Inkjet-printed Wearable Microwave Components for Biomedical Applications

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***Abstract*—This paper presents technology for the implementation of inkjet-printed wearable microwave components on paper substrate for biomedical applications such as washable inkjet-printed antenna, inkjet-printed antenna on artificial magnetic conductor (AMC), and substrate integrated waveguide (SIW). The Parylene-C is deposited on the inkjet-printed antenna to protect antenna from ambient humidity and small AMC which isolates a RF radiator from human body. Lastly, low cost inkjet-printed SIW on paper substrate is introduced for wearable applications.**

***Index Terms*—Inkjet-printed electronics, parylene, artificial magnetic conductor (AMC), substrate integrated waveguide (SIW), paper substrate**

I. INTRODUCTION

Demand for low-cost wireless wearable flexible electronics in the field of biomedical area is rapidly increasing. Inkjet-printed electronics on flexible substrates have attracted a lot of attention and they have been investigated by many research groups because of their many advantages. In other words, they require a cost efficient fabrication process and they can be deposited directly on planar substrates that can be conformed into flexible shapes [1-3]. In addition, utilizing a paper substrate allows implementing some of the lowest cost microwave structures while using a completely eco-friendly material. These properties are of key importance, in the design of wearable microwave components for bio-monitoring applications.

One of the most important factors for the implementation of wearable electronics is to protect the electronic devices from ambient environment such as moisture. This property is also important in any attempt to realize washable wearable electronics. The Parylene-C is chosen as a protect layer among many conformal protection coating technologies because it is completely dry and bio-compatible process [4]. As a proof of concept, dual band monopole antenna is designed, and it is coated by the Parylene-C. The waterproof performance of the coated antenna is presented according to the exposure time into water.

Another challenging issue for the implementation of wearable wireless electronics is the degrading effect of human body [5]. The human body absorbs a large amount of radiated power from the wearable wireless devices since it is a material with high relative dielectric constant (ε_r) and rather lossy. To prevent undesired effect from the human body, a monopole antenna is placed on the artificial magnetic conductor (AMC) ground plane. In this paper, an AMC ground plane with 2x1 resonator array which is reduced from 4x3 resonator array shown in previous work [6-9] is presented to achieve compact miniaturize high gain antenna on human body.

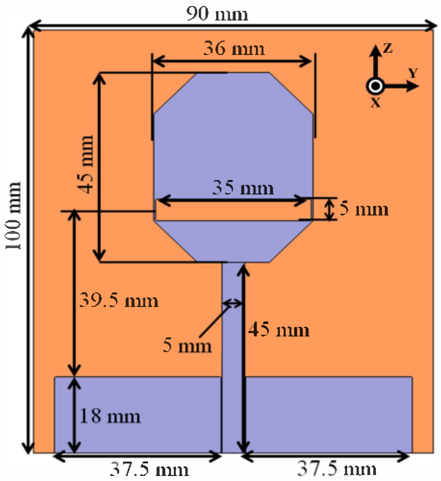


Fig 1. Antenna geometry. The thickness of paper substrate is 0.23mm and the gap of CPW line is 0.25mm

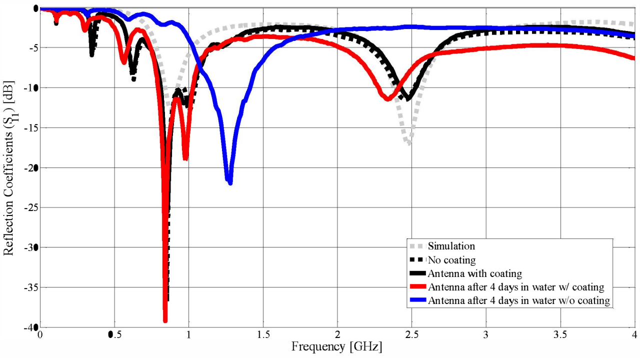
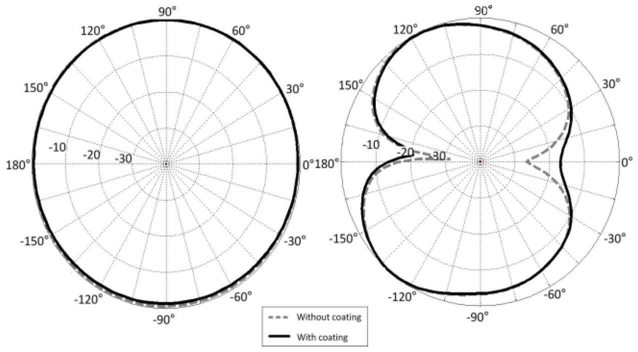


