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Textile Characterization for Wearable Antenna Application Using Transmission Line Method

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Abstract: This proposed work introduces the textile characterisation analysis based on the effects of fabric thickness and dielectric properties using the transmission line method for a wearable textile antenna. The return loss (S_{11}) and transmission loss (S_{21}) were analysed for denim, felt and Tencel in correlation with the conductivity properties using Computer Simulation Technology with Rogers 5880 as the reference sample. By varying the fabric thickness from 0.5 mm to 4 mm, the optimum thickness and type of fabric can be identified from the S_{11} and S_{21} parameters. In the transmission line simulation, the sample-under-test is a stripline with the conductivity values from 10^{-2} to 10^{8} S/m. Results are further plotted against the thicknesses to observe the behaviour of all three textiles samples. The results show that Felt substrate with 3 mm thickness give the best performance. The felt substrate demonstrates the best transmission performance judging from the lowest transmission loss due to the low tangent loss followed by Tencel and denim. For accuracy analysis, the actual and calculated conductivity were also presented to show the textiles performance at low and high region of conductivity. The study reveals the importance of choosing the correct substrate with suitable dielectric and electrical properties before being implemented into the antenna design for good efficiency.

Keywords: Transmission line, conductivity, textile antenna, transmission loss

1. Introduction

With the recent advancement in the Internet of Things (IoT), wearable antenna has gained much popularity in body-centric communication [1]. Originated from the idea of being part of the garment, wearable antenna delivered the features of lightweight, flexible, conforms to the body and most importantly easy to integrate into the clothing. The textile antenna provides the best antenna topology for antenna design to be embedded with regular fabric for wearable application [2]. Adopting the microstrip patch antenna concept, this fabric having dielectric properties is sandwiched between the conductive patch and conductive ground, which provides a potential for full wearable textile antenna implementation.

However, considering the wide range of textiles available for the antenna substrate application, the material selection is crucial due to the variations of thickness, h and relative permittivity, ε_r possessed for each material. The dielectric behaviour of textile depends on the properties of component fibres, the structure of fabrics and porosity level, which developed the electromagnetic properties of the materials [3]. Furthermore, due to the nature of being wearable, the effects of various mechanical deformations such as bending, crumpling and elongation will further reduce the

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functionality of the antenna. As such, the exact correlation of substrate thickness to S-parameter performance must be studied before the antenna is designed as it impacts the performance of bandwidth and antenna efficiency [4].

Despite the abundance of research in wearable textile antennas, little information can be found on textile characterisation, especially on the effects of fabric thickness and conductivity performance towards the transmission behaviour. This is crucial when multiple fabrics are considered; given a different thickness for each. It is imperative to ensure the optimized fabric thickness and the correct conductivity value of the radiating element are used since an incorrect conductivity value will affect the impedance and radiation properties of the antenna [5]. Several studies are shown in [4], [6] and [7] on the performance comparison using different antenna substrates such as cotton, polyester, cordura, lycra, fleece and felt material. However, the findings only demonstrated the antenna design using the originally manufactured thickness without considering the optimised substrate thickness of the relevant material. Meanwhile, the studies in [5] and [8] show the research were conducted comprehensively using transmission line measurement on various electro-textile performance using electromagnetic simulation, measurement, and analysis. Nevertheless, consideration has not been given to the optimisation of substrate thickness. In addition, although the measurement of conductivity for textile-based materials have been done previously via current-voltage (I-V) curve and two-port transmission line technique, the applicability of the methods for other textile samples have not been demonstrated [9].

This paper focuses on a structured textile characterisation method for felt, denim and Tencel for various thicknesses and conductivity values. Using the transmission line method analysis to compare the scattering parameters of S_{11} and S_{21}, the best thickness of textile performance will be further simulated with respect to a range of conductivity values to observe the correlation and to further analyze the textile behaviour.

2. Materials and Method

The process of the textile characterisation can be summarized as shown in Fig. 1. The details of the material used, and the conductive elements are explained.

