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Wearable Textile Antennas' Efficiency Characterization using a Reverberation Chamber

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***Abstract*—Characterization of efficiency is an important consideration to ensure the proper operation of an all-textile wearable antenna. In this work, a small, novel textile antenna is designed based on a planar inverted-F structure (PIFA). The structure incorporates an edge-feeding plate, symmetrical design, and well-placed slot, in order to ease fabrication. A thin conductive textile, Pure Copper Polyester Taffeta Fabric (PCPTF), and fleece is used to fabricate the structure. The efficiency is then verified and measured using a commercial reverberation chamber. Observed results indicate excellent agreements between simulations and measurements.**

Keywords-component; Planar Inverted-F Antenna (PIFA), textile antenna, broadband antennas, wearable antennas

I. INTRODUCTION

The emergence of wearable communication systems has boosted the interest in wearable antennas. Various applications in military, medical, emergency response, and consumer electronics applications have been seen to embed conventional cables, miniaturized electronic components, and connectors altogether in a wearable smart clothing system. The smart clothing electronic system should incorporate wireless communication components made of flexible textile rather than bulky boxes made from rigid materials. This has triggered the need for a flexible and wearable radiating system to suit this purpose, enabling a transparent or 'non-existent' system to the users.

Degradation of the antenna performance when worn on the human body has been one of the major deterrents in a successful implementation, be it in terms of frequency detuning, bandwidth reduction, and efficiency degradation or radiation distortion. In other words, ideally, a wearable antenna must be designed to be immune enough for on-body operation. This makes researchers to be address the fundamental issue of efficiency. Various researchers have come up with a multitude of strategies in order to minimize the effect of this degradation. One strategy is to design an antenna broad enough to cater for the antenna degradation in the proximity of the users' body [1].

A reverberation chamber (*RC*) is basically a metal cavity with many excited modes which are stirred to create a statistically isotropic field environment [2]. Initially used for electromagnetic compatibility (*EMC*), its capability is now expanded in order to measure radiation efficiency, diversity gain, capacity of multiple-input-multiple-output (*MIMO*) systems, etc. The measurements of various conventional antennas and active devices have been investigated in previous works [3]. Although it has been shown recently that efficiencies of small antennas can be accurately measured using RCs, to date there is very little experience with measuring all-textile antenna in such facility. Still, some previous measurements are mentioned in [4].

Antenna efficiency and total radiated power are obtained by measuring and averaging the power transfer function $|S_{21}|^2$ between two or more antennas for many stirring positions [5]. The variation of these average power transfer functions is a metric of the measurement accuracy. The Bluetest AB chamber integrates various stirring methods - mechanical stirring (including platform stirring) and polarization stirring[6]. Through these stirrings, sufficient independent and uncorrelated samples are introduced, ensuring measurement accuracy. In addition to that, this work investigates frequency stirring for textile antenna measurements. This technique is executed by averaging the chamber's power transfer function over a certain frequency stirring bandwidth (δf) to improve measurement accuracy. However, careful selection of δf must be taken into account, as the resulting frequency resolution can be reduced.

