Design and Characterization of Novel Paper-based Inkjet-Printed UHF Antennas for RFID and Sensing Applications

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Abstract- In this paper, inkjet printed antennas on paper based substrates are investigated for the first time as a solution for the mass production of ultra-low cost Radio Frequency Identification (RFID) and Sensing applications. A cavity resonator method and a Transmission Line (TL) method were utilized for the RF characteristics extraction of paper substrate: dielectric constant (ε_r) and loss tangent ($\tan\delta$). A UHF RFID antenna was designed and developed on paper substrate using inkjet printing technology which could serve as a technology for a much simpler and faster method for fabricating RFID tags and ultra-low cost paper-based RF front-ends and antennas. Simulation and experimental results verify the characteristics of paper substrate and the performance of the RFID tag.

I. Introduction

As the growing interest for low cost, flexible, and efficient electronics for automatic identification and sensing applications increases, materials and integration techniques become more complex. For an optimal RF performance, substrate characterization becomes essential especially for low cost materials such as paper. Paper is not only environment friendly, but is the lowest cost material made by humankind and can undergo large reel-to-reel processing. Paper has also a low surface profile with appropriate coating, allowing for direct write methodologies such as inkjet- printing of electronics such as antennas and filters.
In this effort, two EM methods (Cavity Resonator and TL methods) were utilized for the characterization of ε_r and $\tan\delta$ respectively. A passive UHF RFID tag module using stubs for matching of the antenna to the Integrated Circuit (IC) was designed and printed on a paper substrate using conductive paste inkjet-printing.

II. EM Characteristics of Paper-based Substrates

Dielectric Constant- A cavity resonator method, considered one of the most accurate in characterizing dielectric constant, has been utilized [1]. The split-cylinder cavity resonator was fabricated with a circular cylindrical cavity of radius a=6.58mm and length L=7.06mm. Two cylindrical cavities: upper and lower are separated by a gap height which is adjustable to the thickness of the substrate being characterized. The feeding structure is composed of coaxial cables terminated in loops that couple to the cavity. A TE_{011} resonant mode was excited:

$$f_{011} = \frac{3\times 10^8}{2\pi}\sqrt{\left(\frac{3.8317}{a}\right)^2 + \left(\frac{\pi}{L}\right)^2} \qquad (1)$$

The paper investigated was chosen to be hydrophobic with a thickness of 263um for the convenience of inject-printing and to enhance durability. The inserted substrate caused the shifting of the TE_{011} resonant mode of the empty cavity from

34.54GHz to 33.78GHz. Using this information and boundary conditions for the **E** and **H** fields, ε_r was calculated to be 1.6. Simulations were performed in the full wave EM solver HFSS to assist identifying the correct TE_{011} resonant peaks, as shown in Fig. 1(a). Fig. 1(b) shows the measurement data for the S_{21} results of the empty and filled cavity. Since previous characterization of other organic substrates performed by National Institute of Standards and Technology (NIST) features a very flat response of dielectric constant over wide frequency ranges [2], this result is also expected to be effective for very wide frequency bands.

Loss Tangent- The TL method was utilized for the extraction of the dielectric losses of the paper substrate across the UHF RFID region according to [1]:

$$\tan\delta = \frac{\alpha_d \lambda_0 \sqrt{\varepsilon_e}(\varepsilon_r - 1)}{\pi\varepsilon_r(\varepsilon_e - 1)} \qquad (2)$$

where λ_0 is the free space wavelength, ε_e is the effective dielectric constant of the printed lines, and ε_r is the relative dielectric constant of paper. Simulation results for conductor and radiation losses, α_c and α_r respectively; of the microstrip lines were subtracted from the total loss α_{tot}. This was done by simulating a microstrip line with no dielectric loss then extracting α_r+$\alpha_{c,}$ then subtracting these effects from the total measured loss. Two microstrip lines shown in Fig. 2(a) of lengths 111.8mm and 74.8mm were fabricated on 1.2mm thick hydrophobic paper. In order to accurately model and de-embed the conductive losses, 18um thick copper was etched on these two lines. Measurements were recorded over a frequency range from 0.2GHz to 1.2GHz. Fig. 2(b) shows the plot of attenuation vs. frequency where attenuation and consequently tanδ increased as expected with frequency as expected. The attenuation was calculated to be 0.061dB/cm at 0.9 GHz which results in a $\tan\delta = 7.7\text{x}10^{-2}$ according to (2).