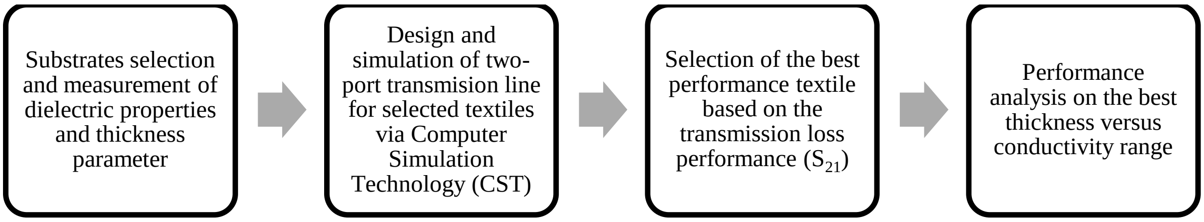


Fig. 1 - Textile characterisation steps

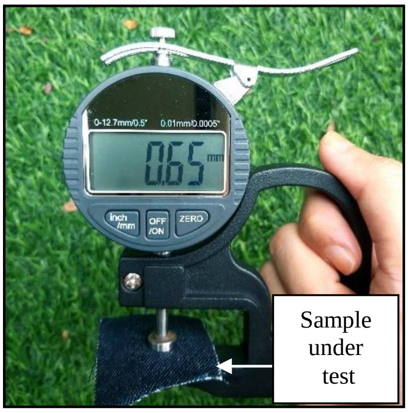
2.1 Substrate Selection and Parameter Measurement

The substrate material selection is crucial to meet the required bandwidth and good antenna efficiency. Therefore, felt, denim and Tencel textile material were selected and analysed based on their excellent performance and popularity in the application of wearable textile antenna. Meanwhile, Rogers 5880 is used as a control sample to ensure the textile characterization method is performed correctly.

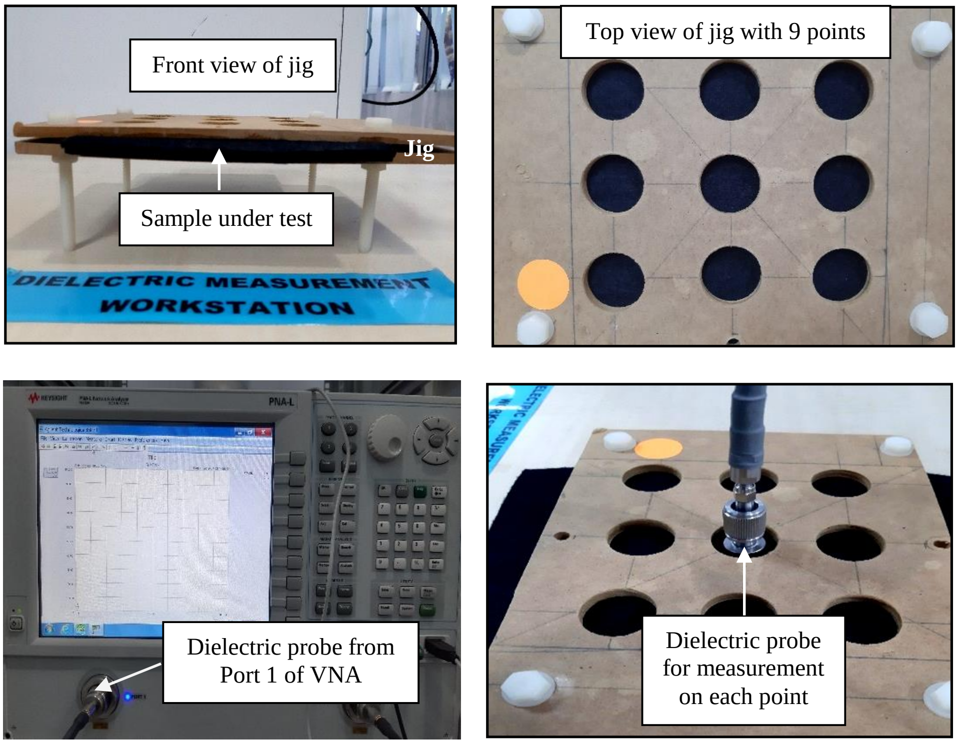
Firstly, textile characterisation (as seen in Fig. 2**)** is performed for all three textiles to measure the dielectric constant (ε_r), loss tangent ($tan\ \delta$) and thickness (h) of each textile. For this process, the equipment needed are the dielectric probe, digital gauge meter, Keysight 85070 Vector Network Analyzer (VNA) and the holding jig which is used to sustain the textile firmness for constant flat surface measurement. To ensure the consistency and accuracy of result, the probe is placed on each 9 points made on the jig for every textile and subsequently the results are average out. To calculate ε_r, the real part of dielectric value, ε' and the imaginary part namely ε'' are obtained from the display of VNA which has been setup earlier with the required operational frequency of 1.575 GHz. The complex relative permittivity, ε_r and loss tangent of $tan\ \delta$ can be determined from the equations below:

$$\varepsilon_r = \varepsilon' + j\varepsilon'' \qquad (1)$$

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} \qquad (2)$$



(a)



