Development and Performance Analysis of Electro-Textile Antenna by using Copper-Covered Yarn for GPS Application

M.S.Amin Nordin[1], N.H.Abd Rahman[1,2], M.T.Ali[1] , A.A.Sharatol Ahmad Shah[1] , N.I.Zaidi[1] , M.R.Ahmad[3]

***Abstract*—The validation of the performance of electro-textile antenna, designed for on-body communication by using copper-covered yarn as a conductive fabric was presented in this paper. The antenna was designed by using a self-manufactured conductive fabric thus, the properties of the textile such as dielectric constant (εr), loss tangent (tan δ) and conductivity (σ) value shall be determined. The antenna was designed at 1.575 GHz based on the allocated spectrum for Global Positioning System (GPS) application. In this research, the performance of electro-textile antenna on customized copper-covered yarns material was designed and validated through electromagnetic simulation and fabrication. Good agreement between simulation and measurement was obtained, where both results give correct resonant frequency and good radiation pattern performance. The compositions of the customized copper-covered yarn as the conductive fabric were presented. The copper-covered yarn was formed by polyester threads (non-conductive) that were twisted with copper threads (conductive) with the ratio of 17.1% and 82.9% respectively. The results show that the resonant frequency, from the measured data of electro-textile antenna prototype has a return loss of -20.56 dB at 1.575GHz. Simulation and experimental results including radiation patterns in the E-plane and H-plane were presented and discussed. Moreover, the effect of bending on the electro-textile antenna have been simulated and measured to determine the degradation of the return loss, bandwidth and radiation pattern.**

***Index Terms*—measurement jig, electro-textile, GPS application, Electro-textile antenna, return loss, wearable application.**

I. INTRODUCTION

Construction and designing antenna for wearable wireless application is a challenging process due to various requirements such as conformability, flexibility and robustness. To confront these, textile antennas were recently introduced based on automated embroidery of conductive textile threads (e-threads) [1-2]. Researchers have shown that wearable antennas are often designed to be flexible and resilient [2]. Normally, wearable substrates such as cotton, polyester, nylon, polypropylene (PP) are used in designing the antenna element so that it could be integrated with wearable devices on human body [3].

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[1] Antenna Research Centre, Faculty of Electrical Engineering, Universiti Teknologi MARA, Shah Alam, Selangor, 40450, Malaysia. [2] Malaysia-Japan International Institute of Technology Universiti Teknologi Malaysia Jalan Sultan Yahya Petra, 54100 Kuala Lumpur, Malaysia. [3] Faculty of Applied Science, Universiti Teknologi MARA, Shah Alam, Selangor, 40450, Malaysia. Email: shakiraminnordin@gmail.com

As the development of various wearable devices such as smart glasses, watches and tracking devices increases, the wireless body area network (WBAN) technologies have received a great deal of attention, due to this wide range of potential applications, specifically for monitoring and communication such as for RFID and GPS system. In this research, the performance of electro-textile antenna for GPS tracking devices was studied.

Electro-textile also known as smart textiles are fabrics or garments that enable microwave radiator and electronic components to be embedded in them in many ways. There are many uncertainties in modelling electro-textile antenna in simulation. In order to model the embedded electro-textile antenna, the actual properties of electro-textile (as a radiating element) and the substrate (polyester fabric) shall be identified. This is because the optimum performance of the device is also greatly affected by the electrical properties of fabric that shall be measured accurately [4]. The air gaps between stacks of fabrics that consist of conductive threads and non-conductive threads may introduce some uncertainties in the modelling thus will also affect the actual resonant frequency of the RF devices [5]. The air gaps are expected to give some affects by lowering the permittivity of the whole electro-textile composition. Meanwhile, conventional wearable antenna design employs normal fabrics integrated with copper based radiating elements such as copper tape, copper foil or copper powder, which may lead to significant degradation of performance during measurement [6][7]. In this case, integration of copper as radiating element in non-conductive can be done in many ways such as manual sewing, ironing, gluing and etc. However, a huge disadvantage of the conventional design is that it can be easily detached from the fabric after being washed or worn for several times[8]. Due to this issue, the development of stable conductive textile (electro-textile) fabric, which is more structurally rigid and strong has been done. Moreover, it can be seen that the resonant frequency of the electronic devices during measurement will shift as compared to original simulation, due to surface discontinuities by low density embroidery and environmental effects [9]. Thus, it shows that selection of conductive elements and integration technique are among the factors contributing to the uncertainties in modeling the antenna or any RF wearable devices. In this research, a new conductive fabric was fabricated by using copper-covered yarns produced by weaving machine, thus the new material was studied and validated for antenna application through simulation and fabrication. On the other hand, the objective of this paper was to construct and design the electro-textile antenna on polyester fabric substrate by using self-manufactured copper-covered yarn as a radiating element operating at 1.575 GHz thus, the properties of the textile such as dielectric constant (Ɛr), loss tangent (tan δ) and conductivity (σ) value shall be determined, hence the performance of the antenna shall be discussed and verified. Fig. 1 shows the flow chart of this project.