III. Inkjet Printed UHF RFID Antenna

Most of the available commercial RFID tags are passive due to cost and fabrication considerations. Passive tags utilize energy from an RFID reader to power up the IC. However, RFID ICs used in passive tags exhibit complex impedance and conjugate impedance matching of the antenna terminals to the IC for maximum power flow becomes a challenge. The antenna is designed to cover the UHF North America RFID frequency band (902MHz→928MHz). UHF frequency band allows a higher data rate and higher read range over other bands typically used in RFID such as HF band operating at 13.56MHz.

The half wavelength tapered width dipole antenna shown in Fig. 3 was designed to have a center frequency of 914MHz. As shown in Fig. 3(b) the two stubs namely: inductive and resistive stubs are responsible for the conjugate matching of the antenna to the reactive and resistive part of the IC respectively [3]. This method of introducing stubs is very effective in matching to any arbitrarily IC impedance (Z_{IC}). The target Z_{IC} used in this design was Philips EPC 1.19 Gen 2 RFID ASIC IC which exhibits a stable impedance behavior of 16-j350 Ω over the frequency 902MHz→928MHz. Return Loss (RL) plot is shown in Fig. 4(a) with a bandwidth of 905MHz→925MHz defined by a value of RL<-10dB, with radiation efficiency of 92%, for an excellent read range of the RFID tag. The RFID antenna was ink jet printed (Fig. 3(a)) with overall dimensions of: 8.2cm x 4.5cm. The radiation pattern of the antenna is quite similar to that of a classic dipole as shown in Fig. 4(b) which is desirable in most RFID applications. The inkjet printing on-paper approach is very repeatable, allows for features down to 20um and can be easily utilized for other passive functions, such as filters, baluns in single or multilayer (multi-sheet) configurations. Results from on-paper active RF modules including embedded batteries and IC's in addition to the antenna and stubs will be presented at the conference for universal (866~928 MHz) operation.

IV. Conclusion

The RF characteristics of paper have been investigated and have enabled the development of a novel inkjet printing approach for the ultra-low cost fabrication of antennas on paper substrate over the UHF frequency range. An RFID tag prototype module using stubs for matching to the IC on paper-based substrates operating in the UHF frequency band was designed and inkjet printed featuring excellent performance. These technologies could potentially revolutionize the RF industry and allow for simple, low-cost "cognitive radio" communication and sensing solutions on regular paper substrates.

References:

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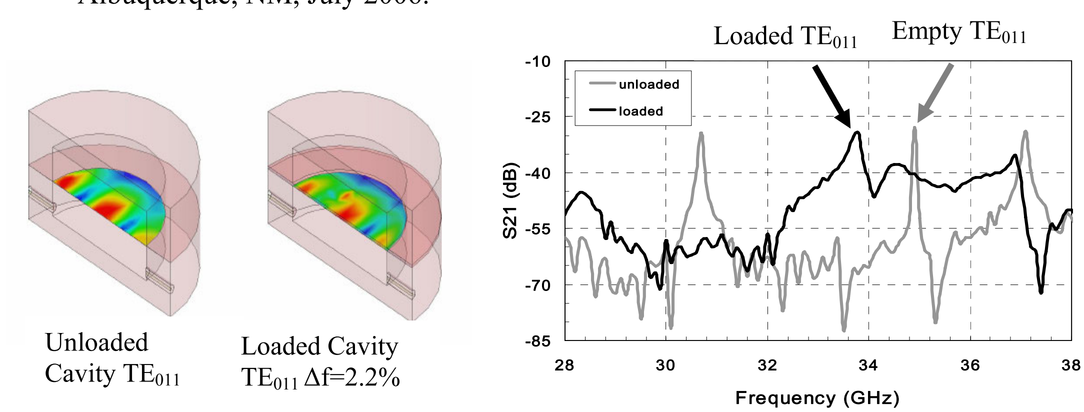
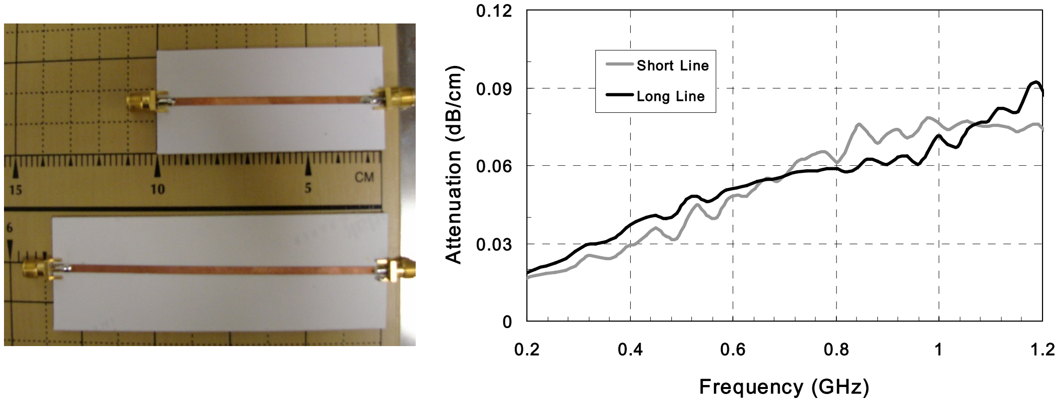