(b)

Fig. 2: Textile characterisation process (a) thickness measurement (b) dielectric measurement

Based on the textile characterisation performed above, the result for the selected substrate used in this study is shown in Table 1 below.

Table 1 - Parameter of selected substrates

Substrate	Relative Permittivity ($\mathcal{E}_r$)	Loss Tangent ($tan\ \delta$)	Thickness, h (mm)
Denim	1.1113	0.0669	0.65
Tencel	1.2215	0.0410	0.45
Felt	1.0980	0.0395	3.00
Rogers 5880	2.2	0.0009	0.508

In addition, the selection of substrate material primarily depends on the placement and utilization of the antenna. As for a wearable antenna, textile selection must consider the body vicinity application which may alter the original antenna structure. Therefore, identifying the deployment location will be an appropriate measure to avoid performance degradation during application.

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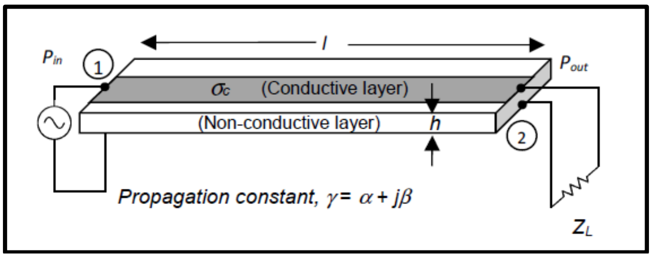
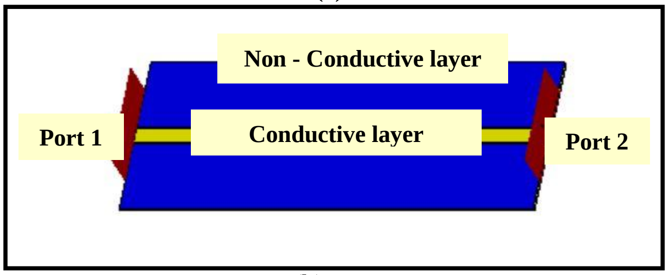
2.2 Transmission Line Method and Design Implementation

The conductive layer of pure copper with the conductivity, σ of 5.86 x 10^7 S/m and sheet thickness of 0.035 mm is used in this study to develop the two-port transmission line model simulation When a new material is proposed or developed as the non-conductive medium, a two-port transmission line method can be used to determine its conductivity based on the measurement of scattering parameters, S_{21} as seen in Fig. 2(a) and Fig. 2(b) below.



(a)



(b)

Fig. 3 - (a) Two-port transmission line model (b) Two-port transmission line model design in CST

Fig. 3(a) shows the fundamental strip line equivalent model that consists of inductance L (H/m), resistance R (Ω/m), capacitance C (F/m) and conductance G (S/m) which derived the propagation constant of γ based on equation (1):

$$\gamma = \sqrt{(R + j\omega L)(G + j\omega C)} \quad (3)$$

In this equivalent model, the conductivity parameter of sigma, σ can be developed from the scattering parameter measurement which represents the transmission loss of the line sample, derived based on equation (2) where ε is the material's relative permittivity, μ is the material's permeability, h is the substrate's thickness and α is the attenuation constant through the S_{21} measurement:

$$\sigma_{calc} = \frac{\omega^3 \varepsilon^2 \mu}{\alpha^2 h^2 (2h^2 + 2\omega^2 \varepsilon\mu)} \quad (4)$$

This transmission line model is design using a conductive layer at the top and a non-conductive layer (i.e., substrate) at the bottom on the two-port simulation line structure (Port 1 and Port 2) as seen in Fig. 3(b). Based on this approach, the impedance measurement is set at 50 Ω by optimising the width of each substrate for each thickness which varies from 0.5 mm to 4.0 mm in 0.5 mm steps (practical wearable application). As seen in Fig. 4, the simulated assessment on the return loss and transmission loss parameters are performed for all fabric thicknesses of each material at 1.575 GHz for Global Positioning System (GPS) application. The result of the best fabric thickness is used further to observe the conductivity performance among all fabrics. A plot to determine the best fabric that demonstrates the minimum transmission loss is plotted.