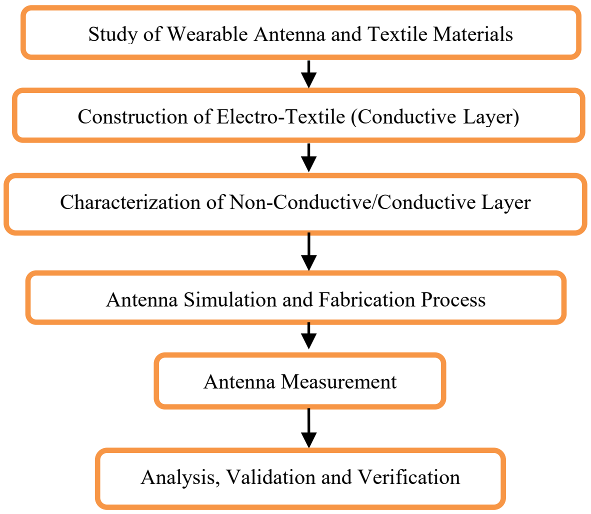


Fig. 1. Project flow chart

II. CONSTRUCTION OF ELECTRO-TEXTILE

The conductive textile is an electro-textile fabric which was made up from 0.14mm copper (conductive) thread and polyester (non-conductive) thread. In order to produce the electro-textile fabric, conductive thread must be constructed. It can be constructed by joining together both conductive threads and non-conductive threads. Hollow-spindle machine was used in the joining process of both threads as shown in Fig. 2. In this research, the machine performed the twisting method by using optimum setting, where the polyester and copper thread were joint side-by-side, as shown in Fig. 3. Polyester thread has been selected to be used in this fabrication of electro-textile antenna due to low dielectric permittivity, thus, is expected to give good performance in terms of reflection coefficient and impedance matching. Moreover, textile antenna was normally fabricated on flexible substrates such as, polyester thus making the structure suitable for wearable applications [3]. On the other hand, polyester is a common fabric that is often used in pants, shirts, and suits because of its wrinkle-resistant property and its ability to retain its shape. Polyester was often used in outerwear because of its high tenacity and durability. It is a strong fiber and consequently can withstand strong and repetitive movements [3].

Fig. 2. Hollow spindle machine YCHN-303 used in constructing conductive threads

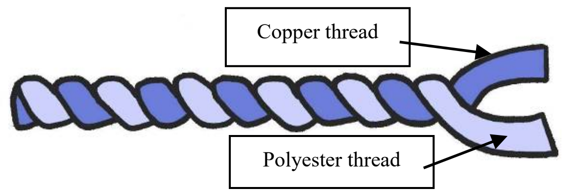


Fig. 3. Twisting technique used for copper-covered yarn construction

After the construction of conductive thread, the process continued with development of electro-textile fabric. In this research, plain weaving technique was implemented in producing the conductive fabric. In the weaving process, SULZER TEXTIL G6300 rapier weaving machine as shown in Fig. 4 was used. This machine was commonly used in industrial factory for heavy production of yarns, threads, fabrics or textiles.

Fig. 4. SULZER TEXTIL G6300 rapier weaving machine

By using the weaving machine, the electro-textile fabric which consists of 25 wefts/inch (horizontal) and 80 warps/inch (vertical). In this electro-textile fabric construction, conductive threads were used as the weft (horizontal direction), whilst non-conductive threads, polyester threads were in the warp direction (vertical) as shown in Fig. 5.