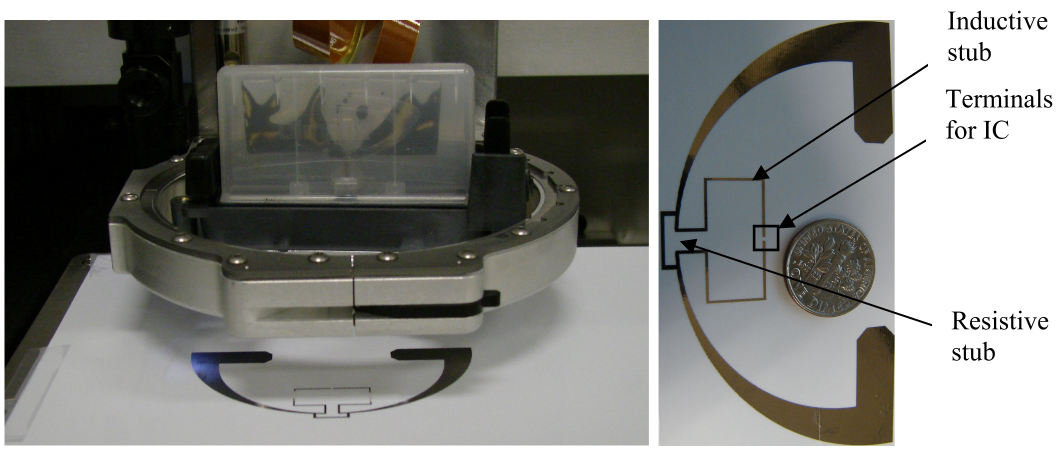
(a) (b)

Figure 1. (a) Simulated field distributions of TE_{011} modes (b) Measured modes shifting unloaded/loaded cavity.



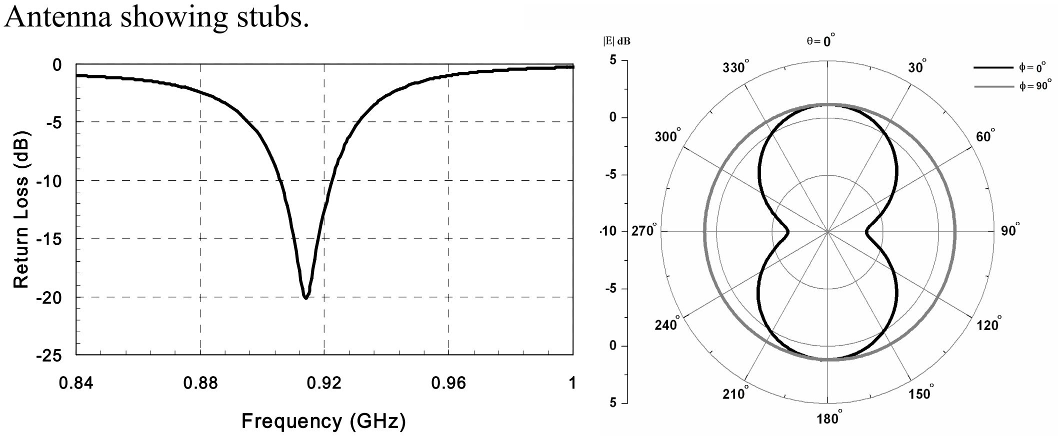
(a) (b)

Figure 2. (a) Photograph of microstrip lines fabricated on paper (b) Attenuation of paper vs. frequency using TL method.



(a) (b)

Figure 3. (a) Photograph of UHF RFID antenna inkjet printed on paper (b) RFID Antenna showing stubs.



(a) (b)

Figure 4. (a) Return Loss of UHF RFID Antenna (b) Omnidirectional radiation pattern of RFID UHF Antenna.