IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received November 29, 2019, accepted December 8, 2019, date of publication December 13, 2019, date of current version December 23, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2959323

Parameters and Factors Affecting Reliability and Accuracy in Measuring Electro-Textile Conductivity Using Transmission Line Method

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This work was supported in part by the Universiti Teknologi Malaysia through the Professional Development Research University under Grant PY/2017/02232, and in part by the Malaysia Ministry of Education through the Fundamental Research Grant Scheme under Grant FRGS/1/2018/TK04/UITM/02/25.

ABSTRACT Designing and analyzing a textile-based antenna requires precise representation of the material in electromagnetic solver. Due to its complex and inhomogeneous thread structure, the exact cross-sectional structure of the conductive textile segment was very difficult to be modeled, and thus the representation was simplified to bulk conductivity characteristic. Incorrect conductivity value will cause significant deterioration in antenna impedance and radiation performance. Therefore, the conductivity for an electro-textile material used for a wearable antenna design shall be accurately measured. Previously, a transmission line technique was proposed, however, the reliability of the method in correlation to operational frequency and other test conditions were not clarified. Furthermore, the practicality of that technique and the proposed equation for an actual electro-textile sample was not demonstrated. In this paper, the validity of the method over wide range of frequencies from 500 MHz to 5GHz was validated through a more practical and simplified equation derived from the two-port transmission line concept. The accuracy of the proposed technique and equation was demonstrated through comprehensive electromagnetic simulation, measurement and analysis. For validation, strip line samples that consist of an off-the shelf conductive fabric called SHIELDIT were fabricated on two low-loss substrates with slightly different dielectric characteristics; Rogers RO5880 and Chukoh CGP-500A at 500 MHz, 2.45 GHz, 3.5 GHz and 5 GHz. For comparison, the applicability of the technique for other samples such as pure laminated copper and self-manufactured electro-textile was also tested as reference. Through analysis, the reliability of the technique for different material's loss characteristics, material's conductivity range and operational frequencies was compared through simulation and measurement. The threshold level for conductivity of the test sample was found to be less than 10^7 S/m, which has been validated from 0.5 GHz until up to 5 GHz as shown by the measurement results in this paper.

INDEX TERMS Conductive textile, electro-textile, textile antenna, wearable technology.

I. INTRODUCTION

Wireless body sensor systems are highly in demand to support many Internet of Things (IoT) applications [1]–[4]. In IoT and wireless sensor network application, wearable antennas are one of the main components that are incorporated in the system to allow wireless data transmission, precise object tracking, wireless sensor integration and many more. There are many types of wearable antennas, including the textile-based antennas that utilize conductive fabrics or electro-textiles (e-textiles) as the radiating elements. E-textiles are made from the integration of copper threads and non-conductive threads to form a conductive fabric that has significant value of conductivity. Although the e-textiles offer flexibility and many interesting features to antenna designer, the textile based antennas also have many design issues related to the conductivity characteristics.

The associate editor coordinating the review of this manuscript and approving it for publication was Shah Nawaz Burokur.

First, in order to design a wearable textile antenna, the textile structure has to be modelled and simulated precisely inside the electromagnetic solver. Due to the inhomogeneous thread structure, it has been difficult to accurately model its physical structure thus, the representation of the electro-textile (e-textile) in antenna design tool was simplified in term of its bulk conductivity, σ. The σ of an e-textile shall be determined accurately to ensure correct antenna design, thus a suitable method to measure the σ, especially of a material intended for radio-frequency application shall be identified.

The second issue is, due to the nature of the textile-based antennas in practical wearable application, the antenna performance is also subjected to various conditions such as bending, high moisture or washing, and on-body effects. Washing a textile-based antenna for many times may cause the antenna performance to degrade, mainly due to the decrease in fabric's conductivity [5]–[7]. The correlation between the material's conductivity and its effects to radiation efficiency have been demonstrated in [8] and [9]. It was concluded that conductivity, σ is the key factor in determining a textile antenna's performance, where an antenna with lower σ will have lower efficiency and gain. Various conditions have been validated in [10] where a detailed investigation was performed through a transmission line measurement. The paper shows that the changes in surface resistance, R_s has significant effects on the scattering parameter, S_{21}. However, in the work, the exact relation between the σ and the S_{21} was not shown, and the σ was determined based on the R_s through a DC measurement setup, which was not frequency dependent.

Similarly in [8], [11], the σ parameter was measured based on the current flow and the voltage source applied to it and not related to its operational frequency, thus this method was seen as less accurate for characterizing materials for microwave application as the dependability on the frequency and skin depth were not taken into consideration. In order to solve this issue, two-port transmission line (TL) technique is chosen. Transmission line has been widely used in the development of antennas and other microwave devices because it is known as the most fundamental impedance-matching circuit for microwave power transmission [12]–[14]. In the context of material characterization for e-textiles, the TL technique was demonstrated in [15] as the most promising technique to measure the σ, but the analysis and experimental works shown were based on the low frequency operation (160MHz), which was insufficient to be adopted for GHz operation. The calculation was based on the assumption that the material was lossless (ideal), and that hypothesis was embedded in the formulation to extract bulk resistance, R from the S_{21} data. However, the correlation of material's loss properties to the reliability of the technique was not investigated. Furthermore, the consistency of the technique for other ranges of operational frequency was not analyzed.

In this paper, a more simplified and straight forward expression in determining the bulk conductivity, σ of the material through the two-port transmission line technique is proposed. Through simplification process and valid assumptions, three forms of expressions are deduced in this article. The accuracy, validity and reliability of all three equations are compared through simulations and measurements. Based on the equivalent model of transmission line, the σ expression is derived through the measured scattering parameter, which represents the transmission loss of the line sample. Theoretically based on all expressions, the σ also correlates with the operational frequency f_o, thus, in this paper, the changes of σ with respect to f_o and $tan\delta$ are clarified. Here, detailed analysis on the reliability of the technique for wider ranges of operational frequencies from 500 MHz to 5GHz is presented. Comparative study is also made between different cases of loss characteristics, and different equations. Simulation data showing ideal (lossless) material behavior is also shown as a reference.