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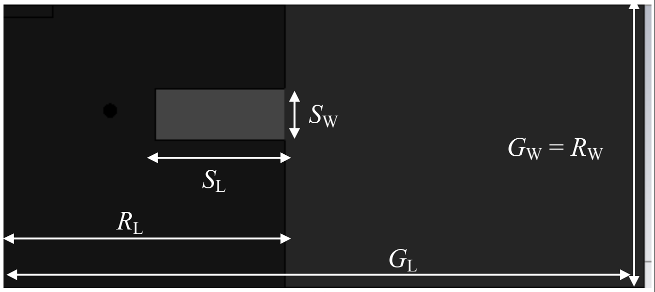
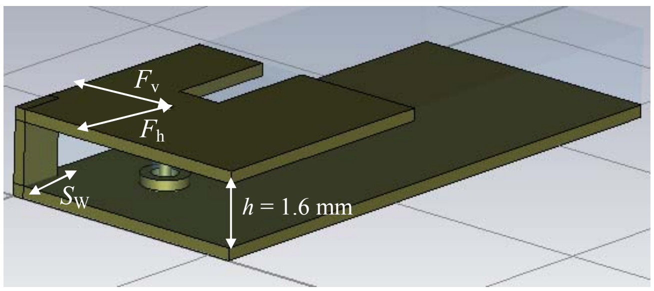
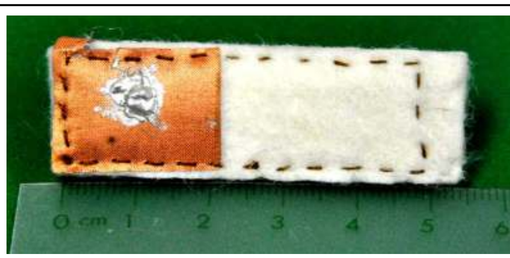


(a)



(b)

Figure 1. Dimension of the proposed SPIFA in CST (a) Top view (b) Perspective view



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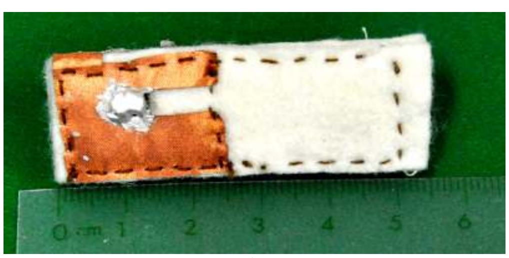

(b)

Figure 2. The fabricated PIFAs (a) Plain (PPIFA) and (b) Slotted (SPIFA)

II. TEXTILE MATERIAL AND ANTENNA DESIGN

The conductive textile material used in this work, PCPTF, is a plain woven polyester textile, plated using copper. This textile material from LessEMF Inc USA, is 0.08 mm thick, and possesses a surface resistance, R_s, of less than 0.05 Ω/sq. It has been used to form the conductive components of the PIFA, i.e the radiator, ground plane and shorting wall, all in a single and continuous structure. A 50 Ω SMA connector is used to feed power into the radiator. It is attached to the textile radiator and ground plane using EE129-4 conductive epoxy from Epotek Inc USA. To ease integration into normal clothing, the radiator and ground plane area are spaced by a 6 mm thick fleece, which is estimated to possess a relative dielectric constant, ε_r of 1.26 [7]. Initial calculation of the dimensions for a center frequency of 2.45 GHz is carried out using the procedure defined in [8]. The structure is then simulated and optimized using CST Microwave Studio. The topology is shown in Fig. 1.

Calculation yields a ground plane dimension of G_L x G_W = 50 x 24 mm, a radiator sized at R_L x R_W = 36 x 24 mm, a shorting wall width (S_W) of 5 mm and a feeding location at the center of the radiator, F_h and F_v are 10 and 12.5 mm, respectively. Optimization further miniaturized the overall dimensions, resulting in G_L = 50 mm, R_L = 23 mm, $G_W = R_W$ = 19 mm, S_W = 5 mm, F_h = 10.5 mm, and F_v = 7.7 mm.

Two types of radiator topologies are fabricated and tested, one with a plain radiator (*PPIFA*), and another with a slot (*SPIFA*) dimensioned at S_L x S_W = 9 mm x 6 mm, placed at the edge of the radiator. Fabrication of the antennas is performed using simple, manual dimensioning and cutting tools. Thus, fabrication inaccuracy is expected to be slightly larger in comparison to fabrication of conventional antennas using Printed Circuit Board (*PCB*) technology. For each topology, two samples (labeled as *PPIFA1*, *PPIFA2*, *SPIFA1* and *SPIFA2*, respectively) are fabricated as carefully as possible, and then tested for performance. This is done to investigate the extent of the anticipated fabrication inaccuracies. In addition, prototypes 1 and 2 are fabricated using different sizes of fleece, to investigate whether effect of the overall size of the antenna will be significant. The *P1* and *P2* fleeces are sized at 25 mm x 80 mm, and 25 mm x 55 mm, respectively. Besides, *P1* and *P2* prototypes are also fabricated one month apart to investigate the effect of textile/epoxy aging. The fabricated antennas are shown in Fig. 2.

