

## Bending Investigation of Broadband Wearable All-Textile Antennas

<sup>1,2</sup>Ping Jack Soh, <sup>2</sup>Guy A.E. Vandenbosch, <sup>1</sup>Fwen Hoon Wee, <sup>3</sup>Mohamad Zoinol Abidin Abdul Aziz

<sup>1</sup>School of Computer and Communication Engineering, Universiti Malaysia Perlis (UniMAP), Pauh Putra Campus, 02600 Arau, Perlis, Malaysia.

<sup>2</sup>ESAT-TELEMIC Research Div., KU Leuven, 3001 Leuven, Belgium.

<sup>3</sup>Telecommunication Engineering Dept., Faculty of Electronics and Computer Engineering, Universiti Teknikal Malaysia Melaka (UTeM), 76100 Durian Tunggal, Melaka, Malaysia.

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**Abstract:** This investigation proposes a method of consistently evaluating wearable textile antennas when operating in bent conditions. This is to emulate the usage of these antennas in practice, when operating on a real human arm in bent conditions. Two similarly-shaped Planar Inverted-F Antenna (PIFA) made from a common substrate and different flexible metallic conductors and are studied. Both antennas are bent in two different orthogonal axes on three different cylindrical sizes, 20, 40 and 60 mm in radius. These cylinders are defined using electrical properties similar to the human arm at 2.5 GHz. Bending in the axis along the antenna's radiating edge, i.e. at the x-direction using the smallest sized cylinder was found to be the worst performing configuration in terms of reflection coefficient, bandwidth, and gain.

**Key words:** Conformal antennas, textile antennas, bending investigation.

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### INTRODUCTION

In recent years, body-centric wireless communication becomes an important part of fourth generation mobile communication systems (4G). In supporting the increasing interest in antennas and propagation research for body communication systems, the IEEE 802.15 standardization group has been established to standardize applications intended for on-body, off-body or in-body communication. Body-centric communications takes its place firmly within the sphere of wireless personal area networks (WPANs) and wireless body area networks (WBANs). Wearable antenna for WPAN applications should be made flexible and conformal, and it is only natural that textiles be used to achieve these requirements. Wearable antennas are electrical radiators being made flexible enough to be worn and to work in the proximity of a user's body. Effective implementations of WPANs are expected to effectively contribute to advancements in emergency services, medical, military, identification, navigation, sports, etc (Mohd Rais *et al.*, 2009; 2013, Mercuri *et al.*, 2013). Various effort has been channelled to enhance its usability, e.g., by incorporating beam-switchability (Jais *et al.*, 2013), direction-of-arrival (DoA) estimation (Soh *et al.*, 2013) and multiple-input-multiple-output (MIMO) (Van Torre *et al.*, 2011) features. However, degradation of the antenna performance when worn on the human body has been one of the major deterrents in its robust implementation, be it in terms of frequency detuning, bandwidth reduction, and efficiency degradation or radiation distortion (Soh *et al.*, 2012). In other words, ideally, a wearable antenna must be designed to be immune enough for an on-body operation. Moreover, a flexible antenna made from textile is regarded as a realistic candidate due to the advancements in conductive textiles and the ergonomic properties that it is able to offer.

Commonly, wearable antenna requirements for all modern application require light weight, low cost, almost maintenance-free and no installation. One of the dominant research topics in antennas for body-centric communications is concerning the performance of these wearable, fabric-based antennas under bent conditions. This work attempts to introduce a simple evaluation method in determining any wearable antenna performance under bent conditions. The sample antennas are based on our previous reported topology in (Soh *et al.*, 2010; 2011; 2012).