Designing antennas that are made of fabric-based materials requires accurate computer modelling, and thus the unique electrical, physical and material properties shall be considered. Through the detailed analysis and validation works performed in this paper, the proposed method is verified to be able to improve the accuracy of the non-homogenous electro-textile antenna structures intended for wearable microwave application. This is due to the conductive losses and frequency factor that have been taken into consideration in modelling the electrical characteristics of the antenna structure during the designing process.

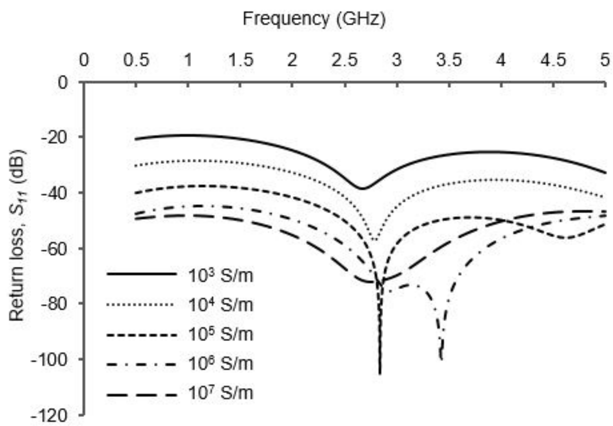


FIGURE 1. Simulated return loss, S_{11} (dB) of electro-textiles in the form of transmission line structure for various σ from 10^3 to 10^7 S/m.

II. OVERVIEW OF TECHNIQUE AND TEST SAMPLES

Figure 1 and 2 show the correlation of σ to the scattering parameters S_{11} and S_{21}, obtained through the simulation of two-port transmission line structure. The transmission line model which consists of a conductor layer at the top and a low-loss substrate at the bottom, with its key parameters are illustrated in Figure 3. Based on figure 2, for a sample with high σ (10^6 S/m or higher), the S_{21} performance from 500MHz to 5GHz is very consistent and the value is close to 0 dB. However, when the σ is lower than 10^6 S/m, the S_{21} is degraded significantly. This situation shows a very clear correlation between the σ to the transmission line performance

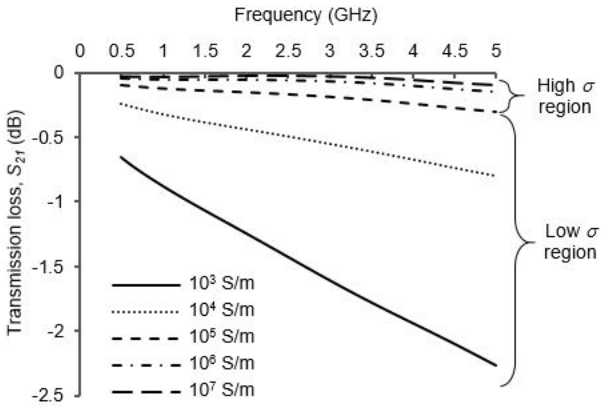


FIGURE 2. Simulated transmission loss, S_{21} (dB) of electro-textiles in the form of transmission line structure for various σ. High σ region is represented by $\sigma = 10^5$ to 10^7 S/m, while the low σ region is for $\sigma < 10^5$ S/m.

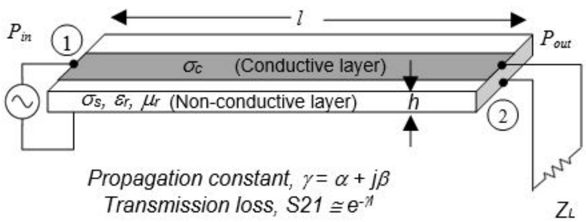


FIGURE 3. Transmission line model and important parameters such as conductivity (σ_s and σ_c), dielectric constant (ε_r), dielectric relative permeability (μ_r) and load impedance (Z_L).

and also to the wearable antenna that are normally designed by using a textile material with lower conductivity than a pure copper.

As shown by figure 3, during operation, the transmission line of length l is excited at port 1 and a 50Ω termination load is connected at port 2. The transmission line can be represented by an equivalent circuit as shown in Figure 4, where R, L, G and C represent the resistance per unit length (Ω/m), inductance per unit length (H/m), conductance per unit length (S/m) and capacitance per unit length (F/m) respectively. Two fundamental parameters known as propagation constant γ and characteristic impedance Z_o are identified, and the relations to attenuation constant α, phase propagation constant β, resistance R_o and reactance X_o are clarified by established equations as shown by equation (1) and (2)[16]:

$$\gamma = \alpha + j\beta \tag{1}$$

$$Z_o = R_o + jX_o \tag{2}$$

The γ represents the general transmission line characteristics through the R, L, G and C parameters as shown in equation (3). It is also part of the exponential term for scattering parameter such that $S_{21} = e^{-\gamma l}$. Thus, by taking into account the absolute value, the α from equation (1) can be theoretically expressed by equation (4).

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

$$\alpha_{sim} = \frac{-S_{21}[dB]}{20l \log_{10} e} \tag{4}$$

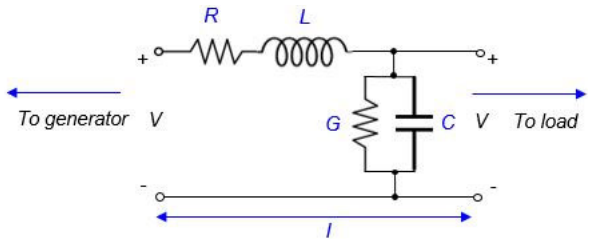


FIGURE 4. Equivalent circuit model of a two-port transmission line of length l [16].