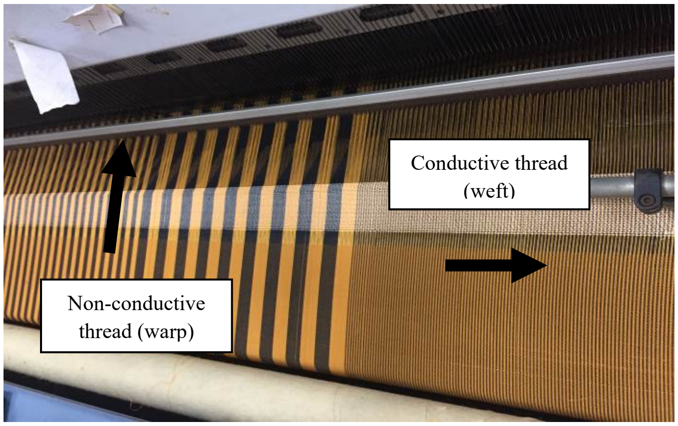


Fig. 5. Warp and weft of electro-textile fabric

The structure and composition of electro-textile have been studied and examined by following the American Society for Testing and Materials standard ASTM D3776 [10], which is a standard to determine the composition of fabric based on mechanical detachment process. A few samples of the conductive threads were tested and the mass per unit area of the fabric was calculated as per the ASTM D3776 standard. The percentage of the electro-textile was calculated from average total weight of the samples and was displayed in Table 1. Based on the calculation in Table 1, the average composition of conductive thread was tabulated.

TABLE 1
COMPOSITION OF CONDUCTIVE THREAD

No. sample	Copper + Polyester (g)	Copper (g)	Polyester (g)
1	0.373	0.318	0.064
2	0.386	0.302	0.062
3	0.381	0.316	0.06
4	0.375	0.321	0.06
5	0.38	0.314	0.064
Average (g)	**0.379**	**0.3142**	**0.062**
Composition (%)		**82.90**	**17.10**

III. DETERMINATION OF ELECTRICAL AND DIELECTRIC PROPERTIES FOR NON-CONDUCTIVE AND CONDUCTIVE LAYER

Parameters such as dielectric relative permittivity shall be determined through laboratory measurement prior to simulation to ensure accurate analysis. In this stage, measurement was conducted by using coaxial probe technique to determine the dielectric relative permittivity of the textile[11]. The dielectric permittivity (εr) was measured by contacting the probe to the flat surface of the textile. The reflected signal in terms of S-parameter was measured and converted to dielectric permittivity (εr). The measurement was performed by using PNA-L KEYSIGHT N5232A vector network analyzer. The holding jig has been developed in [12] to ensure the accuracy of the measurement as shown in Fig. 6. During measurement, the textile was placed in between the proposed jig to hold the sample to ensure consistent reading on the substrate surface.

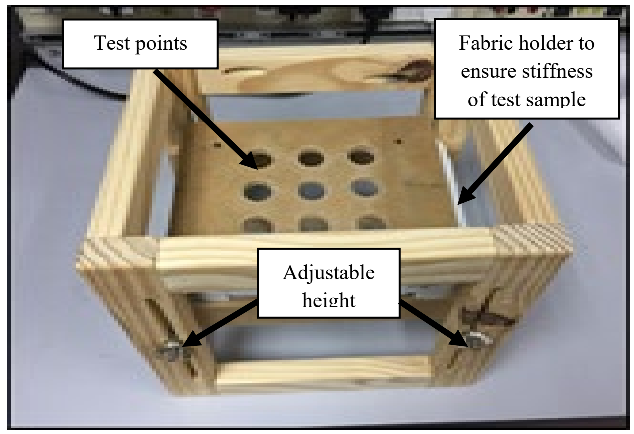


Fig. 6. Measurement tool (jig) for textile parametric measurement

Table 2 shows the readings of dielectric constant, εr and loss tangent, tan δ. Based on the data, average value of dielectric relative permittivity, εr and loss tangent, tan δ were taken for simulation.

TABLE 2
DATA OF DIELECTRIC RELATIVE PERMITTIVITY (εr) AND LOSS TANGENT (TAN δ) OF POLYESTER FABRIC

Test Points	Dielectric relative permittivity, (εr)	Loss tangent, (tan δ)
1	1.36	0.02
2	1.37	0.03
3	1.37	0.02
4	1.36	0.03
5	1.36	0.03
6	1.36	0.03
7	1.37	0.03
8	1.36	0.02
9	1.36	0.03
Average	**1.36**	**0.03**