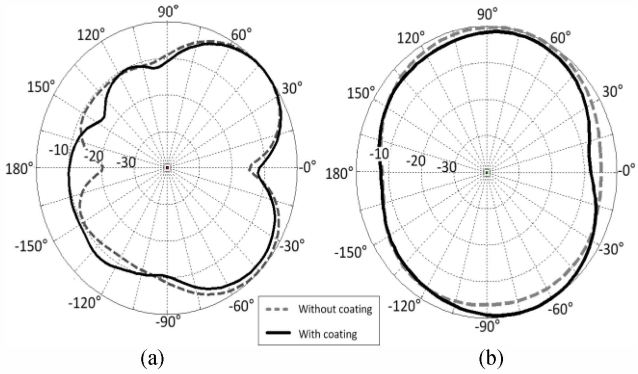
Fig 2. Reflection coefficients of the antenna with/without coating and antennas in the water during 4 days

Lastly, a substrate integrated waveguide (SIW) on paper substrate is presented. The SIW allows the integration of electronic components on the same substrate, and this technology has advantages for both microstrip structures and metallic waveguides [10]. This technology is very useful for wearable mmWave applications such as a radar for bio-monitoring. Basic straight microstrip-to-SIW transitions in different lengths are presented as a result of preliminary research for future wearable wireless systems and devices.



(a) (b)

Fig 3. Radiation patterns of the antenna at 900 MHz (a) E-plane (b) H-plane



(a) (b)

Fig 4. Radiation patterns of the antenna at 2.45 GHz (a) E-plane (b) H-plane

II. INKJET PRINTED WEARABLE MICROWAVE COMPONENTS

A. *Parylene coated washable antenna*

Many wearable bio-monitoring devices are vulnerable to ambient moisture when implemented on hydrophilic substrates such as paper substrate. Most of researches on washable and wearable antennas are realized/integrated on commercially available fabrics [5][6]. The direct integration of the antenna with clothes in high flexibility is the advantage of this approach but the metallic area of the antenna is generally exposed to the environment without any protective layers. This results in the quick rusting and degradation of the antenna performance.

To protect the inkjet-printed electronics, Parylene-C has been deposited on top of an inkjet-printed dual band antenna on paper substrate and its geometry is shown in Fig 1. The measured and simulated reflection coefficients (S_{11}) of two identical antennas with/without Parylene coating are presented in Fig 2. In addition, the fabricated antennas with/without coating are immersed in distilled water for 4 days to study their waterproof ability. As can be seen from the results in Fig 2, the antenna without coating has lost its dual band property because the antenna doesn't resonate at 2.4 GHz, while the antenna with coating has maintained its dual band property. Measured radiation patterns, on E and H planes, at each frequency (900 MHz and 2.4 GHz) are presented in Figs 3 and 4.

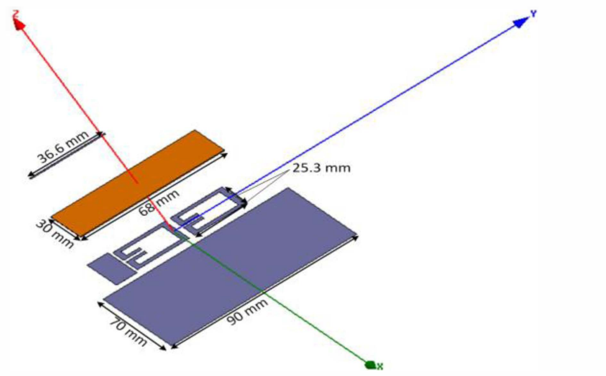


Fig 5. Monopole antenna on AMC

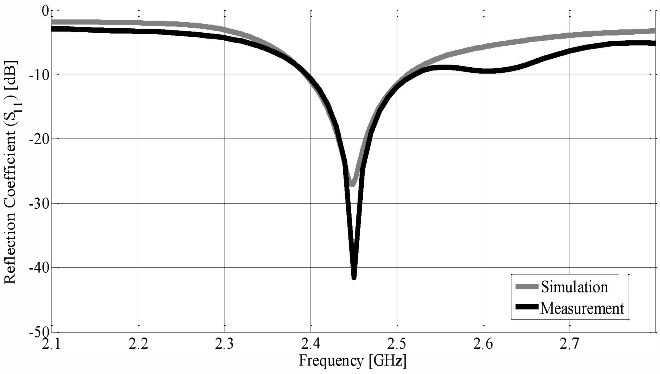
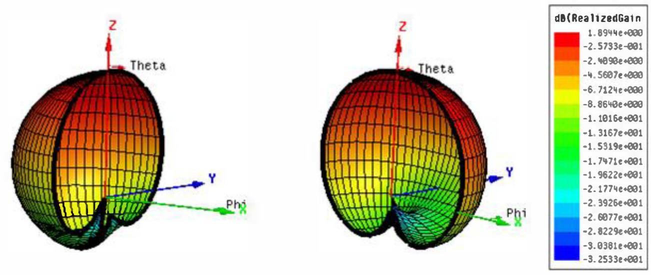