#### **Antenna Design and Material Characterization:**

The antenna prototyping materials consist of two textile types, conducting and non-conducting. The former is typically used to form antenna conductive elements (radiator, ground plane, shorting wall, etc.) whereas the latter is used to form the substrate, spacer, etc. Since these materials are either newly introduced or have been traditionally used for other purposes, e.g., electromagnetic interference (EMI) shielding or grounding, one of the important and yet challenging aspect of this work is to properly characterize its electrical properties at the intended frequencies. Two different flexible and conductive materials were used for the antenna designs, listed as follows:

- a. ShieldIt Super from Less EMF.Inc: a ripstop, woven polyester textile coated with copper and nickel. Its listed surface resistivity,  $R_s < 0.05 \Omega/\text{sq}$ . The thickness,  $t$ , is 0.17 mm, its estimated weight is  $230 \text{ g/m}^2$ .
- b. Copper foil tape: with a thickness,  $t$ , of 0.035 mm, coated with an electrically 0.03 mm thick conductive acrylic adhesive provides reasonably homogeneous surface resistivity/conductivity and good mechanical stability.

In the case of the analyzed planar inverted-F antenna (PIFA), conductive textiles are used as its radiator, ground plane and shorting wall, whereas the non-conductive felt is used as the substrate. Its optimized dimensions are listed in (Soh *et al.*, 2010; 2011; 2012), and the topology is shown in Fig. 2. The parameter of prime importance is the equivalent conductivity of the conductive textile, which ultimately determines the efficiency and gain of the antennas. The homogenized conductivities were calculated based on the surface resistances provided by the manufacturer. The material thicknesses are chosen to be distinct, i.e., copper tape's thickness is 0.035 mm and ShieldIt's is 0.17 mm. The conductive textiles are defined as a lossy metal to simplify analysis, with an estimated conductivity of  $\sigma_s = 1.18 \times 10^5 \text{ S/m}$  for ShieldIt using an approximate equation proposed in (Lilja and Salonen, 2009). For copper foil, the conductivity is taken as  $\sigma_c = 5.88 \times 10^7 \text{ S/m}$ .

Its felt substrate permittivity ( $\epsilon_r$ ) and loss tangent ( $\tan\delta$ ) are given in literature within the following ranges:  $\epsilon_r$  in between 1.18 (Kennedy *et al.*, 2009) and 1.45 (Locher *et al.*, 2006) and  $\tan\delta$  in between 0.004 (Kennedy *et al.*, 2009) and 0.025 (Hertler *et al.*, 2007). This illustrates that a proper measurement of felt characteristics is still an issue. In order to determine the most appropriate value for our experiments, two techniques were considered. One was the proposed technique in (Wee *et al.*, 2009) based on the free space, non-contacting method, and another based on a commercial contacting method. This contacting method was then chosen due to the characteristic of the samples, besides the need to evaluate the textile substrate over a broad frequency range. Samples of 6 mm thick have been measured using commercial HP85070E Dielectric Probe Kit available at Universiti Teknikal Malaysia Melaka (UTeM) between the intended analysis frequency of 1 and 4 GHz. The measured substrate permittivity and loss tangents are shown in Fig. 1. Three measurements were performed with a maximum uncertainty of 4.2%. The averaged readings are used as the input for further antenna analyses using the commercial electromagnetic solver, CST Microwave Studio (MWS).

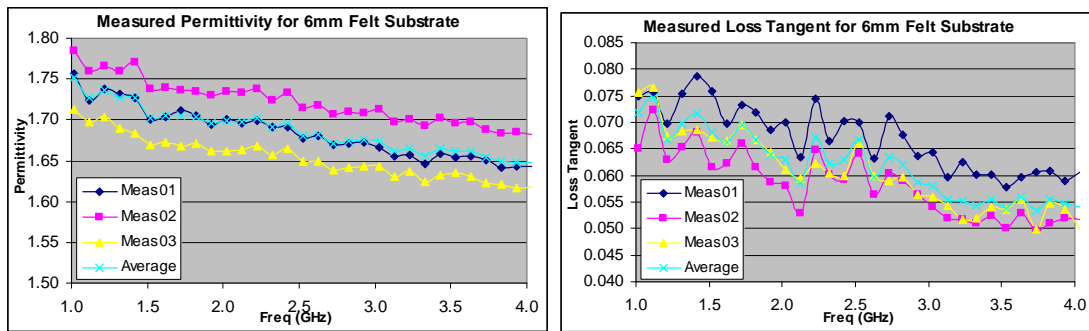


Fig. 1: Felt measurements using the HP85070E setup: (a) permittivity ( $\epsilon_r$ ), and (b) loss tangent ( $\tan\delta$ ).