On the other hand, one of the most important parameters such as conductivity of the radiating element (electro-textile) shall be determined, thus, this value was included in the simulation part as shown in Section IV. The measurement was conducted by using I-V probe method to determine the value of resistivity (ρ) of the radiating element (electro-textile)[13]. The conductivity (σ) was calculated by contacting the tip of two probes (like needles) to the flat surface of the material as shown in Fig. 8. During I-V measurement, a voltage, *V* was applied across the sample material, causing a current, *I* to flow through the sample. The amount of current, *I* that flows through the material was measured while the resistance, *R* of the material was identified, given by the equation (1)[13]:

$$R = V/I \tag{1}$$

Based on equation (1), the value of resistivity, ρ can be calculated from equation (2), where *L* is the length of the material tested and *A* is the cross sectional area of the sample [13],

$$\rho = RA/L \tag{2}$$

The value of the conductivity shall be determined by inversing the value of resistivity, ρ as shown in equation (3)[13],

$$\sigma = 1/\rho \tag{3}$$

Based on Fig. 7, it shows that the gradient of resistance, *R* was calculated by plotting the value of current, *I* against voltage, *V*. Furthermore, the parameter shown in Table 3 was considered when determining the value of conductivity, σ. Fig. 8 shows the I-V probe measurement setup in calculating the value of resistivity, ρ.

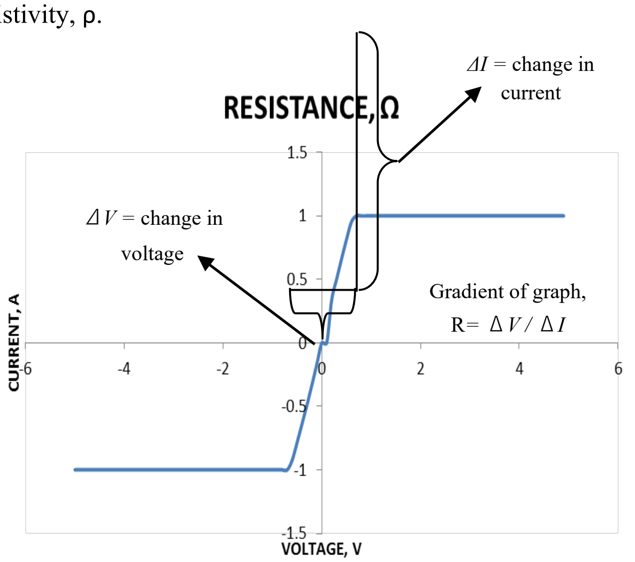


Fig. 7. Extracted resistance value from the I-V probe measurement tool

TABLE 3
PARAMETERS OF ELECTRO-TEXTILE TEST SAMPLE

Parameter	Numerical Values
Diameter of copper thread, (mm)	0.14
Cross-sectional area of sample, A (m^2)	1.97×10^{-6}
Width of sample, *w* (m)	0.0041
Height of sample, *t* (m)	0.00048
Surface resistivity of sample, (Ω/m^2)	3.306×10^{-5}
Value of conductivity, σ (S/m)	3.02×10^{4}

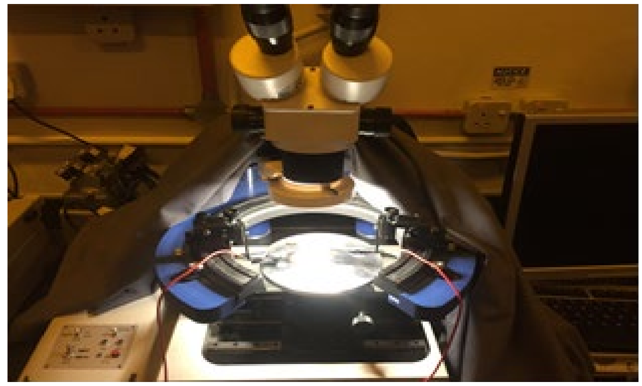


Fig. 8. Measurement setup to calculate conductivity of electro-textile sample based on I.V curve

IV. SIMULATION OF ELECTRO-TEXTILE ANTENNA

In this part, the development of the electro-textile antenna was studied and discussed through antenna structure simulation and fabrication. The proposed wearable GPS patch antenna was simulated by using 3D electromagnetic tool, CST Microwave Studio 2016. This design consists of a single radiating element with a full ground plane. The antenna was designed and fabricated by using polyester as a substrate and conductive textile as the radiating patch. The parameter shown in Table 4 was considered when designing and fabricating the antenna. Fig. 9 shows the antenna structure in CST STUDIO SUITE. The antenna was designed by using the actual values that had been obtained from earlier stage which include the dielectric permittivity value and loss tangent. Here, in this paper, due to the complexity and inhomogeneous structure of electro-textile, the modelling of textile antenna in simulation is simplified in terms of its bulk conductivity, σ. Thus, the conductive part is represented by a copper structure with reduced conductivity, σ (≈3.02×10^4 S/m). For non-conductive part, it was modeled in terms of its loss tangent, tan δ and Ɛr. The actual structure of the proposed textile antenna is shown in Fig. 10.