Fig 6. Reflection coefficients of the monopole antenna on 2x1 AMC



(a) (b)

Fig 7. Radiation pattern (a) E-plane (b) H-plane

The radiation patterns with/without Parylene coating are almost the same and their gain, in the maximum directivity direction, is also very similar. The measured gain with/without coating at 900 MHz is about -3 dBi and at 2.45 GHz is about 1 dBi. These results suggest that Parylene coating does not affect the antennas' performance since the reflection coefficient, gains and radiation patterns do not change significantly after the deposition of the Parylene layer.

In this work, the washable/waterproof capability of Parylene-C is demonstrated. This coating technique can be applied to various inkjet-printed RF devices to protect them from ambient moisture and potentially lead to washable wearable RF electronics for bio-medical applications.

B. *Wearable antenna on AMC*

In previous work, an inkjet-printed monopole antenna on AMC for bio-monitoring application was presented [6-9]. The proposed antenna has positive gain (0.95 dBi) on human body

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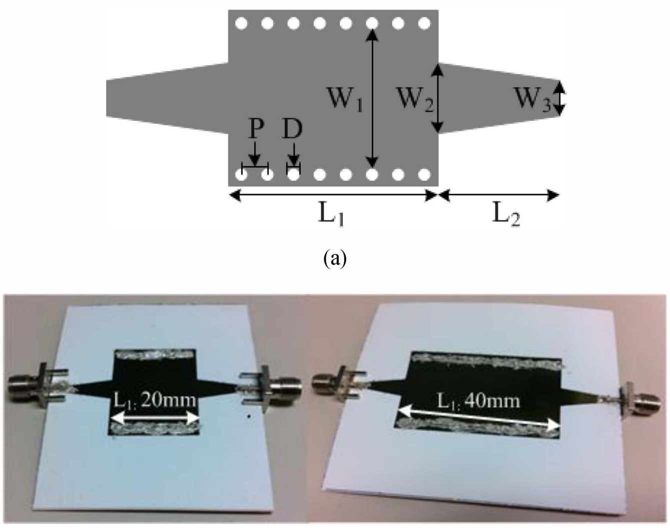
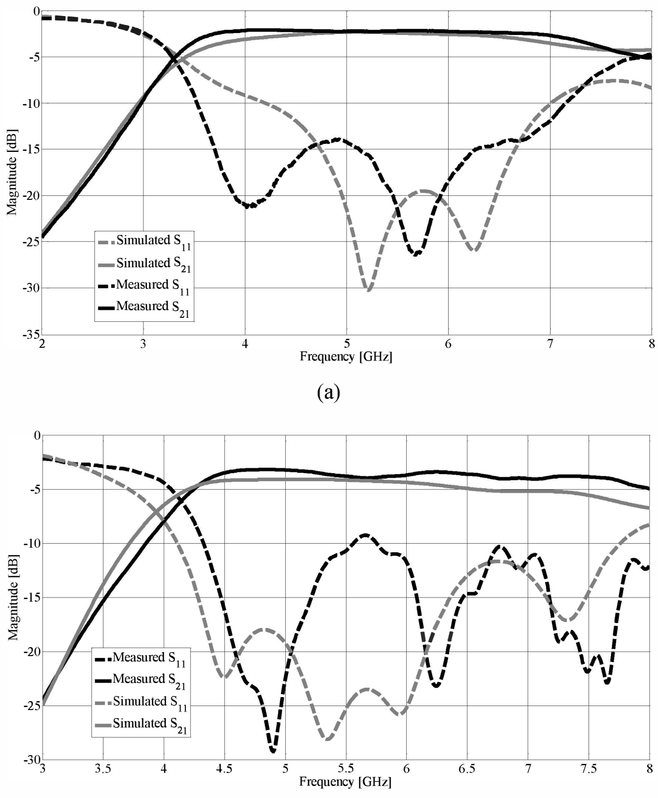