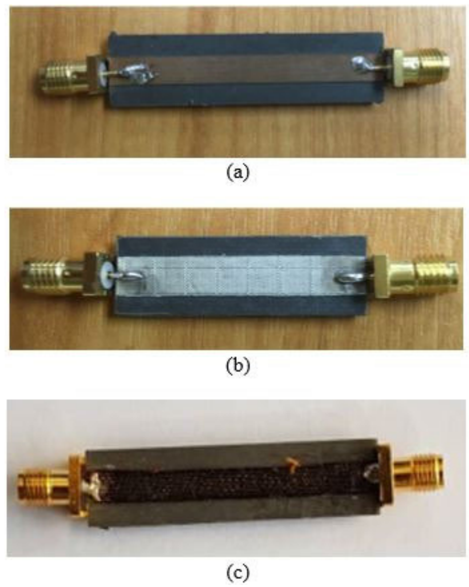


FIGURE 5. Three fabric samples fabricated on low-loss substrates in the form of two-port strip line structures; (a) copper, (b) SHIELDIT, (c) self-made e-textile.

Figure 5 shows the samples of transmission line models studied in this paper, where the material-under-test (MUT) is fabricated on top of the low-loss substrate. Low loss substrates with a slight $tan\delta$ difference were used in this method to minimize the parameter uncertainties that could affect the accuracy of the readings. In order to measure solely the conductivity, other uncertainties such as impedance mismatch or losses due to other materials that may affect the characterization of the conductivity properties shall be minimized or if possible, alleviated completely. This was including the substrate material that the MUT was integrated on.

The third sample, e-textile was used to demonstrate the real textile-like conductive element. The characteristics of all samples are summarized in Table 1. For measurement, two types of substrates were used. A low loss substrate, Rogers RO5880 with dielectric constant, ε_{r1} of 2.2 and loss tangent, $tan\delta_1$ of 0.0009 was used in sample 1A, 2A and 3A, while another substrate called Chukoh CGP-500A that has a dielectric constant, ε_{r2} of 2.6 and loss tangent, $tan\delta_2$ of 0.0018 was used in sample 1B and 2B. These two substrates were chosen based on the low-loss characteristics and to ensure the consistency of the data and analysis. Meanwhile, for the MUT, three types of conductive materials were used. A pure laminated

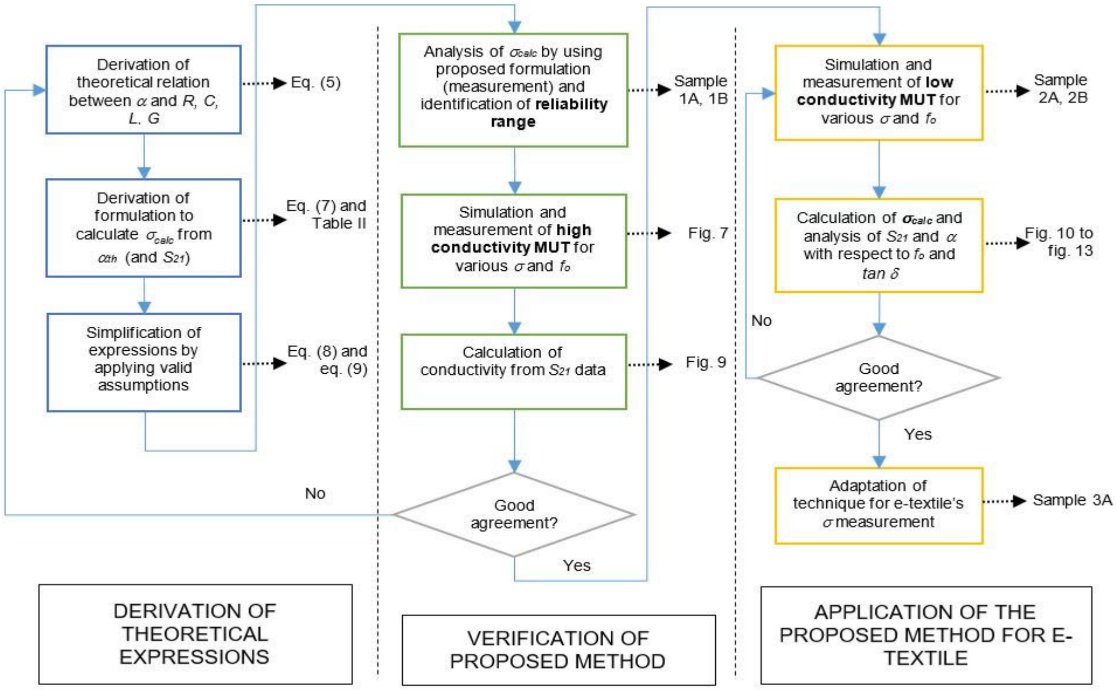


FIGURE 6. Flowchart of the validation works for the proposed technique. The work begins with the derivation of theoretical expressions, verification of the proposed method and the demonstration of the proposed method for self-manufactured e-textile.

TABLE 1. The characteristics of fabricated test samples.

Sample No.	Conductive element	Non-conductive substrate	Dielectric constant, ε_r	Dielectric loss, *tan δ*	Expected σ_c
1A	0.035 mm copper	Rogers RO 5880	2.2	0.0009	
1B	0.035 mm copper	CHUKOH CGP-500A	2.6	0.0018	~10^7 S/m
2A	0.17 mm SHIELDIT™	Rogers RO 5880	2.2	0.0009	
2B	0.17 mm SHIELDIT™	CHUKOH CGP-500A	2.6	0.0018	~10^5 S/m
3A	0.48 mm e-textile	Rogers RO 5880	2.2	0.0009	<10^5 S/m

copper (with $\sigma \sim 10^7$ S/m) is used as the reference material, and an off-the-shelf conductive fabric called SHIELDIT (with $\sigma \sim 10^5$ S/m) is chosen for comparison.