TABLE 4
PARAMETERS OF THE ELECTRO-TEXTILE ANTENNA

Parameter	Numerical Values
Operating frequency (GHz)	1.575
Dielectric relative permittivity, εr	1.36 (polyester)
Loss tangent, tan δ	0.03
Substrate thickness, *h* (mm)	1.4
Conductive layer thickness, t (mm)	0.48

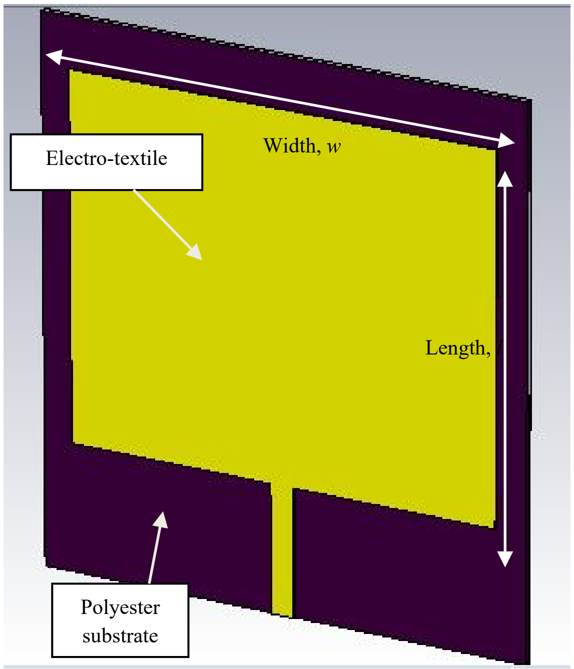


Fig. 9. Electro-textile antenna designed in CST solver

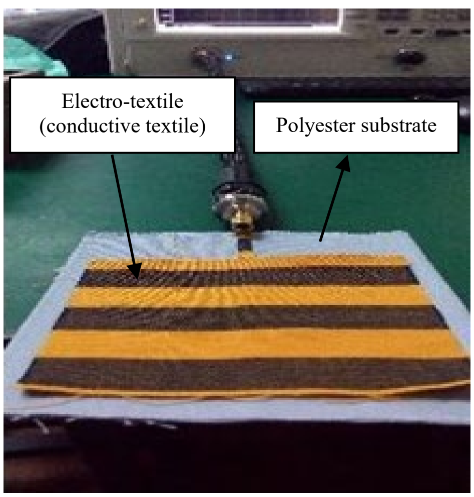


Fig. 10. Electro-textile antenna on polyester fabric

V. MEASUREMENT OF E-TEXTILE ANTENNA PERFORMANCE

Measurement of the reflection coefficient has been performed by using KEYSIGHT N5234A vector network analyzer (VNA). The results obtained in Fig. 11 shows a comparison between simulation data and experimental data for the resonant frequency and the reflection coefficient (S11) of electro-textile antenna. Simulation data were calculated using full-wave 3D electromagnetic solver. Based on the graph, it can be seen that a good reflection coefficient has been obtained. Good agreement was acquired between fabricated and simulated antenna, but with slightly higher return loss on the measured antenna. The resonant frequency from the measured data and the simulated data of electro-textile antenna prototype has a return loss of -20.56 dB and -16.57 dB at 1.575GHz, respectively.

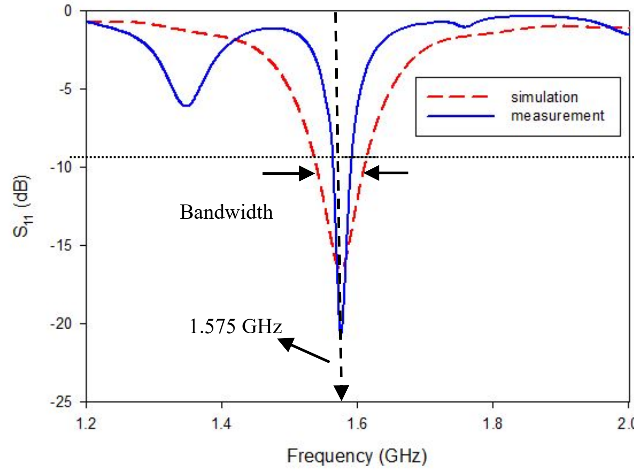


Fig.11. Comparison between simulation and experimental data obtained for the return loss of the electro-textile antenna

On the other hand, Table 5 shows the summary of antenna performance in comparison between simulation and measurement result, including bandwidth, gain, and VSWR. As shown in Table 5, the gain value was degrading in the measurement due to the high loss tangent, (tan δ ≈0.03) introduced by the non-conductive polyester layer, which can affect the value of antenna gain. Other than that, the conduction losses and surface resistivity, (≈3.306 x 10^{-5} Ω/m^2) of conductive layer also affected the conductivity performance of the electro-textile. Furthermore, there were probably some errors in fabrication and measurement process in cutting and attaching the feed probe. Despite that, the construction of electro-textile antenna by using copper-covered technique can still achieve good agreement between simulation and measurement.