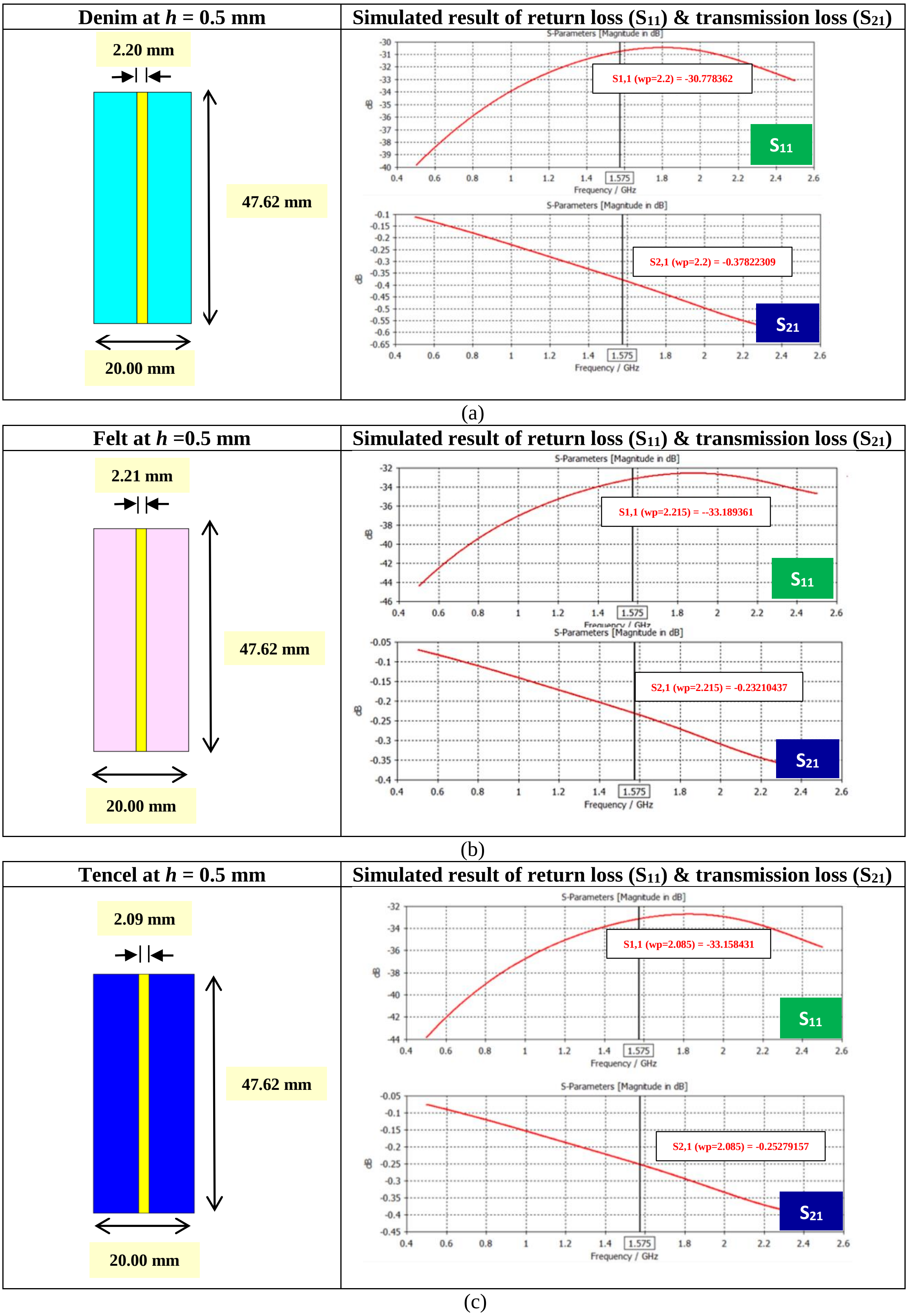


Fig. 4 - Two-port transmission line simulation for the measurement of return loss (S_{11}) and transmission loss (S_{12}) of (a) denim (b) felt and (c) Tencel at *h* = 0.5 mm. The simulations are further iterated for *h* = 1.0 mm, 1.5 mm, 2.0 mm, 2.5 mm, 3.0 mm, 3.5 mm and 4.0 mm