Based on the validation work from sample 1 and 2, the technique was then adopted for the self-manufactured e-textile, denoted as sample 3. Sample 3 is a potential e-textile material for wearable antenna that was developed 82.9% out of copper thread as the main conductor and 17.1% out of polyester thread as the base material in this research. Due to the presence of non-conductive polyester thread, the σ of this material (sample 3) is expected to be very low as compared to other MUTs. The value is predicted to be lesser than the σ of SHIELDIT due to its thread interconnectivity issue caused by the textile construction process and the limitation of the conductive fabrics, that are not formed purely from conductors. In weaving process for e-textile, copper thread was used as the weft (horizontal direction), and to strengthen the fabric, polyester thread was used as the warp (vertical direction) with the wefts-to-warps ratio of 25:80 per inch. The flow of the research and validation works is shown in Figure 6.

As explained previously, the attenuation constant, α is related to the scattering parameter S_{21} as the real part of γ [16]. Theoretically, the α can be simplified in terms of angular frequency ω and other parameters such as *R, L, C* and *R*. In this paper, a direct relation between these parameters to α_{th} is derived as shown by equation (5). Here, *R* is the only parameter that includes the main property of the conductive layer σ, whilst *G* is the only parameter that considers the conductivity of the substrate (non-conductive layer), σ_s :

$$\alpha_{th} = \frac{\omega CR + \omega LG}{\sqrt{2}\sqrt{-RG + \omega^2 LC + \sqrt{K}}} \quad (5)$$

Here, *K* is an author-defined parameter as shown by equation (6):

$$K = R^2G^2 + \omega^4L^2C^2 + \omega^2C^2R^2 + \omega^2L^2G^2 \quad (6)$$

By inserting the required parameters to the α_{th}, the expression is derived in a form of a fourth degree polynomial (also known as a quartic polynomial) as shown in equation (7) and table 2. The variable x shown in equation (7) represents the square-root of conductivity, $x = \sqrt{\sigma}$ and thus, $x^2 = \sigma$.

$$Ax^4 + Bx^3 + Cx^2 + Dx + E = 0 \quad (7)$$

Based on table 2, when the conductivity of the substrate is assumed to be negligible, $\sigma_s = 0$ S/m and the material is regarded as lossless where $tan\delta = 0$, there are only three (3)

TABLE 2. Expressions of the quartic polynomial for theoretical relation between conductivity and transmission line parameters.

Coefficient	Expressions
A	$\omega^2\mu^3h^4\sigma_s^4 - 4\omega^2\varepsilon\mu^2h^4\sigma_s^2\alpha^2 - 4\mu h^4\sigma_s^2\alpha^4$
B	$4\omega^2\varepsilon\mu^2h^3\sigma_s^3\sqrt{2\omega\mu} + 4\mu h^3\sigma_s^3\alpha^2\sqrt{2\omega\mu} - 8\omega^2\varepsilon^2\mu h^3\sigma_s\alpha^2\sqrt{2\omega\mu} - 8\varepsilon h^3\sigma_s\alpha^4\sqrt{2\omega\mu}$
C	$-8\omega^3\varepsilon^3\mu h^2\alpha^2 + 12\omega^3\varepsilon^2\mu^2h^2\sigma_s^2 + 16\omega\varepsilon\mu h^2\sigma_s^2\alpha^2 - 8\omega\varepsilon^2h^3\alpha^4$
D	$8\omega^3\varepsilon^3\mu h\sigma_s\sqrt{2\omega\mu} + 8\omega\varepsilon^2h\sigma_s\alpha^2\sqrt{2\omega\mu}$
E	$4\omega^4\varepsilon^4\mu$

expressions involved, which are from coefficient C and E. If this scenario is adopted, therefore, based on the theoretical derivation of α_{th} and the quartic function, a more practical and straightforward formula to calculate the sample's conductivity, σ_{calc} is derived in this research work as shown in equation (8), where ε is the material's permittivity, μ is the material's permeability, h is the substrate's thickness and α is the attenuation constant obtained through the S_{21} measurement:

$$\sigma_{calc} = \frac{\omega^3\varepsilon^2\mu}{\alpha^2h^2(2h\alpha^2 + 2\omega^2\varepsilon\mu)} \tag{8}$$

However, by taking into account all terms in the coefficient C, the expression can be expanded as in equation (9), where the substrate's conductivity, σ_s is also included. The σ_s is calculated from its relation to the angular frequency ω and $tan\delta$ properties [16].

$$\sigma_{calc} = \frac{\omega^3\varepsilon^3\mu}{2\omega^2\varepsilon^2\mu h^2\alpha^2 - 3\omega^2\varepsilon\mu^2h^2\sigma_s^2 - 4\mu h^2\sigma_s^2\alpha^2 + 2\varepsilon h^3\alpha^4} \tag{9}$$

In the analysis shown in this paper, both equations, equation (8) and equation (9) are compared with the actual expression, the quartic polynomial shown by equation (7) by using a Wolfram tool. The accuracy of all three expressions are compared in this paper through simulation and measurement verification over wide ranges of frequency.

III. VALIDATION OF TECHNIQUE THROUGH SIMULATION, MEASUREMENT AND ANALYSIS

Previously in [15], the characterization of the electrical properties of a material was based on the assumption that $tan\delta = 0$, which implies that the material was lossless and thus, the α can be theoretically simplified in term of bulk resistance R such that $\alpha_{th} = R/2Z_o$, where Z_o is the characteristic impedance. Figure 7 shows the simulation data of a transmission line sample operating at 2.45 GHz with various conductivity values from $\sigma = 5.96 \times 10^{-2}$ S/m to $\sigma = 5.96 \times 10^{10}$ S/m. Based on the S_{21} results for each σ, the conductivity is re-calculated by using the derived equation (8). When $\alpha_{th} = R/2Z_o$ is used (lossless condition), the calculated σ_{calc} agrees well with the actual σ loaded in the simulation file. This trend is consistent with the theoretical calculation when the substrate's conductivity, σ_s and $tan\delta$ are neglected ($G = 0$ S/m). However, when the actual case is simulated by introducing small losses ($tan\delta_1 = 0.0009$), the proposed equation is only valid until $\sigma \leq 10^7$ S/m and seems less reliable for $\sigma \geq 10^8$ S/m, which is also consistent with the theoretical calculation when G is taken into account ($G \neq 0$). This is due to the absence of parameter G or σ_s in the proposed equation (8) hence, the slight difference is observed.