TABLE 5
SUMMARY OF ANTENNA PERFORMANCE

	Simulation	**Measurement**
Return Loss, S_{11} (dB)	-16.57	-20.56
Bandwidth (GHz)	0.07	0.03
Gain (dB)	1.17	-9.26
VSWR	1.4	1.21

In order to assess the radiation performance of the electro-textile antenna prototype, radiation pattern measurement was conducted. The electro-textile antenna was measured in an anechoic chamber as shown in Fig. 12.

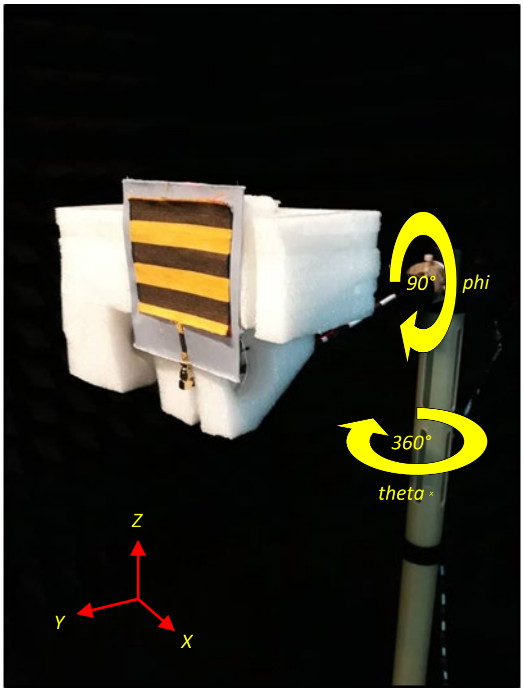
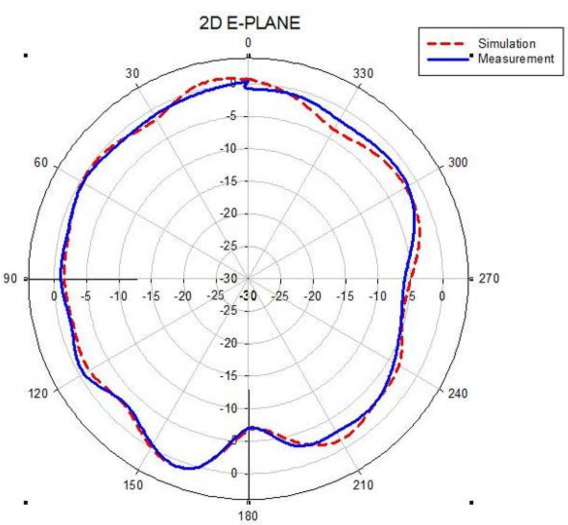
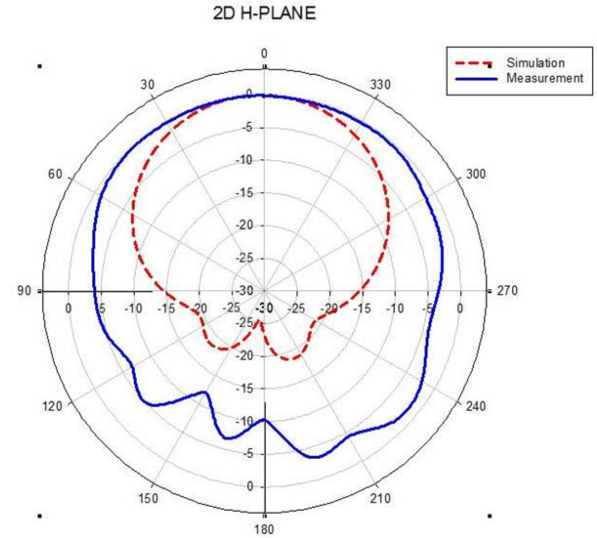


Fig. 12. Experimental setup of electro-textile antenna in an anechoic chamber for far-field radiation patterns

From Fig. 13, simulation and measured results were compared, normalized to the maximum gain of the antenna. It shows that 2D radiation pattern comparison was done through *yz* and *xz* plane. Based on these results, the measured radiation patterns agree very well with the simulated result with degradation in gain was observed.