III. EFFICIENCY MEASUREMENT SETUP

The reverberation chamber from Bluetest AB used in the measurement is sized at 1.8 x 1.7 x 1.2 m^3. Mechanical stirring is performed by two plates (one horizontal and another vertical) moving step-wise, while the Antenna under Test (*AUT*) is placed onto a rotating platform. In such way, the rotating platform creates a 20-position measurement, spaced by 18^o. On the other hand, both stirrer plates were moved at 10-positions both horizontally and vertically. Polarization stirring is also introduced by the implementation of three wall antennas mounted at three orthogonal walls. Due to the antennas' broad bandwidth, measurements of the *AUT* are carried out between 1.5 – 3.0 GHz, with a 1 MHz interval. Since the numbers of points are limited to 1601 points per measurement, two consecutive measurements are carried out for the same antenna, one from 1.5 to 2 GHz, and another from 2 to 3.5 GHz. However, minimal error is expected since no physical changes are applied to the antenna in between measurements.

During the measurements, the chamber was loaded with a brain equivalent liquid-filled head phantom. Initially, a 700 MHz to 6 GHz discone antenna with known efficiency is chosen as the reference antenna, and measured for its power transfer function. Next, the *AUT* is placed in the chamber and measured using the same procedure and load. The ratio of

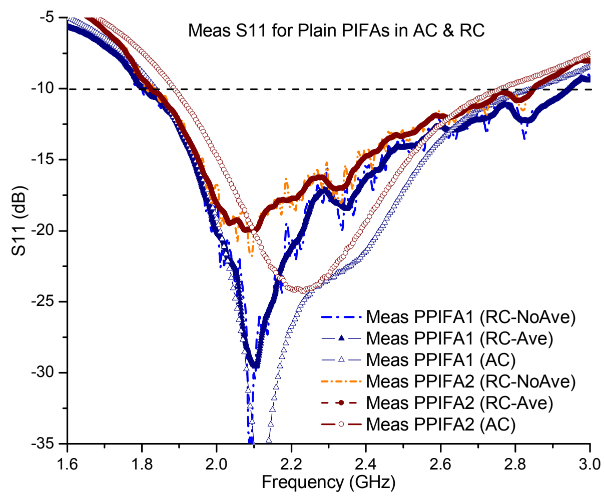

Figure 3. Measured reflection coefficient (in dB) for both plain PIFA prototypes

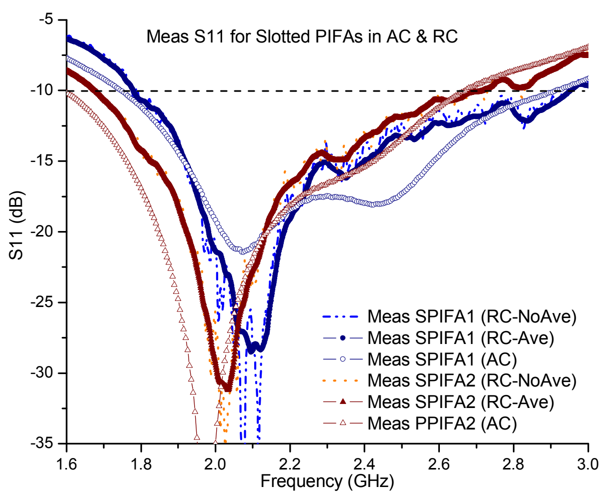

Figure 4. Measured reflection coefficient (in dB) for both slotted PIFA prototypes