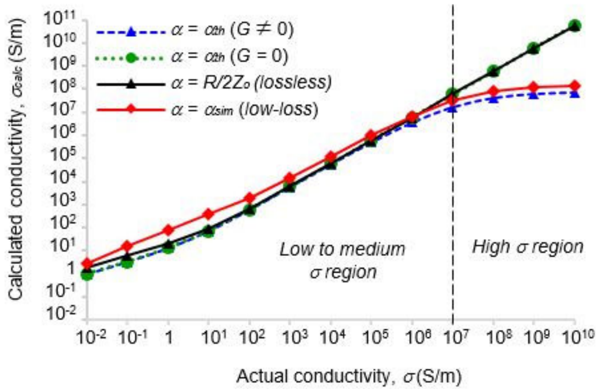


FIGURE 7. Theoretical values and derived values of conductivity obtained through S_{21} for lossless and low-loss material. The reliability region is divided into high-σ region and low-to-medium σ region.

At very high σ, the resistance of the conductor is low (~ 0) thus the resistance from the substrate (non-conductive) becomes very significant and cannot be neglected, which in other word implies that the σ_s is significant and not negligible for high conductivity MUT cases. Nevertheless, as most of the electro-textiles are known to have low conductivity (around 10^3 to 10^6 S/m), this method is considered as a good alternative as compared to the I-V curve measurement [17] that has been adopted for general electronic devices. In the proposed two-port strip line technique, the operational frequency is applied and the conductivity value can be accurately analyzed through frequency-dependent scattering parameter, S_{21}. Thus, the accuracy and practicality of the technique for materials used in microwave application is expected to be better as compared to the previous I-V measurement.

All samples from figure 5 were measured by using Keysight Vector Network Analyzer (VNA) as shown in figure 8. Before measuring the S_{21}, the impedance of the line was ensured to be 50 Ω. This was done to minimize other uncertainties such as reflection loss that may influence the accuracy of the technique. Figure 9 illustrates the results when the derived expressions, equation (8) and equation (9) are adopted for sample 1 that consists of laminated copper as the MUT and Rogers RO5880 and CHUKOH CGP-500A as the low-loss substrates. Due to the close agreement between

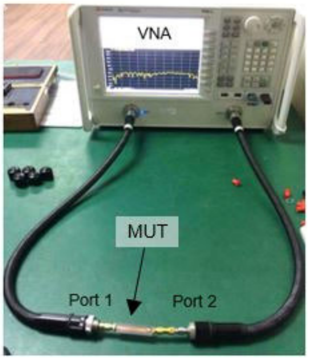


FIGURE 8. **Measurement configuration to calculate the σ of MUT based on S_{21} parameter.**

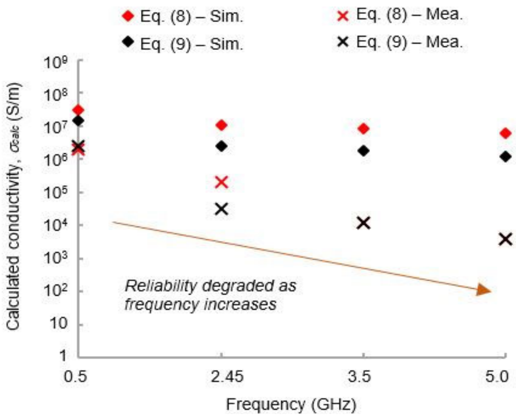


FIGURE 9. **Conductivity calculated through the simplified formulas based on the simulated and measured S_{21} for sample 1.**

the results obtained from the samples fabricated on these two substrates, only one result is plotted. For all cases, the samples are fabricated and measured for four operational frequencies; 500 MHz, 2.45 GHz, 3.5 GHz and 5GHz.

Based on the graph, the differences between the simulated and measured data are higher as the frequency increases. However, this scenario is predicted due to two factors; frequency and conductivity. As shown previously in figure 7, the lossless approximation used in equation (8) is only valid at the low-to-medium σ region, and no longer accurate for $\sigma \geq 10^8$ S/m. As the laminated copper has high conductivity, this condition becomes the main cause of the significant deviation. On the other hand, as shown in figure 2, σ is a frequency-dependent parameter hence the big deviation is observed at greater frequencies. The analysis was then performed for SHIELDIT fabric that has lower σ. As the technique is shown to be more accurate for $\sigma \leq 10^7$ S/m region, hypothetically, the technique is very suitable for SHIELDIT that has an expected σ of 10^4 to 10^5 S/m.

In order to generate simulation data for sample 2A and 2B, the fabric's conductivity as specified in the datasheet, $\sigma = 7.28 \times 10^4$ S/m was used. As predicted, based on figure 10, when the fabricated samples were measured, the graph of σ_{calc} shows a gradual drop as the frequency increases. This indicates that the *S*-parameter has increased in magnitude as

