Novel Manufacturing Processes for Ultra-Low-Cost Paper-Based RFID Tags with Enhanced "Wireless Intelligence"

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Abstract

The objective of this study is to demonstrate ultra-low-cost paper substrates for the realization of inexpensive RFID tags that can be integrated with batteries and sensors for wireless sensing, tracking and monitoring applications. The first step toward achieving this goal is to demonstrate "conductors on paper substrates" from processing standpoint and to characterize the electrical performance of paper substrates up to 2 GHz form design standpoint. The conductors are achieved by (i) direct-write ink jet printing technology with tailored conductive ink and by (ii) conventional copper etching upon lamination of metal foils on to the paper substrates. There are several issues in optimizing the processes in either of the two approaches. For example, ink jet printing would require smooth surface finish, good adhesion, less smearing of the ink, fast curing profile, and ultimately copper-like conductivity of the printed ink and rapid prototyping for high volume manufacturing. On the other hand, metallization using copper will require bonding of copper onto paper surface, adhesion, compatibility with copper etch solutions and lithography, and moisture sealing. Both approaches have been successfully demonstrated for printing conductors on paper substrates which can be easily scaled to large-quantity manufacturing. For the electrical characterization of the paper substrates up to 2 GHz, one microstrip ring resonator was designed and fabricated for extracting dielectric constant and dielectric losses. The copper metallization of paper substrates and the dielectric characterization of paper up to 2 GHz are reported for the first time.

Introduction

Paper is considered as one of the best organic substrates for RFID tags. First of all, paper is environmentally friendly and can undergo large reel to reel processing. In addition, paper is compatible with circuit printing by direct write methodologies. This is one of the biggest advantages of paper since active tags require additional modules like sensors and batteries to be mounted or embedded. A fast ink jet printing process can be used efficiently to print these modules on or into the paper substrate. Paper can also host nano-scale additives (i.e. fire retardant textiles) and can be made hydrophobic. Most importantly its dielectric constant ε_r (~3) is close to that of air (5-6 % power reflection), therefore, electromagnetic power can still penetrate easily even if the RFID is embedded in the substrate.

The trend in RFID technology today is toward achieving more functionality ("wireless intelligence") at lower cost. In order to keep up with the demand, more complicated RFIDs must be built with progressively lower cost materials and processes that can be easily-integrated with other surface and/or embedded modules. Embedded paper electronics is a promising solution for this, and thus the goal for this study is to show the path toward achieving conductive interconnects for the realization of complex circuitry on the cheapest material made by humankind. It is envisioned that integration of RFIDs with paper-based pallets and containers would be one of the most critical requirements for item tracking and inventory control in hospitals, supply chain, aerospace and health care facilities. The flexibility and affordability of paper-based RFIDs opens possibilities for new applications such as anti-counterfeit protection and Electronic Article Surveillance. In addition to this, low thickness profiles can be easily achieved with paper enabling a new generation of wearable sensor networks.

Experimental Selection criteria for paper-substrates

Among critical needs for the selection of the *right* paper are the surface planarity, water-repelling, lamination for 3D module development, via-forming ability, adhesion, and co-processability with low-cost manufacturing. For the trial runs, the selection was made by the utilization of commercially available papers that allow for inkjet printing. The reported processes were developed for layer-to-layer lamination with inter-layer adhesion, copper foil lamination and etching, and with good quality of ink-jet printing with conductive inks. Application of hydrophobic coating on paper substrates is currently under progress for efficient moisture sealing.

Conductors by ink-jet printing

Two methods were qualified for printing conductors. The first was an ink-jet printing similar to direct write method, where a low-cost Dimatix printer system was used with a specially formulated conductive silver ink from Cabot Corporation. Figure 1 shows a fabricated RFID tag on an ink-jet paper surface. However, high throughput would be required for commercialization with ink jet type direct printing method. The ink jet printing technology has already been adopted for direct writing passives components such as capacitors, resistors, and inductors by numerous companies.