TABLE I. SUMMARY OF SIMULATED AND MEASURED PIFA PERFORMANCE

	PPIFA1	PPIFA2	SPIFA1	SPIFA2
Sim *BW* (MHz)	912		940	
Meas *AC* *BW* (MHz)	970	1010	1160	1080
Meas *RC* *BW* (MHz)	1024	1134	1173	1042
Sim e_{Rad} (dB)	-0.088		-0.085	
Sim e_{Tot} (dB)	-0.317		-0.319	
Meas e_{Rad} (dB)	-0.668	-1.241	-0.804	-2.176
Meas e_{Tot} (dB)	-0.845	-1.443	-0.997	-2.366

average power transfer functions, $(1/N)\sum_{n=1}^{N}|S_{21}|^2$,of the two measurements is the ratio between the efficiencies of the two antennas. Using both the absorption losses (e_{Rad}) and mismatch factor (1-$|S_{11}|^2$), the total radiated efficiency (e_{Tot}) of the antenna is then obtained through:

$$e_{Tot} = e_{Rad}\left(1-|S_{11}|^2\right) \quad (1)$$

IV. RESULT AND DISCUSSION

An accurate value of the reflection coefficient (S_{11}) is critical to ensure good accuracy. Thus a comparison of S_{11} is carried out. A reflection coefficient measurement is first carried out in an anechoic chamber (*AC*) available at KU Leuven before it is transported to Chalmers for measurement in the Bluetest *RC*. The *AC* measurement is carried out using 401 points from 1.5 GHz to 3.5 GHz, which produces a S_{11} reading every 5 MHz. In Chalmers, the measurement is carried out within a similar range, but using a 1 MHz frequency resolution. This is labeled as *RC-NoAve*. These *RC* readings are then smoothened out with a 5 MHz frequency stirring to produce the same resolution as in the *AC* for comparison, as can be seen in Figs. 3 and 4, being labeled as *RC-Ave*. It can be seen that the measurements at both locations, using both *AC* and *RC*, are agreeing well with each other, especially above -10 dB. Below that, it is more difficult to measure S_{11} accurately. A slight S_{11} degradation/shift is seen for the slotted PIFAs due to the presence of the slot, which is not secured onto the fleece substrate. A slight change in performance originating from the transportation between *AC* and *RC* is also not ruled out.

Generally, bandwidth (*BW*) in this work is defined at the -10 dB borders of the antennas' S_{11}. Measurements in both *AC* and *RC* are agreeing well, showing more than 1 GHz of *BW*. Differences of less than 50 MHz are seen between both measurements. This is reasonable; considering that the flexible antenna is only supported by an SMA connector and the RF cable at the bottom of the PIFA during measurements. This is done to avoid electromagnetic coupling to nearby objects in both rooms. As a result, rotator movements in *RC* during measurement have possibly altered the physical conditions of the flexible antenna, resulting in the discrepancy. On the other hand, simulations produced about 100 MHz less bandwidth for both slotted and plain structures. This is due to the modeling assumption that there is almost zero dielectric loss in the fleece substrate.

Efficiency measurements performed in the Bluetest *RC* of all four antenna prototypes are shown in Figs. 5 and 6, while e_{Rad} and e_{Tot} are listed in Table I. It can be clearly seen from the measurements that both plain and slotted prototypes with a larger fleece, and thus total antenna size, are agreeing better with the simulations. Simulated and measured e_{Tot} differ by about 0.5 dB for *PPIFA1* and about 1 dB for *SPIFA1*. On the other hand, a fair agreement is seen for prototype 2. More than 1 dB and 2 dB of measurement-simulation difference are seen for *PPIFA2* and *SSPIFA2*, respectively. This indicates that additional substrate area has significantly increased the radiation resistance (R_r), and in turn, increased radiated power