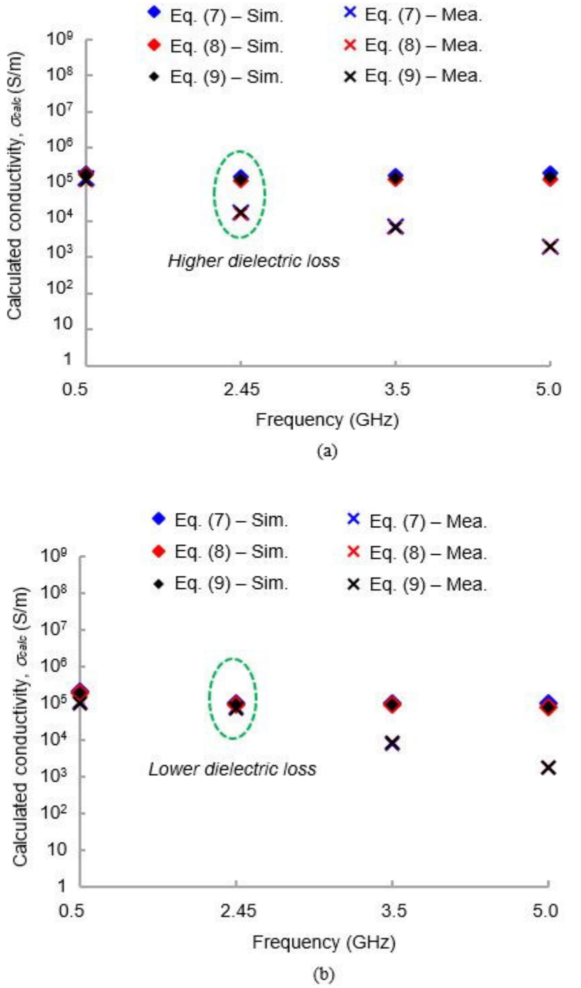


FIGURE 10. **Conductivity calculated through the simplified formulas based on the simulated and measured S_{21}; (a) Sample 2B (SHIELDIT as MUT, CGP-500A as substrate), (b) Sample 2A (SHIELDIT as MUT, RO 5880 as substrate).**

the frequency rises, and consequently the conductivity has slightly changed based on the operational frequency. In order to reduce the uncertainties, and also to ensure better accuracy, a very low loss substrate was used. The improvement on the reliability of the technique through different substrates is demonstrated in figure 10(a) and 10(b).

Another important observation from this analysis is the good agreement between all formulas; equation (7) - (9) for both cases. This finding is very significant as the lossless assumption used in equation (8) can be regarded as valid due to only a slight variation was observed in calculating σ as compared to the theoretical equation (7) as well as partially optimized equation (9). As compared to high σ MUT shown by sample 1 in figure 9, this technique seems to be more reliable and accurate for low-to-medium conductivity MUT as demonstrated by sample 2. This is judged based on the very small deviation shown by the σ_{calc} data between each formulation. Therefore, based on the findings, the proposed technique is very suitable to be used for characterization of a new electro-textile material having low-to-medium conductivity

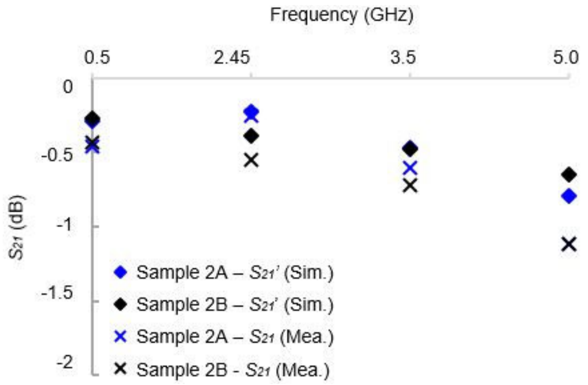


FIGURE 11. **Measured and re-calculated S-parameters (S_{21} and S_{21}') for sample 2A and 2B.**

and operating at low-range GHz application. As for the difference between the simulation and measurement values, this scenario occurred due to the non-frequency dependent σ data (datasheet value) that was loaded initially in the simulation file to generate the preliminary S-parameter result. This data however, has been clarified to be inaccurate through both measurement and detailed simulation which have shown that the σ is a frequency-dependent parameter which shall be characterized systematically.

The accuracy of the claims in this paper was validated further by loading the new measured σ_{calc} data into the simulation file. The new S-parameter, S_{21}' was recorded based on the measured σ_{calc} and the revised conductivity, σ_{calc}' was compared with the initially measured value. Based on figure 11, the same trend is observed where the S_{21} has decreased to lower value as the frequency increases, which directly correlates with the decrease of attenuation constant, α and α' as shown in figure 12. The most important observation here is the minimal deterioration between the measured data (S_{21} and α) and the revised data (S_{21}' and α') obtained through the re-simulation of sample 2A and sample 2B which indicates that the equation model is appropriate in characterizing the electrical properties of the sample intended for radio frequency application.

Based on the optimized data, as illustrated by figure 13, the measured conductivity σ_{calc}' obtained through the S_{21} measurement shown in figure 8 is plotted with respect to two derived equations, equation (7) and equation (8). The most significant behavior is demonstrated by this graph where there is a very good agreement between these two techniques. Equation (8) is a simplified expression by taking assumption that the sample is lossless. However, when the full quartic function given by equation (7) is used, almost similar values are obtained, and thus the applicability of the expression and the proposed technique, provided that the assumption is taken into consideration is validated.

Therefore, based on the analysis presented in this section, it can be verified that the proposed technique and formulation is very accurate, provided that the conditions in Table 3 are met. The frequency range that was validated in this paper

TABLE 3. **Reliability conditions of the proposed technique.**

Parameter	Symbol	Description
Operational frequency	f_o	$f_o \leq 5$ GHz (validated)
Dielectric loss	$tan\ \delta$	0.0009 or lower
MUT's conductivity	σ	$\sigma \leq \sim 10^7$ S/m

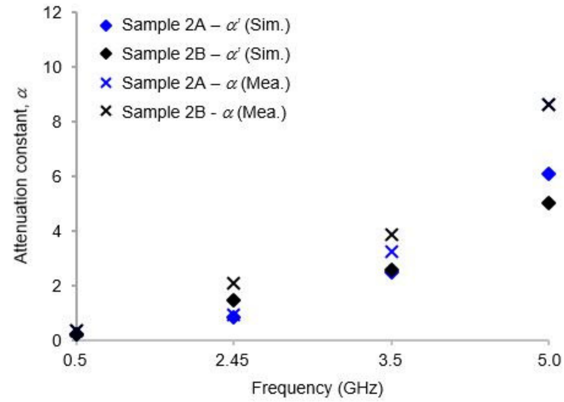


FIGURE 12. **Measured and recalculated attenuation constant (α and α') for sample 2A and 2B.**