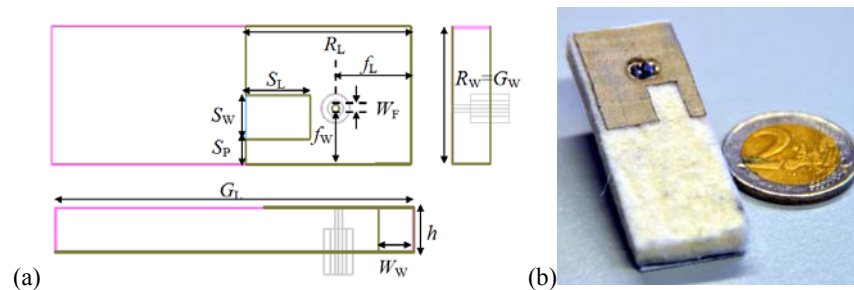
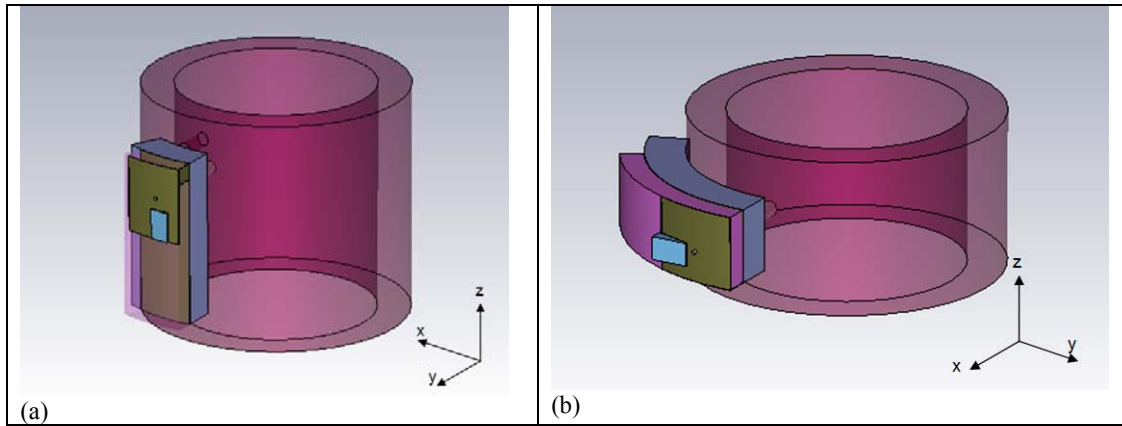


Fig. 2: (a) Dimensions of the analyzed PIFA structure, and (b) its fabricated prototype using ShieldIt.