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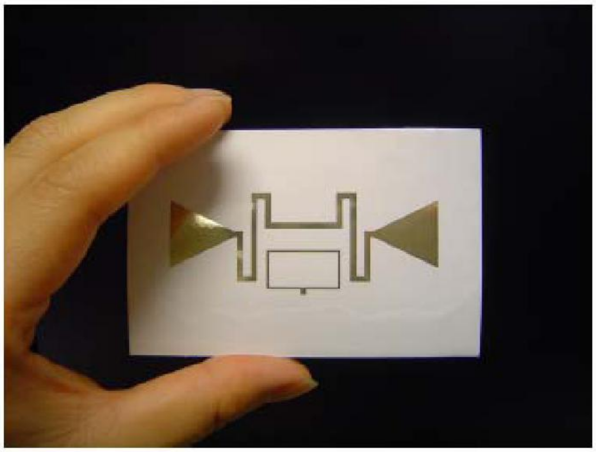

Figure 1. Ink-jet printed RFID tag on paper using Dimatix printing system.

Realization of Conductors by copper lamination and etching

The second method was based on conventional lamination and copper etching chemistries. This is much more operator intensive but can be easily adopted in a PCB fabrication house and therefore is more attractive toward large volume manufacturing at lower cost. This method has also been optimized with five layers of laminated paper substrates with top and bottom layers of laminated 18 micron copper followed by etching of copper. A ring resonator with calibration lines was fabricated using conventional copper etching for dielectric characterization of paper substrates. Figure 2 shows the photograph of the test vehicle in 12 in x 12 inch format. The lamination process was optimized by varying temperature, pressure, and residence time, as well as the heating and cooling rates. The copper foil was bonded without any visible delamination or voids. The photolithography process was conducted using a dry film photoresist followed by UV exposure and finally etching copper using a slow etching chemistry. The laminated board was then dried in an oven at 100°C for 30 minutes. The fabricated structures had good adherence to the paper substrate as was evident by a simple scotch tape test.

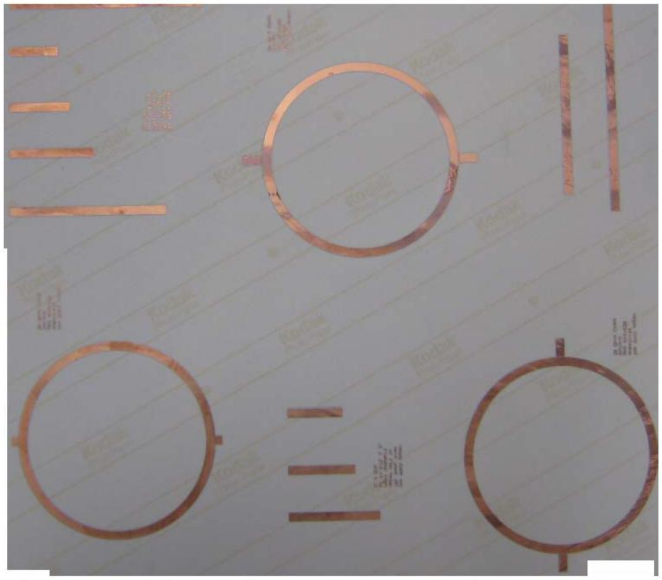

Figure 2. Fabricated ring resonators on 12 in x 12 laminated 5-layer paper substrate

RF Measurement of dielectric constant and dielectric loss of the paper substrates

This is the critical step for the qualification of the paper material for a wide range of frequency domain applications. Precise methods for high-frequency dielectric characterization include microstrip ring resonators, parallel plate resonators, and cavity resonators [1]. In our extensive literature review, such properties were not found to be available for paper for the desired application frequency range (above 900 MHz). In order to measure the dielectric constant (ε_r) and loss tangent (tan δ) of paper up to 2 GHz, the resonator structure shown in Fig. 3 was used with through-reflect-lines (TRL) calibration to de-embed the effect of the feeding lines. However, tanδ extraction using the microstrip ring resonator approach requires reliable theoretical equations for the estimation of the conductor losses [2]. The characterization covers the UHF RFID frequency band that is utilized by applications that are commonly used in port security, inventory tracking, airport security and baggage control, automotive and pharmaceutical/healthcare industries.