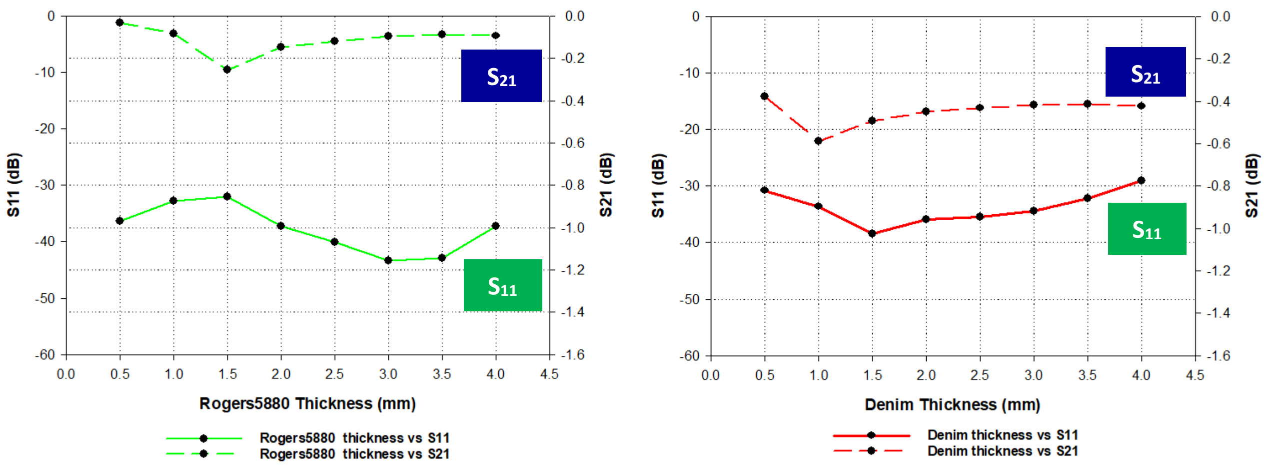
3. Results and Discussion

The result in Table 2 presents the simulated performance of two-port transmission line showing the return loss and transmission loss for fabric thickness of denim, felt and Tencel at 0.5 mm, 1.0 mm, 1.5 mm, 2.0 mm, 2.5 mm, 3.0 mm, 3.5 mm, and 4.0 mm.

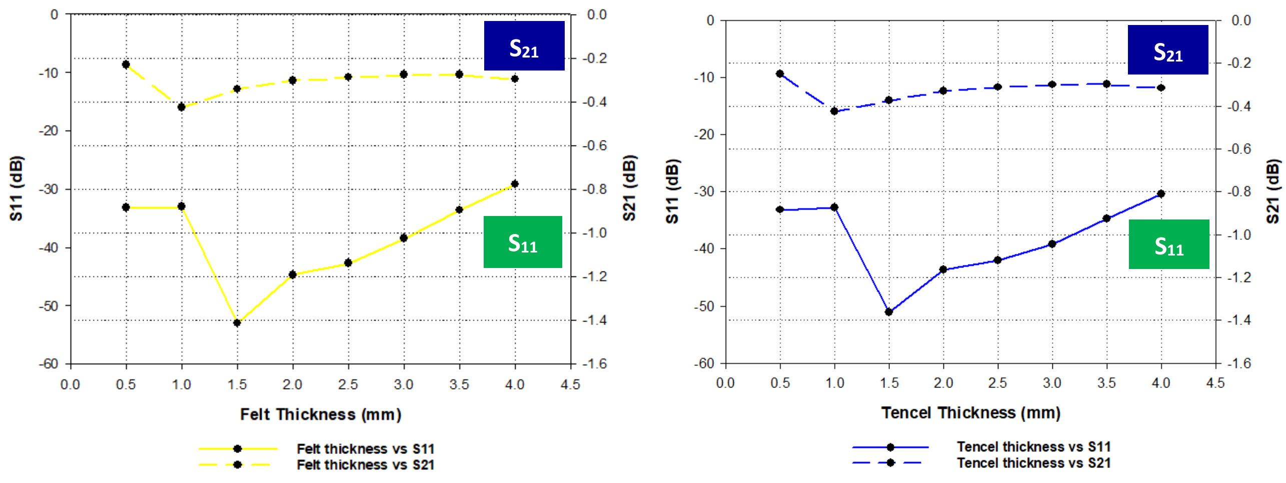
Table 2 - Fabric thickness performance on return loss (S_{11}) and transmission loss (S_{21}) parameter