(a)



(b)

Fig. 13. a) Simulated and measured radiation patterns of the electro-textile antenna at 1.575GHz for E-plane (*yz*-plane). b) Simulated and measured radiation patterns of the electro-textile antenna at 1.575GHz for H-plane (*xz*-plane)

VI. DEFORMATION CONDITION (BENT) ON ELECTRO-TEXTILE ANTENNA PERFORMANCE

In this section, the deformation condition such as bent condition for electro-textile antenna was discussed by showing the simulation result with 125° angle of radius which resembles the human shoulder. The curvature angle, (θ) of bent conditions for electro-textile antenna was determined by using equation (4). *S* represents the width of the antenna while *r* is the radius of an imaginary cylinder that been use in the simulation. The radius was set up to 46 mm as shown in figure 14 which represents curvature angles, θ of 125°.

$$S = r\theta \tag{4}$$

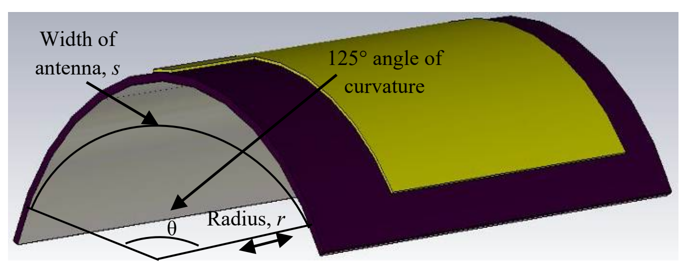


Fig. 14. Electro-textile antenna in bent condition at 125° angle of curvature in CST simulation

Based on the graph from figure 15, it can be seen that a good reflection coefficient has been obtained between simulation and measured result. Good agreement was acquired between both simulation and measurement result on bent condition. Based on simulation data, the resonant frequency on bent condition has shifted to the left with a return loss of -17.01 dB. However at 1.575 GHz, the antenna has an acceptable return loss of around -10 dB. Similarly, for the measured data, the resonant frequency has shifted to 1.565 GHz with a return loss of 22.66 dB and at 1.575 GHz, the return loss is -10.71dB. The graph showed that antenna with 125° bent had slightly shifted to the left and the return loss value was narrower and deeper compare to the simulation result. This may be due to the structure of the antenna that was not correctly imitated in the simulation process in order to bend in the form of human shoulder (125°) [14]. Moreover, there were probably some errors had occurred during measurement process. This result shown although the antenna is in a bent condition, the S11 performance has a good agreement. Table 7 shows summary of antenna performance in bent condition, while fig. 16 shows the actual electro-textile on bent condition on 125° foam that resembles human arm.

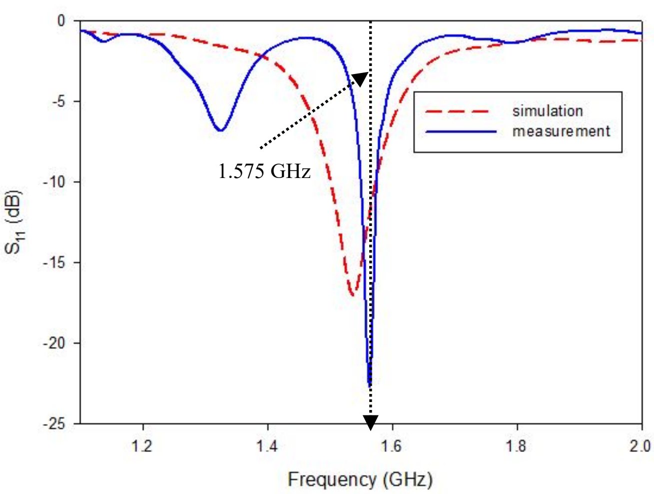


Fig.15. Comparison of S_{11} between simulation and experimental data obtained for bent condition