The ring resonator produces S_{21} results with periodic frequency resonances. In this method, ε_r can be extracted from the location of the resonances of a given radius ring resonator while tanδ is extracted from the quality factor (Q) of the resonance peaks along with the theoretical calculations of the conductor losses. Measurements of S_{21} were done over the frequency range 0.4 GHz to 1.9 GHz using Agilent 8530A Vector Network Analyzer (VNA). Typical SMA coaxial connectors were used to feed the ring resonator structure. TRL calibration was performed to de-embed the input and output microstrip feeding lines effects and eliminate any impedance mismatch.

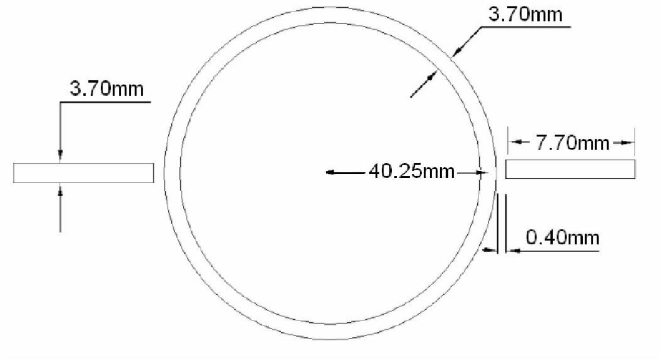

Fig. 3. Microstrip ring resonator configuration diagram.

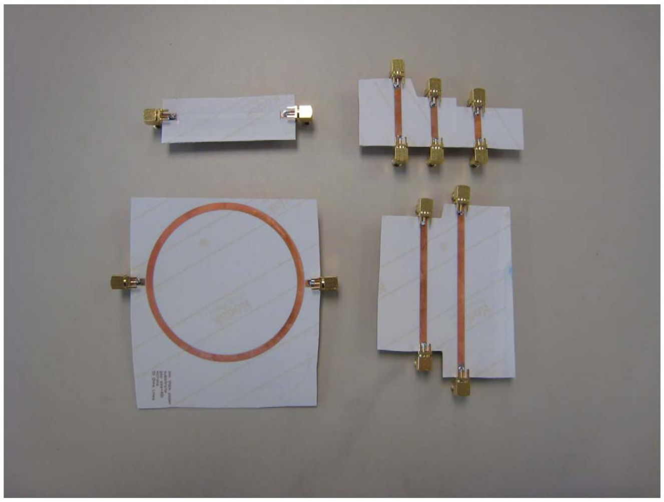

Fig. 4. Photo of fabricated Microstrip ring resonators and TRL lines bonded to SMA connectors.

Fig. 3 shows a layout of the ring resonator along with the dimensions for the microstrip feeding lines, the gap in between the microstrip lines and the microstrip ring resonator, the width of the signal lines, and the mean radius r_m. Fig. 4 shows fabricated ring resonators with the TRL lines. S_{21} magnitude vs. frequency data were then inserted in a Mathcad program and the dielectric constant and loss tangent were extracted [1,2]. A plot of S_{21} vs. frequency is shown in Fig. 5.

A. Dielectric constant

In order to extract the dielectric constant, the desired resonant peaks were first obtained according to [1]:

$$f_o = \frac{nc}{2\pi r_m \sqrt{\varepsilon_{eff}}} \tag{1}$$

where f_o corresponds to the n^{th} resonance frequency of the ring with a mean radius of r_m and effective dielectric constant ε_{eff} with c being the speed of light in vacuum. The extracted ε_r value at 0.71 GHz and 1.44 GHz of Fig. 5 was obtained using equation 1 and is shown in Table I.

