Printed Electronics for Next Generation Wireless Devices

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***Abstract*— In this talk, inkjet-printed structures on paper and other polymer substrates are discussed as means for low-cost mass-production of next generation wireless devices and Wireless Sensor Nodes. Three sample prototypes are outlined. The first system demonstrates a gas sensing prototype for home land security applications, where printed carbon nanotubes (CNTs) are utilized to sense ammonia gas traces. The second system demonstrates the potential of using printed electronics in producing low-cost location-finding systems for health-care applications. The third prototype shows the feasibility of using the printed technology for enabling wireless communications in the mm-Wave frequencies.**

I. Introduction

A quick look at the most common techniques for the fabrication of printed circuits for wireless systems reveals that photolithography has been the most dominant technology. 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 "green" technique is thus needed.

Inkjet printing of conductive inks on paper sheets enables the realization of low-cost environment-friendly light-weight systems. Paper possesses a number of intriguing attributes that makes it appealing for low-cost "green" electronics. It is one of the most abundant man-made materials which is truly ubiquitous in modern society. It is cellulose in nature, thus considered as a renewable resource. Additionally, paper can be easily processed in a reel-to-reel fashion enabling low-cost manufacturing solutions. Driven by the fact that it is challenging/cost-inefficient to apply photo-lithography techniques to paper and polymer substrates, ink-jet printing of conductive particles provides a promising solution. Interestingly, such printing technology has grown to be a viable technology for use in printed electronics such as flexible displays, RFIDs, sensors, solar panels, fuel cells, batteries, and most recently in antennas for low frequency applications [1-4].

Here, we discuss the potential of such emerging technology in the production of next generation low-cost wireless devices and Wireless Sensor Nodes. Three sample prototypes are outlined. The first system demonstrates a gas sensing prototype where printed carbon nanotubes (CNTs) are utilized to sense ammonia gas traces. The second system demonstrates using conductive ink-jetting in producing low-cost location-finding systems for health-care applications. The third prototype addresses the feasibility of using the printed technology for enabling wireless communications in the mm-wave frequencies.

II. Technology Outlines

A. *Printing Setup*

Inkjet printing for RF applications is a challenging endeavour, where precise control of the achieved dimensions and surface roughness are required to ensure good conductivity at the frequencies of interest. In general, there are two critical factors that affect the print quality: the ink properties, and the settings of the printing system itself. The most notable ink properties to observe are viscosity, surface tension, and dispersion stability (printing with high contact angle, high viscosity, and high tension ink produces smaller sized dot patterns). The most crucial settings of the printing parameters include the volume of the jetted ink, the travelling velocity of the ejected droplet, the gap distance between each droplet, the printing frequency, the temperature of the jetted ink, the temperature of the substrate, and the sintering/curing mechanism performed on the printed structures. In this work, we have utilized the DMP2800 ink-jet printer which is a table-top printer available from Dimatix Inc (www.dimatix.com). To ensure good RF properties, an in-house recipe was developed considering all of the aforementioned parameters. In all prints, the utilized Dimatix 1pL cartridges (DMC-11601) were kept at a distance of 0.5mm from the surface of paper on a DMP-2800 printer. The printer head was adjusted to achieve a print resolution of 2540 dpi, which ensures good RF conductivity up to several GHz. Cabot conductive ink

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CCI-300 (www.cabot-corp.com) was then jetted at a temperature of 40 °C, while the paper substrate was maintained at 60 °C. Each printed structure was then cured in a thermal oven for two hours at 120 °C.

Fig. 1. Table-top Ink-jet printer used in this work.

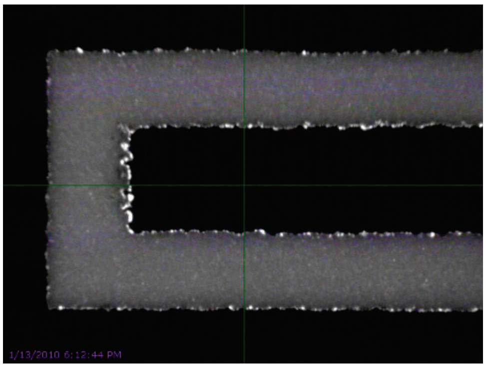

Fig. 2. Realized printed structure with feature size of 50um.

B. Paper Characterization

The properties of the benchmarking paper substrates were studied up to mm-Wave frequencies through the use of the split-post dielectric resonator technique [5]. Several cavities covering the band from 1GHz to 40GHz 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 (up to 10GHz) for the extracted relative permittivity of the 10mil thick cured paper up are shown in Fig. 2. The dielectric permittivity remains bounded between 3 and 2.8 up to 40GHz. The measured dielectric loss tangent values were bounded between 0.06 and 0.07 for the whole frequency range up to 10GHz [6]. It increases to 0.12 at 40GHz.