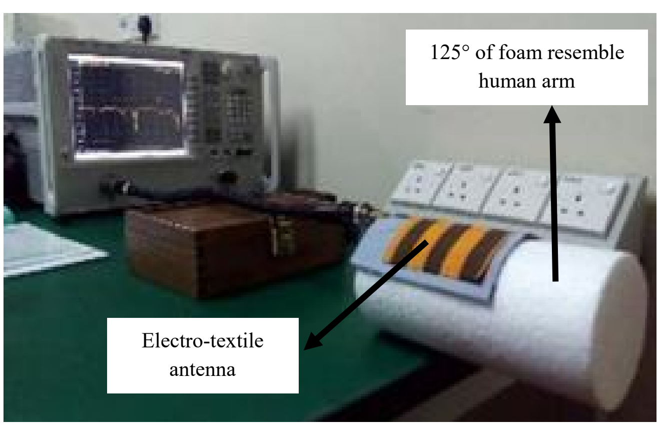
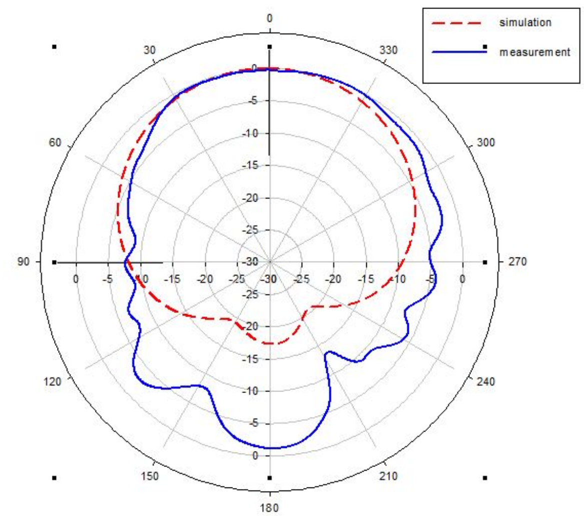


Fig. 16. Electro-textile antenna in bent condition on 125° foam

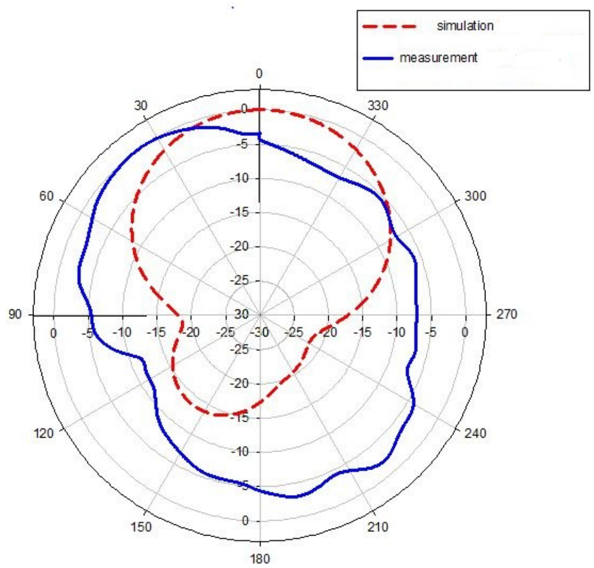
TABLE 7
SUMMARY OF ANTENNA PERFORMANCE ON BENT CONDITION

	Simulation	Measurement
Return loss, S_{11} (dB) @resonant frequency	-17.01 @ 1.539	-22.66 @ 1.565
Return loss, S_{11} (dB) @ 1.575 GHz	-9.85	-10.71
Bandwidth (GHz)	0.069	0.019
VSWR	2.94	2.12

From Fig. 17, it shows a comparison between simulation and measured result for bent electro-textile antenna which have been normalized to the maximum gain in an anechoic chamber. It shows the electro-textile antenna for far-field radiation pattern in *yz*-plane and *xz*-plane. Based on these results, the measured radiation patterns agree very well with the simulated result with only small degradation on the performance of electro-textile antenna.



(a)



(b)

Fig. 17. (a) Simulated and measured radiation patterns of the electro-textile antenna on bent condition for E-plane (yz-plane) (b) Simulated and measured radiation patterns of the electro-textile antenna on bent condition for H-plane (xz-plane)

VII. CONCLUSION

Results obtained in this designed electro-textile antenna show a good comparison between simulation data and experimental data for resonant frequency and reflection coefficient (S11). The measured result showed that, the antenna resonates at the correct frequency, with a good improvement on the return loss. Furthermore, the method of determining the actual value of dielectric permittivity, εr and loss tangent, tan δ of the polyester fabric was one of the most important parts in this work. The readings of εr and tan δ were calculated and verified several times to achieve optimum value, which can lead to good performance of the antenna. On the other hand, the bent performance of the antenna in the simulation and measurement part had shown a good agreement, which had a good performance in term of return loss, bandwidth and VSWR. Despite the structure limitation, this prototype antenna can still achieve good behavior, thus, the proof-of-concept of electro-textile antenna by using copper-covered yarn as a conductive radiating element was verified. This study is very useful for further analysis and design of wearable application.

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