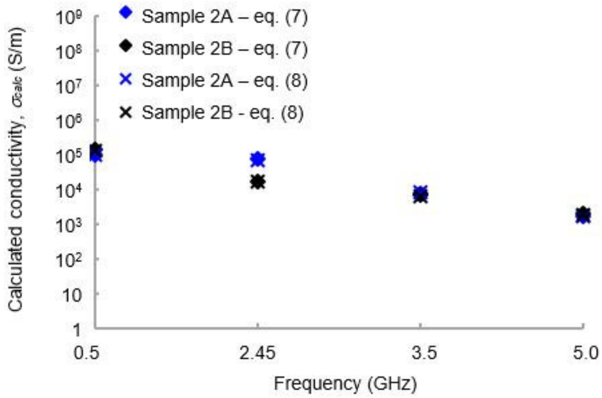


FIGURE 13. **Comparison of the measured conductivity, σ_{calc} for sample 2A and 2B by using two formulations.**

is from 0.5 GHz to 5 GHz, however, the technique can be further validated for higher spectrum band. At higher frequency, the accuracy is affected, mainly when $\sigma \geq 10^7$ S/m because in this case, the resistance of conductive layer is almost 0 and the substrate's resistance becomes very significant. Due to practical issues, the length of fabricated sample shall be increased to $\lambda/2$ at higher frequency. The electrical length shall be increased to ensure that it is practical for measurement, however, electrically long sample will be more susceptible to higher transmission loss. Through simulation data, figure 14 shows the situation when the proposed method is used at lower and higher frequencies. As seen from this graph, when the frequency is increased, the accuracy at higher σ material has degraded, however the method is still reliable for MUT having $\sigma \leq 10^7$ S/m.

In this paper, the validation works through lab measurement have covered up to 5 GHz reliability range. Due to the

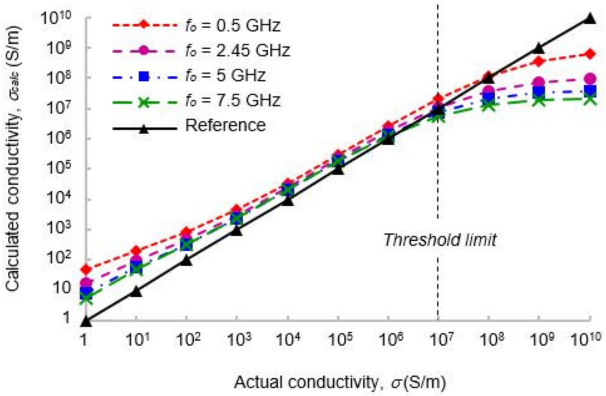


FIGURE 14. Calculated values of σ_{calc} for electro-textile sample operating at various frequencies.

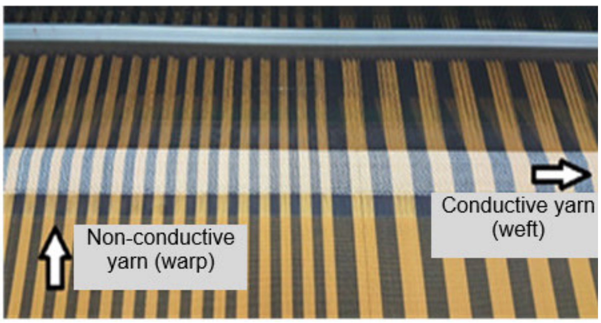


FIGURE 15. Custom made electro-textile that is developed as the main material for wearable antenna. The ratio of the copper-to-polyester thread is 83:17 respectively.

limitation and complexity of the fabricated sample at higher band, the verification at higher band was not performed as the length of the sample used in this paper (λ/4) will get smaller when the frequency is higher. Based on the findings in this paper, the clarification with respect to the accuracy and reliability of the method in relation to its frequency, dielectric loss and MUT conductivity have been studied. The method was then applied to a real self-made electro-textile.

IV. APPLICATION OF THE PROPOSED TRANSMISSION LINE METHOD FOR SELF-MADE ELECTRO-TEXTILE STRUCTURE

After the reliability assessment of the proposed method was conducted for the high-σ sample (laminated copper) and the medium-σ sample (SHIELDIT), the same method was applied to the low-σ self-made electro-textile material (sample 3A) as shown in figure 15. Similar to previous structure, to ensure the consistency of the results, this material was also fabricated in a form of a two-port λ/4 transmission line on low-loss substrate, Rogers RO5880. The sample was measured at ISM band, 2.45 GHz, which was the targeted application for the e-textile antenna.

Figure 16 shows the derived conductivity, σ_{calc} of sample 3A (e-textile), when it was simulated at various σ. Based on the graph, the trends are similar, where the threshold limit is $\sim 10^7$ S/m. This frequency-dependent method is compared to

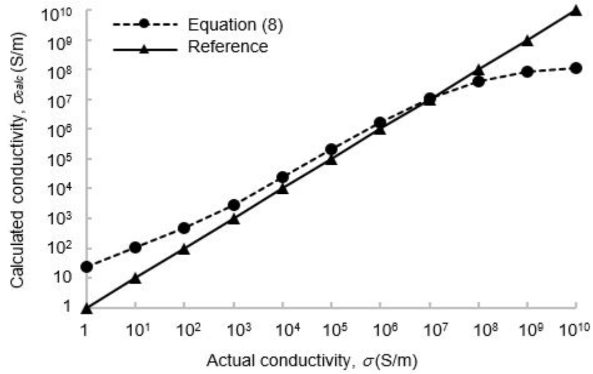


FIGURE 16. Actual and derived σ obtained through simulated values of scattering parameters S_{21} for sample 3 (e-textile).