C. Ink Characterization

The conductivity of the printed conductive ink was studied through the use of the Signatone Four Point Probe (www.signatone.com). To ensure good RF 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 DC conductivity in the range $9x10^6$ [S/m] – $1.1x10^7$ [S/m].

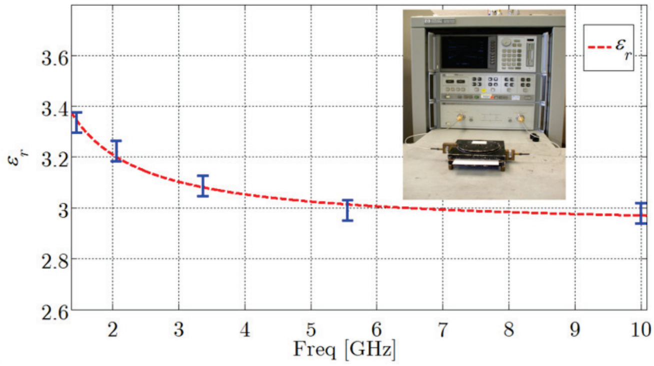

Fig. 3. Characterization of the paper material through the split ring resonator method.

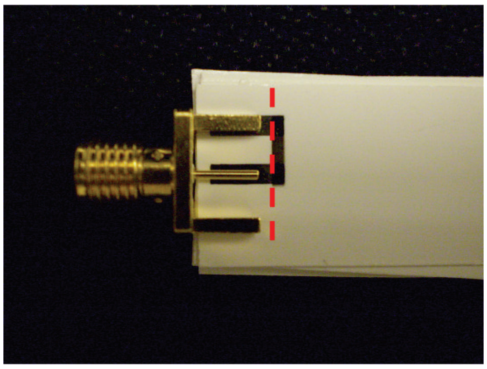

Fig. 4. CNT film placed at the edge of printed silver lines.

III. Applications in Gas Sensing

The first system application discussed here is using inkjet printing of carbon nano-tubes and silver nano-particles on paper sheets for low-cost sensing of ammonia gas. Carbon nanotubes have been researched extensively for gas sensing applications due to their unique electrical, chemical, and structural properties [7, 8]. Single-walled carbon nanotubes (SWNTs) have been predominantly used due to their superior electrical conductivity and higher sensitivity relative to multi-walled carbon nanotubes [9]. To realize a sensing system with high sensitivity, we utilized functionalized SWNT's in order to enhance the gas detection sensitivity (see [10] for details about functionalized SWNTs). Unlike other work where the SWNTs are grown on special substrates through a cost-expensive process in clean rooms [11-13], we incorporate the SWNTs through ink-jet printing. Our proposed process involves a thin film of the functionalized SWNT ink-jetted on paper to characterize its behavior at frequencies from DC to few GHz. The adopted sensor concept then relies on incorporating the functionalized SWNT's thin film as a load into a nano-silver printed patch antenna. Upon exposure to gas, the SWNT thin film load will change its RF properties and thus the return loss of the antenna will reflect such change.

Such a concept realizes a remote-sensor with much higher sensitivity than previously recorded (see [11-13] for example). In our labs, the loaded antenna was measured in a closed system environment (Sealed Glass Chamber) to quantify the sensitivity for low concentrations of ammonia gas (which is usually associated with explosives). The proposed antenna-based wireless gas sensor can be utilized in several remote-sensing applications, given its small form factor, light weight, and little to no power requirements. Fig. 4 shows the CNT thin film characterization setup. Fig. 5 plots the resulting change in its equivalent capacitance upon exposure to household ammonia in a non-controlled environment (open lab room). Fig. 6 shows a prototype of the sensor with figures 7 and 8 outlining sample results for non-controlled and controlled exposures, respectively. Further details about this application can be found in [14-16].

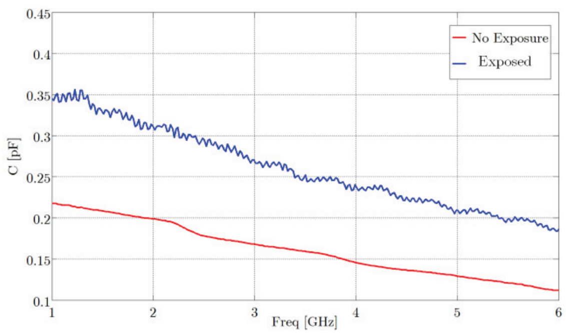

Fig. 5. Equivalent capacitance of the CNT thin film (before and after gas exposure).