Thickness (mm)	Parameter	Simulated Fabric Performance (dB)		
		Denim	Felt	Tencel
0.5	S_{11}	-30.78	-33.19	-33.16
	S_{21}	-0.3782	-0.2321	-0.2528
1.0	S_{11}	-33.61	-33.03	-32.82
	S_{21}	-0.5889	-0.4261	-0.4264
1.5	S_{11}	-38.49	-53.03	-51.10
	S_{21}	-0.4924	-0.3432	-0.3762
2.0	S_{11}	-35.89	-44.74	-43.67
	S_{21}	-0.4507	-0.3034	-0.3297
2.5	S_{11}	-35.44	-42.75	-42.07
	S_{21}	-0.4317	-0.2891	-0.3127
3.0	S_{11}	-34.41	-38.50	-39.20
	S_{21}	-0.4188	-0.2784	-0.3010
3.5	S_{11}	-32.25	-33.63	-34.78
	S_{21}	-0.4150	-0.2780	-0.2993
4.0	S_{11}	-29.12	-29.20	-30.39
	S_{21}	-0.4246	-0.2975	-0.3170

Fig. 5 shows the plot of S_{11} and S_{21} performance for fabric of denim, felt and Tencel with Rogers 5880 as the control sample. The trends demonstrated for all are consistent with the reference substrate of Rogers 5880. These plots are further merged to exhibit an overall comparison on all fabrics thickness performance.



(a) (b)



(c) (d)

Fig. 5 - S_{11} and S_{21} performance plots for fabric of (a) Rogers 5880, (b) denim, (c) felt and (d) Tencel

Meanwhile, Fig. 6 shows the merged plot of S_{11} and S_{21} for denim, felt, Tencel and Rogers 5880 against the range of fabric thicknesses. From the observation, the best thickness, *h* of all fabrics is identified at 3 mm for S_{11} & S_{21} performance.

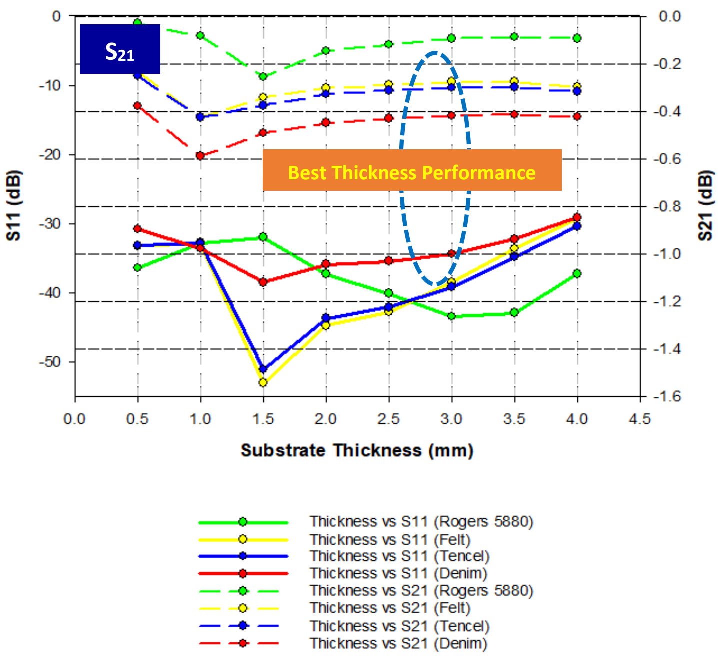


Fig. 6 - Merged plot of S11 and S21 performance for denim, felt, Tencel and Rogers 5880

Referring to Fig. 7, as the magnitude of σ increased, the S_{21} parameter is approaching 0 dB (loss-free) and degraded significantly as the σ value is decreasing. This pattern indicates a consistent and good performance for all substrates in comparison to the result shown for Rogers 5880. In addition, when the parameter of S_{21} is approaching the loss-free level, it explained that a gradual reduction of transmission loss has taken place. A reduction in transmission loss of the antenna will render a better radiated power and subsequently improved the antenna efficiency.