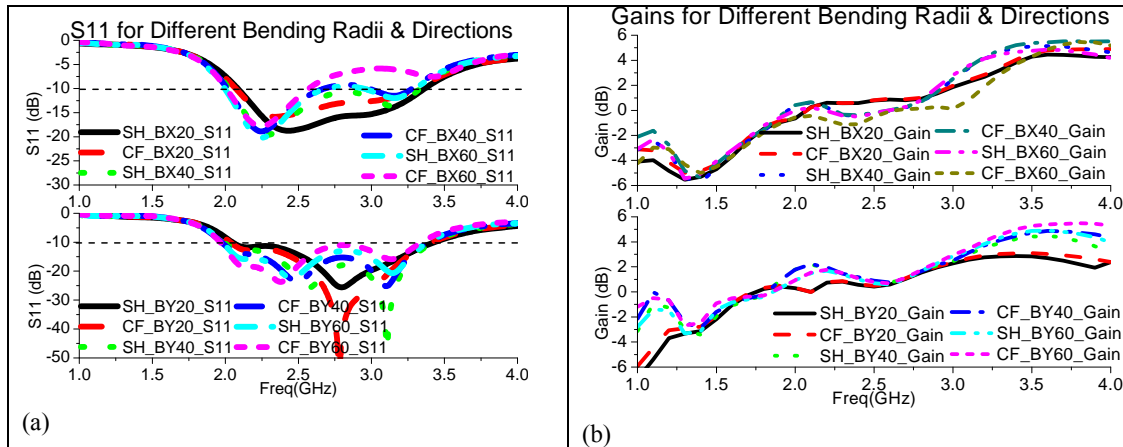
## RESULTS AND DISCUSSION

The antenna prototyped from the two different materials are curved over a cylinder, both in the x- and y-directions on three cylindrical sizes. The radii are  $r = 20, 40$  and  $60 \text{ mm}$ . The cylinders are defined similarly to

the electrical properties of an arm at 2.45 GHz, as recommended by European Committee for Electrotechnical Standardization (CENELEC), with  $\epsilon_r = 42$  and  $\sigma = 0.99$  S/m. As to cater for a practical distance between the antenna and the arm ( $d$ ), this initial distance is set at 10.3 mm (Soh *et al.*, 2012). These evaluation setups are shown in Fig. 3.



**Fig. 3:** Bent evaluation setups for bending at: (a) x-direction and (b) y-direction.



**Fig. 4:** Performance of bent antennas: (a) reflection coefficient ( $S_{11}$ ) and (b) gain.

As observed in Fig. 4(a), the reflection coefficient ( $S_{11}$ ) at the higher frequency deteriorated when the antenna is bent in the x-direction. For instance, bending using  $r = 60$  mm cylinder resulted in the decrease of the bandwidth, i.e. the range of antenna operation in terms of frequency. This bandwidth is defined at the -10 dB borders of the  $S_{11}$ , as marked using a horizontal line. Meanwhile, bending in the y-direction on the arm did not result in the significant bandwidth changes in general. However, it is noticed that the lower frequency suffered a degradation as the cylinder size is decreased. These observations are valid, considering the x-direction bending is performed on the antenna's radiating edge. Therefore, the mechanical changes in the y-direction is expected not to affect the surface current flowing on the radiator, which is the antenna's main resonance generating mechanism.

Looking at Fig. 4(b), bending at the x-direction using the largest  $r$  actually degraded the antenna gain at 2.45 GHz, similar to the previous observation. This is mainly due to the antenna's non-resonance at that frequency point. Gain variation when bent in the y-direction seems more intuitive, and provides a fair comparison for all bending directions and cylindrical sizes since all these configurations operated with satisfactory  $S_{11}$ 's. Bending using a reduced  $r$  resulted in the slight decrement of gain. From this investigation, it can be summarized that care must be taken when designing antenna for operation on-body, especially in bent configurations. Bending along the radiating edges will definitely result in performance degradation in terms of reflection coefficient. Moreover, it is also important that the antenna is operating with satisfactory reflection coefficient prior to comparison for other parameters, e.g., gain, efficiencies and radiation characteristics.

### **Conclusions:**

An investigation using a systematic method for evaluating wearable textile antennas when operating in bent conditions is proposed. Characterization using two similarly-shaped PIFA bent in two different orthogonal axes on three different cylindrical sizes: 20, 40 and 60 mm in radius. Bending in the axis along the antenna's radiating edge using the smallest sized cylinder, i.e. at the x-direction was found to be the worst performing configuration in terms of reflection coefficient, bandwidth and gain.

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