(a)

(b)

Fig 8. (a) SIW geometry (b) Fabricated SIWs in different length



(a)

(b)

Fig 9. Scattering parameters of the SIWs (a) L_1: 20 mm (b) L_1: 40 mm

phantom and high front-to-back ratio (24.3 dB) but the AMC size was much larger than that of the radiating monopole. In this paper, a significantly improved design is presented with more than 60% size reduction of the AMC while the antenna maintains its advantages such as the positive gain during operation adjacently to human body. The layers of the suggested design are shown in Fig 5. The thickness of the AMC is increased as a trade-off for reducing the resonators' array dimensions from 4x3 to 2x1. The overall size of the single ring resonator array is 25.3 × 25.3 mm with gap of 2.53 mm. The thickness of the resonator is 2.53 mm and the distance between ground plane and resonator array is 4 mm. The gap is filled with Styrofoam slabs and extra ground plane of 20 mm is extended from each side of the antenna as shown in Fig 5. Measured and simulated reflection coefficient (S_{11}) of the fabricated antenna is presented in Fig 6. The measurement is well matched to the simulation while the bandwidth is reduced compared to the previous work. The fractional bandwidth of the antenna with reduced AMC is 4.49 % which is about one half of the fractional bandwidth of the antenna with the larger AMC (10.06 %). The simulated radiation patterns at 2.45 GHz are shown in Fig 7. The thicker black boundary line of the surface shows E- and H- plane distributions. Both the antenna with larger AMC and with reduced AMC exhibit high front-to-back ratio of 24 dB which results in effective isolation of the antenna's RF radiation from ambient environment when the antenna is mounted on the human body.

C. *Inkjet-printed SIW components*

SIW structures are similar to traditional rectangular waveguides and are implemented in dielectric substrates by using rows of metalized via holes [11]. SIW structures and components allow the integration of every component on the same substrate, including passive structures, active components, and antennas [12]. SIW technology has the advantages of classical microstrip circuits such as low cost, easy fabrication, compact size, and low weight, and at the same time the advantages of metallic waveguides, like low loss, complete shielding, and high power handling capability. SIW structures appear particularly suitable for implementation on paper since the capability to easily realize multilayered topologies and conformal geometries can be exploited. In addition, SIW structures and components can support mmWave and high power applications such as radars for bio-monitoring [10]. The geometry of inkjet-printed SIW structures on paper substrate is shown in Fig 8. The diameter (D) of a via hole is 0.8 mm, the distance between vias (P) is 1.6 mm and the thickness of the substrate is 0.69 mm. The width of the SIW (W_1) is 24 mm. The widths of microstrip-to-SIW transition, W_2 and W_3, are 1.88 mm and 6 mm, respectively. The length of the transition (L_2) is 12 mm. Two different length of SIW (L_1=20mm and L_1=40mm) are designed and measured for comparison as shown in Fig 8(b). For the vias fabrication, mechanical drill is utilized to make the holes since it doesn't damage the substrate unlike the laser drilling process which produces blackening. The drilled via holes are metalized by inserting cylindrical copper rivets. The

The cutoff frequency of the designed SIW line is set to 3.75 GHz which enables the SIW line to have operation frequency of 5GHz. The dimensions of the via diameter and pitch are chosen to minimize any fabrication errors and the radiation leakage. The measured scattering parameters of the designed SIW lines with different length of 20 mm and 40 mm are shown in Fig 9. The simulations and measurements are in very good agreement all over the frequency range. The measured insertion loss (IL) of the 20 mm long SIW line, was 2.23 dB, and the losses for the 40 mm long SIW line was 3.43 dB. The discrepancy between simulation and measurement are resulted from the fabrication error of the different SIW interconnects and the vias alignment.

This work consists the basic, preliminary study for future wireless systems and wearable devices which have the advantages of low cost, flexibility and being environmentally friendly. Based on this result, the more SIW components such as filters and antennas for wearable applications can be developed.

III. CONCLUSION

In this paper, recent accomplishments on inkjet-printed microwave components for bio-monitoring applications are introduced. Parylene coated inkjet-printed antenna suggests the possibility of washable waterproof inkjet-printed electronics for implantable/bio-monitoring applications. Inkjet-printed monopole antennas on miniaturized AMC and SIW on paper substrate for body area network (BAN) that can be used for full scale wearable systems, operation adjacently to human body, have been presented.

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