The same trend is also observed in the S_{11} parameter whereby the higher the magnitude of σ, the higher the return loss value is achieved. A close observation from the same figure shows that the acceptable return loss of -10 dB for all substrates is seen from the conductivity of 10^{-1} S/m and above. Based on this scenario, these three substrates have the potential to be implemented for textile antenna. This is due to the fact that most of the electro-textiles (e-textiles) such as Shieldit Super, Zelt, or Pure Copper Taffeta fabric [10] that is commonly used as a conductive layer in wearable application have the conductivity of 10^{5} S/m at minimal. Therefore, based on this observation, it is clear that the antenna will attain an optimal performance when it is designed on a suitable substrate that synergized well with the conductive layer at the optimal magnitude. This statement is supported by a study done in [11] showing the effects of radiation efficiency by the increased of conductivity level in logarithmic manner.

Taking the graphical observation into account, a reduced scale version shown in Fig. 8 is plotted to clearly demonstrate the performance of fabrics distinctively. It is observed from this plot that felt textile possessed the best fabric performance of all after Rogers 5880, followed by Tencel and lastly denim. As the best fabric thickness is identified at 3 mm, this situation provides an advantage for felt fabrication as it comes in as 3 mm under the manufactured thickness. Therefore, the additional layer which will further complicate the fabrication process is not required due to the fulfilment to the benchmark set for the best substrate thickness. From this figure, it can also be observed that by applying the conductive layer with σ of at least 10^5 S/m, the transmission loss can be reduced by 0.5 dB for denim while more than 0.4 dB is depicted for felt and Tencel.