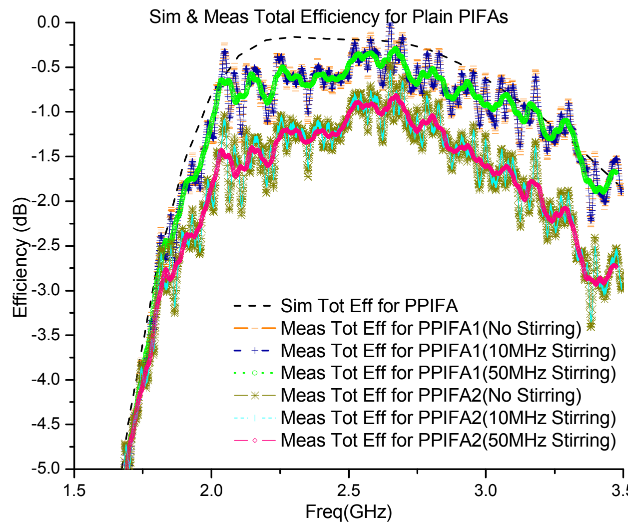

Figure 5. Simulated and measured total efficiency for plain PIFAs

P_r. This is assuming a fixed ohmic resistance (R_{Ohm}). These quantities are related by:

$$e_{Rad} = \frac{R_r}{R_r + R_{Ohm}} \quad (2)$$

Initially, it was thought that the textile and epoxy's ageing would affect the antenna performance over a specified period of time. This is due to the textile, which is plated using layer of pure copper, which could suffer from oxidation, in this way reducing its conductivity. Moreover, the conductive epoxy used for the textile-SMA interconnection might have also degraded mechanically, especially under bending conditions. However, from this investigation, it can be observed that at least these antenna prototypes, fabricated a month apart, did not show any significant degradation. Differences are largely due to fabrication inaccuracies and dielectric substrate's size instead.

Frequency stirring with proper *BW* can improve measurement accuracy, yet a too large frequency stirring *BW* will degrade frequency resolution. We examine the frequency stirring effect on the efficiency in Fig. 5 and Fig. 6. Frequency stirring tends to result in a smoother curve, reducing uncertainty due to statistical variations with frequency. For the present antennas, the actual frequency variation of the efficiency is so slow (see theoretical curve) that we can frequency stir 50 MHz or even more.

V. Conclusion

A set of four planar inverted-F antennas (PIFAs) using conductive textile has been successfully designed, fabricated and tested. Characterization of efficiencies in a reverberation chamber has also been carried out, indicating values larger than -3 dB. Although the two prototypes are affected by fabrication inaccuracies and the substrate sizes are different, measurement results of the prototypes *PPIFA1* and *SPIFA1* indicated an excellent agreement with simulations, with a difference of less than 1 dB. Larger efficiency disparity, of about 0.2 dB, is observed for the slotted antennas, due to the existence of the unsecured slot. This also proved that increased practical tolerances must be catered in the fabrication of more complicated textile antenna structures.

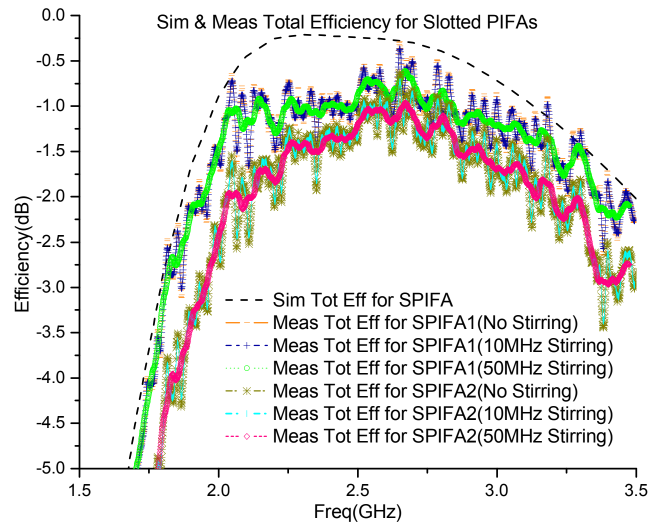

Figure 6. Simulated and measured total efficiency for slotted PIFAs

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