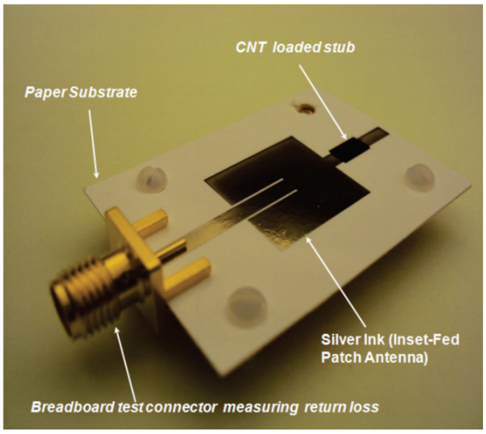

Fig. 6. Prototype of the sensor

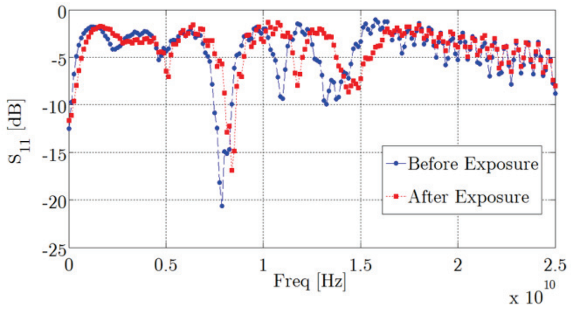

Fig. 7. Results upon exposure to household ammonia in a non-controlled environment.

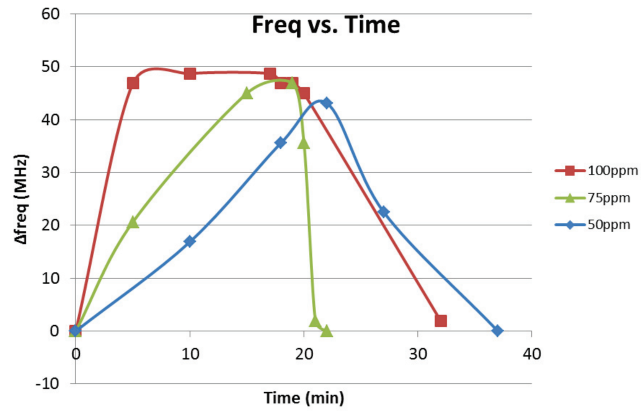

Fig. 8. Results upon exposure to household ammonia in a controlled environment.

IV. Applications in Health-Care

The second system discussed here features a demonstration of indoor location-finding proposed for healthcare applications. This choice of application emerged from the Zigbee Alliance and the Continua Health Alliance which announced a liaison agreement to collaborate on defining interoperable communication standards for personal health solutions based on low-power wireless local area networks [17].

Our proposed low-cost solution is an integrated wireless module on a flexible paper substrate operating at 2.4 GHz. The system employs a system-on-chip wireless microcontroller that is interfaced through a flash memory, a 32 MHz crystal, and a coin-sized lithium cell battery.

Fig. 9 shows the entire unpopulated nano-silver ink-jetted board on a paper substrate. A differentially fed Antenna is interfaced to the chip through one of its 56 pins on the top layer (smallest dimension ~125 um). Fig. 10 shows the S11 plot for the antenna. It is to be noted that the data shown in Fig. 10 takes into consideration the simulation of the entire printed module. Further details about this application can be found in [18].

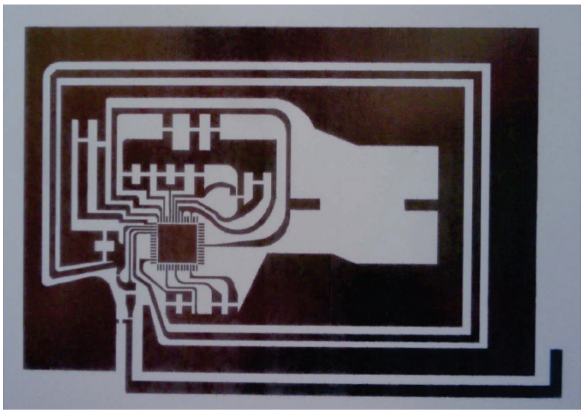

Fig. 9. Un-populated ink-jetted board.

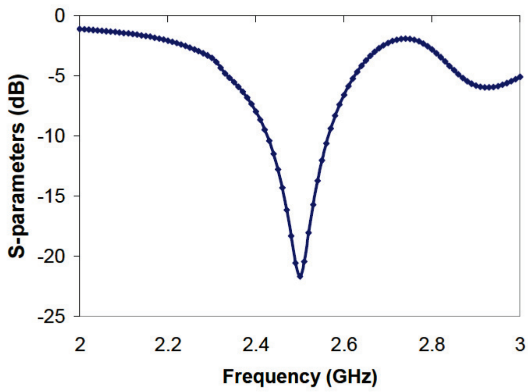

Fig. 10. Input reflection coefficient of the printed antenna.