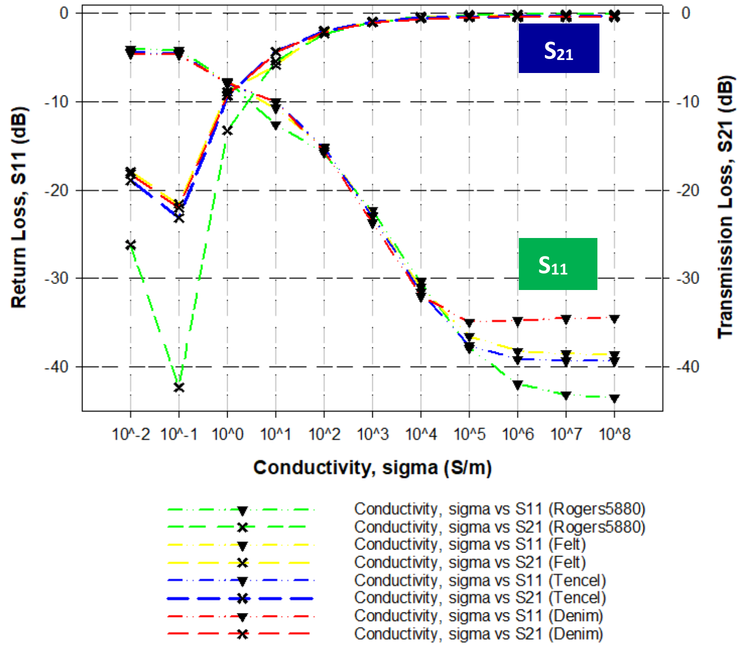


Fig. 7 - S_{11} and S_{21} versus conductivity plot

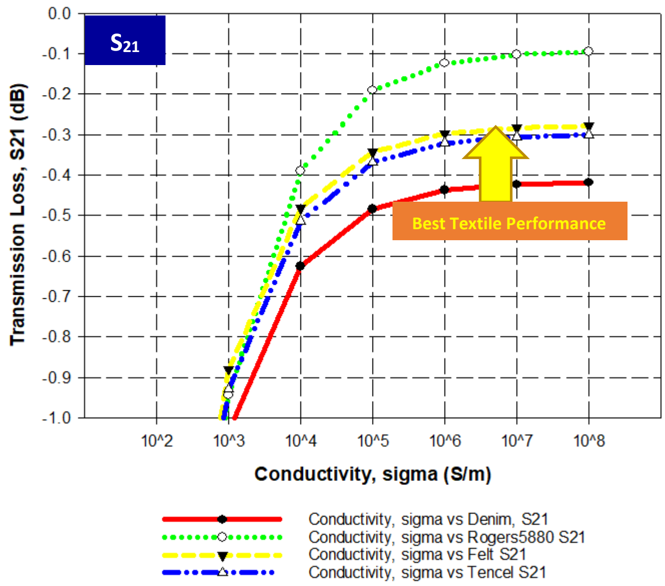


Fig. 8 - Refinement plot of S_{21} versus conductivity plot

Based on the simulated results of S_{21}, the conductivity value is re-calculated using equation (4) to validate the accuracy of the proposed two-port transmission line method for fabric characterisation. Fig. 9 illustrates the actual and calculated conductivity of Rogers 5880, felt, Tencel and denim for conductivity values from $\sigma = 10^{-2}$ (S/m) to $\sigma = 10^9$ (S/m). From observation, the trend of calculated conductivity for fabric samples matched the conductivity of the lossless control sample i.e., Rogers 5880. It can be seen from the graph that the trend of Rogers 5880 has small deviation as compared to the trend shown in reference. This resulted from the influence of low loss tangent (0.0009) in Rogers 5880 which does not affect the signal transmission from port 1 to 2 unlike other fabrics sample which demonstrate significant value of loss tangent and subsequently generate a higher transmission loss. In comparison to the actual conductivity, the fabric samples show a similar trend with the reference until it reaches $\sigma = 10^6$ (S/m) and subsequently shows a stagnant inclination at higher conductivity region, which agrees very well with the analysis done in [8]. This due to a circumstance whereby; when σ is low, the resistance of conductive layer is high due to the effective resistance are derived from both conductive and substrate layer. In contrast, when σ is in the high region, the resistance magnitude for conductive layer is low as the significant resistance is only derived from the substrate layer. In conclusion, the proposed technique of two-port transmission line is suitable to be used for multiple fabric characterisation of textile antenna having low-to-medium conductivity. Hence, the implementation of fully textile antenna is viable as most of the available conductive textile material demonstrates the conductivity region of 10^5 S/m.

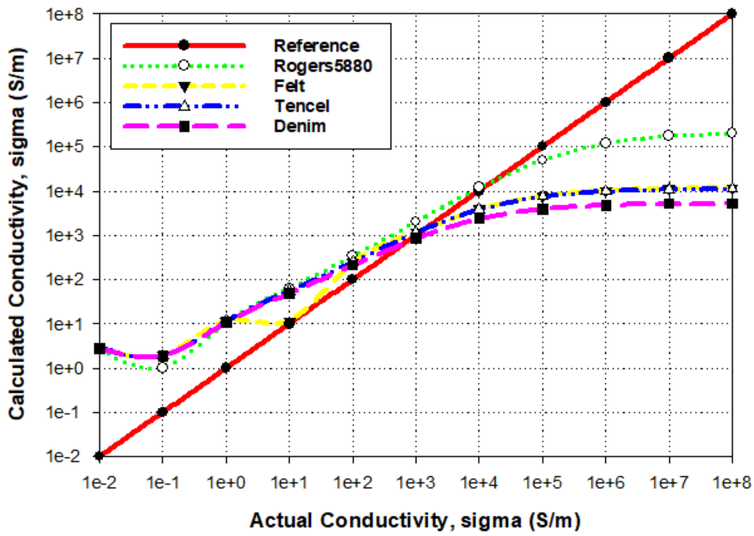


Fig. 9 - Actual and calculated values of conductivity of Rogers 5880, felt, Tencel and denim

4. Conclusion

The effect of substrate thickness in regard to return loss S_{11}, transmission loss S_{21} and conductivity, σ of the wearable antenna design is studied in this paper. By using the transmission line method, three types of textiles namely denim, felt and Tencel were chosen for data simulation to demonstrate their performance at a practical thickness range for wearable application that is from 0.5 mm to 4.0 mm. From the simulated result, 3 mm thickness has shown the best performance result for S_{11} and S_{21}. Further analyses were carried out on the correlation between best thickness of all textiles versus radiating element conductivity ranging from 10^{-2} to 10^8 S/m. Simulated result shows that felt is the best material among all which made it a potential substrate candidate for the implementation in wearable textile antenna design. As an overall conclusion, it can be concluded that with an optimise selection of fabric thickness, the textile antenna performance can be enhanced by observing the good region of conductivity that synergised well with the chosen substrate material for wearable implementation.

Acknowledgments

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