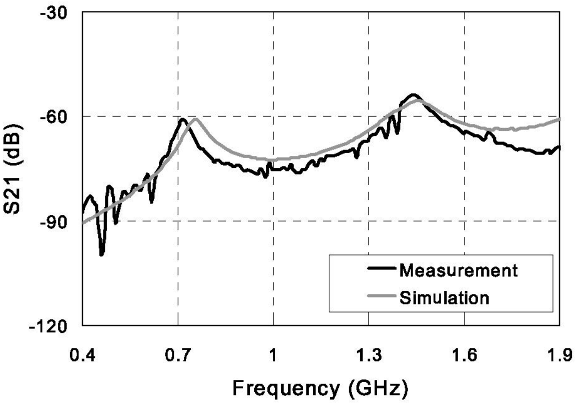

Figure 5. S_{21} vs. frequency for the ring resonator

B. Dielectric Loss

The extraction of loss tangent was performed calculating the theoretical values of conductor and radiation losses. This is done in order to isolate the dielectric loss α_d since the ring resonator method gives the total loss at the frequency locations of the resonant peaks. The loss tangent is a function of α_d (in Nepers/m) according to [1]:

$$\tan\delta = \frac{\alpha_d \alpha_o \sqrt{\varepsilon_{eff}}\,(\varepsilon_r - 1)}{\pi \varepsilon_r (\varepsilon_{eff} - 1)} \tag{2}$$

where λ_o is the free-space wavelength, ε_r and ε_{eff} are the same as described above.

Table 1. Extraction of dielectric constant from Ring Resonator Measurement

Mode	Resonant Freq (f_o)	Insertion Loss (|S_{21}|)	BW$_{\text{3dB}}$	ε_r	tanδ
N=1	0.71 GHz	-61.03 dB	42.12 MHz	3.28	0.061
N=2	1.44 GHz	-53.92 dB	75.47 MHz	3.20	0.053

Available theoretical methods for calculating conductor loss and radiation loss have been dated from the 1970s [1]. Tanδ results are shown in Table I after subtracting the calculated conductor and radiation losses.

It is to be noted that the density of the paper substrate slightly increases after the bonding process described above. This may slightly increase the calculated dielectric properties in Table I for multilayer paper-based RF modules.

Figure 6. Parallel plate capacitors on 1 mm thick paper substrate.

3D Paper-on-Paper with Embedded Passive Components

To achieve the ultimate goal of 3D paper-on-paper structures (similar to LTCC approach) with embedded passives, MEMS, RFIDs, sensors, thin film batteries, and discretes and ICs, several bottlenecks need to overcome since none of these processes have been optimized or even addressed. Among them are (i) producing thick substrate by conventional lamination process, (ii) formation of conductor lines, (iii) via formation for layer-to-layer connectivity, (iv) realization of passives such as resistors, inductors, and capacitors, (v) formation of complex antenna structures, (vi) cavity formation for embedding chips, and (vii) sthermo-mechanical integrity. The first two have been demonstrated in this paper. For realization of embedded passives, Figure 6 shows the parallel plate capacitors fabricated on paper substrate through copper foil lamination and etching. Low frequency (1 KHz to 10 MHz) measurements of capacitance and dielectric losses are in progress. Resistors and inductors were also fabricated on the laminated paper substrates using copper lamination and etching and finally screen printing of polymer thick films. Through lamination and selective etching, we have also realized resistors, capacitors, and inductors on ONE layer using copper and pre-deposited resistor film on copper foil (GOULD TCR material). The current work is focused toward ink jet printing of passives and antennas and then laminating them to form a multi-layer structure with cut out cavity for embedding ICs inside the core.

Conclusions

In a cost driven market, the ultimate success will depend on the choices of lowest cost material and manufacturing processes. To address the cost issues, the authors are looking into realization of embedded components, actives, sensors, RFIDs for wireless sensing that can be adopted in the application horizon covering supermarkets to bio-hazards, security, medical as well as defense application. This article elutes the basic steps toward application of paper-based substrates for functional circuitry. The first step is to form conductive paths on the paper surface. Two approaches have been taken – conventional lamination/etching of copper as well as ink-jet printing. The copper lamination and etching has been reported for the first time. The second step in authors view is to characterize electrical properties such as dielectric constant and dielectric loss as a function of frequency up to at least 2 GHz which has also been achieved for the first time for the paper substrates. 3D paper-on-paper packages similar to LTCC green sheets are under constructions. Hydrophobic coatings are being investigated for the protection of moisture penetration that could affect the electrical performances. The outcome in the near future would be a flexible 3D package with embedded actives and passives and thin film battery in paper-substrates which is expected to be the *lowest* cost solution for wireless sensing with RFID tags for large volume applications.

Acknowledgments

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