V. Applications in MM-Waves

The third example demonstrates the possibility of realizing low-cost mm-Wave passives and antennas using inkjet printing of silver nano-particles. Fabrication of mm-Wave antennas and circuits using the typical (deposit/pattern/etch) scheme is a challenging and costly process, due to the strict limitations on permissible tolerances. Such fabrication technique becomes even more challenging when dealing with flexible substrate materials, such as liquid crystal polymers. On the other hand, inkjet printing of conductive inks allows the deposition of conductive particles directly at the desired location on a substrate of interest, without need for mask productions, mask alignments, or conductor etching. This is why inkjet printing of conductive materials could present the future of environment-friendly low-cost rapid manufacturing of RF/mm-Wave circuits and antennas.

While paper substrates are currently less appealing for most mm-Wave applications due their inherent loss, Liquid Crystal Polymers have received considerable attention as a high frequency circuit substrate as well as a packaging material [19]. This is mainly due to its impressive electrical characteristics; nearly constant relative permittivity at 3.2 and stable loss tangent below 0.005 up to 110GHz. Thermal expansion characteristics of LCPs are equally desirable since their controllable coefficient of thermal expansion (CTE) can be engineered to match various materials such as copper or silicon. From an environment perspective, LCPs are recyclable, impervious to most chemicals, and can withstand relatively high temperatures (up to 350°C). Thus, Liquid crystal polymers are potentially useful in the conformal packaging of many antenna systems and circuits, particularly in the evolving mm-Wave indoor communication, sensing, and imaging applications at 60, 77, and 94 GHz, respectively.

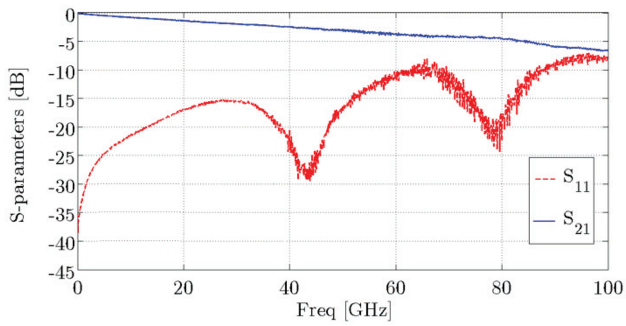

Fig. 11. S-parameters for a 2.5mm printed line.

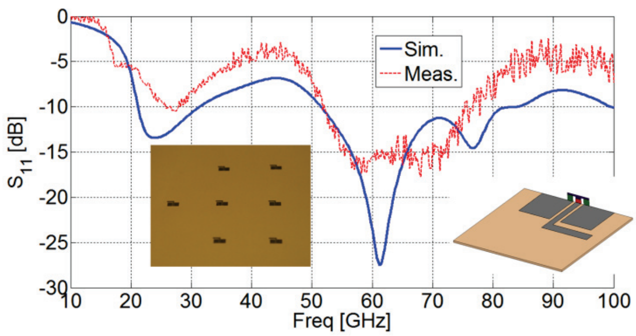

Fig. 12. Results for the probe-tip measurements of the antenna.

To this end, we present a proof-of-concept simple multi-band printed antenna structure for the 24/60/70GHz bands. It is noteworthy to mention that several inkjet-printed antennas were demonstrated at low frequencies. However, the fabrication of such antennas was not quite challenging, due to their relaxed tolerances.

The utilized antenna is a variation of the planar monopole antenna. By controlling the size of the ground plane as well as the length of the center conductor along with the width to gap ratio, one can optimize the antenna to cover the aforementioned bands. Here, optimization was conducted using a commercially available FEM solver (Ansoft HFSS). The antenna was modeled as a thin conductor 5 um thick, with 1um surface roughness and conductivity of $3X10^6$ [S/m]. The antenna model was fed in a GSG probe-mimicking scheme. Fig. 11 shows the S-parameters for a 2.5mm printed line. Measurements of the printed antenna were quite challenging.

Several ripples were present in the measurements due to measurement uncertainties (Fig. 12). Nevertheless, this proof of concept proto-type reveals that it is possible to realize printed flexible antennas with good efficiencies (60% or better for the presented prototype) at mm-Waves [20]. With LCP's capabilities as a packaging material, and conductive ink-jetting as a low-cost deposition technology, integrated mm-Wave systems may be one step closer to reality.

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