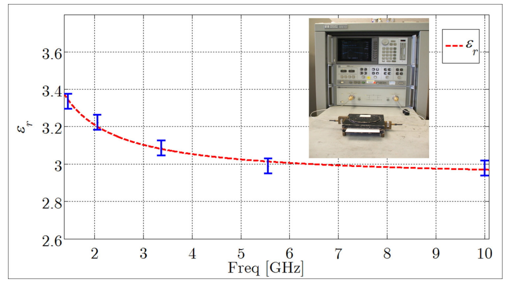

Fig 4. Characterization of the paper material through the split ring resonator method.

IV. ANTENNA DESIGN AND RESULTS

To investigate the applicability of inkjet-printed paper-based technology for the realization of UWB structures, a planar UWB monopole was adopted in this work for its simplicity [2] as a proof-of-concept geometry. The design was optimized through full-wave FDTD simulations -including the ink thickness effect along with the frequency-dependent permittivity of the paper substrate- using a commercially available solver from SPEAG (www.semcad.com). The antenna was printed on a paper sheet following the aforementioned guidelines. Paper was cut to a square slice of 50mmX50mm to form the overall antenna. Agilent 4-port PNA-X network analyzer (N5245A) was used for the measurements. Fig. 5 shows good agreement of the simulated versus the measured responses at the input port of the antenna up to 16 GHz.

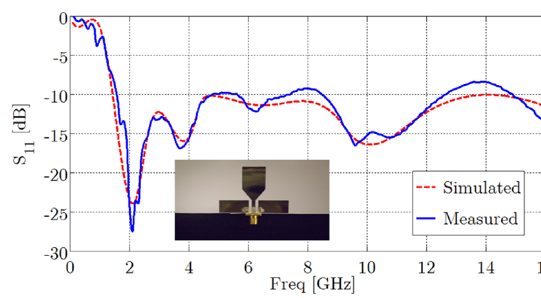

Fig. 5 Simulated and Measured S11 performance of the UWB Antenna.

V. Conclusions

In this work, and for the first time, we demonstrate the feasibility of realizing ultra-wideband antennas through ink-jetting of conductive inks on commercially available paper-based substrate. This work extends previous ones in dielectric characterization of paper (up to 10GHz). Characterization of the conductive ink as well is presented as well as DC characterization of silver epoxy with conductive ink on paper to provide an idea for electrical connections and mounting of surface mount devices. This work is one step further towards the development of low-cost environment-friendly conformal printed antennas/electronics for ad-hoc wireless sensor networks operating in rugged environments

Acknowledgment

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