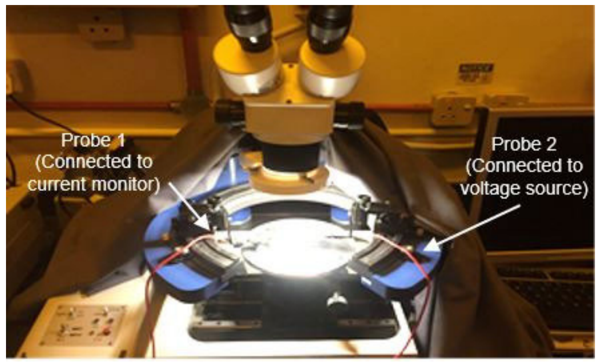


FIGURE 17. Measurement setup to calculate σ of samples based on I-V curve.

the I-V curve measurement as illustrated in figure 17. In I-V measurement, the σ was calculated based on the resistance, R derived from current, I measured when a set of voltage, V was applied to the test sample [17]. Preliminary measurement was conducted by using a pure copper wire, and the resulted σ was very close to the datasheet, 5.8×10^7 S/m. The process was then repeated for all transmission line samples and recorded for comparison analysis.

In order to compare the accuracy and reliability of the technique for a random electro-textile material with unknown conductivity, a comparison graph showing the measurement data of sample 3 and other samples tested at 2.45 GHz is shown in figure 18. As expected, the plotted graph shows good agreement between the measured and simulated data of transmission loss, S_{21} and attenuation constant, α for sample 1 and 2. For sample 2, only small deviation is observed which is due to fabrication inaccuracies. In performing analysis of sample 3, due to the unknown value of actual σ, the simulation data was obtained by inputting the σ_{calc} derived from measured S_{21} into the simulation tool at a complete matched condition.

Based on the simulation, the S_{21} or transmission loss shall be smaller. The discrepancies are expected due to the effects of manual cutting and assembly of fabrics, as well as the instability of fabric caused by the inhomogeneous thread structure. Nevertheless, when translating these parameters into σ_{calc} as shown in figure 19, the difference ($\Delta\sigma_{calc}$) is

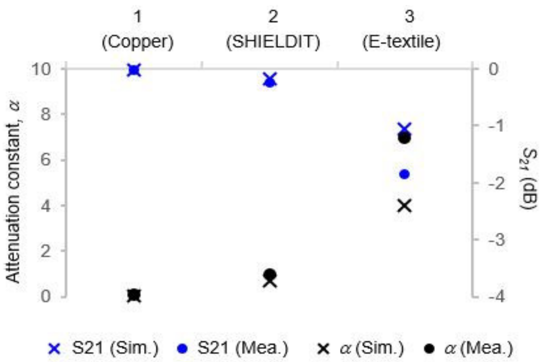


FIGURE 18. Comparison between transmission loss (S_{21}) obtained from simulation and measurement.

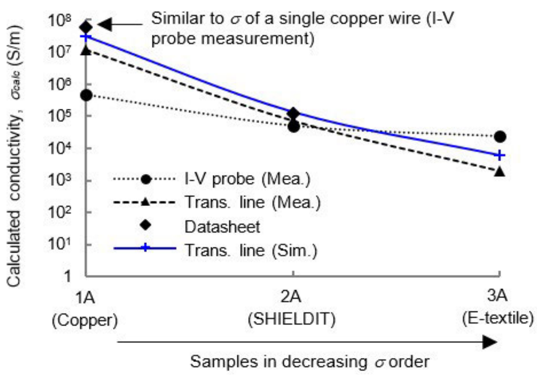


FIGURE 19. Measured σ obtained through I-V method and 2-port transmission line method, and comparison with σ defined in datasheet for sample 1 and 2.

small, and the curve follows the same trend as shown by sample 1 and 2. Therefore, it can be observed that this method is very effective for e-textile's conductivity calculation and the slight difference in α has not affected the derived σ_{calc} significantly.

Figure 19 also shows the comparison of data obtained through I-V method and 2-port transmission line method, and also the comparison with σ defined in the datasheet for sample 1 and 2. The σ data obtained through the transmission line technique shows relatively similar trend with the simulation, which indicates that the method is reliable in determining the electrical properties of materials intended for radio frequency application due to the theoretical formulation that has taken into consideration the operational frequency and other design parameters such as impedance properties. By comparing the measurement result with the datasheet, it can be generally observed that although both results show very close agreement, the datasheet's σ (for sample 1 and 2) is higher than the proposed technique.

Inconsistencies are also shown in I-V probe method. These are due to the frequency factor that has not been taken into account in the I-V probe method, which also neglects significant ohmic loss and surface roughness seen at microwave frequency. On the other hand, the I-V probe method seems inaccurate to be employed for the test samples in this article due to the transmission line-based structures that were not designed for such measurement, that has also resulted in big deterioration in the copper's σ_{calc} value as compared to the σ_{calc} of a single core wire. In this article, the test samples' structures were inclusive of non-conductive substrate at the bottom which may have greatly influenced the readings and resulted in the inaccuracy of the I-V measurement for the material intended for RF design. Table 4 shows the comparison between the proposed work with other methods used in the literatures.

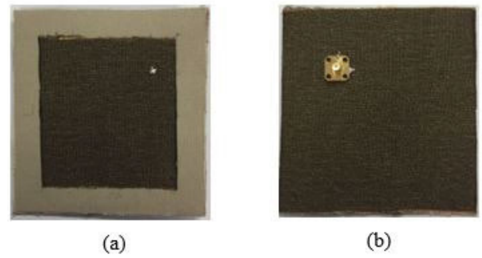


FIGURE 20. Fabricated rectangular planar antenna made of self-manufactured e-textile as the radiating element and polyester fabric as the non-conductive element.

TABLE 4. Comparison of the proposed technique with other methods used in determining electrical conductivity of materials.

Method	References	Description
I-V curve generation	Ref. [11], [12], [[18]	Based on the voltage measured when direct current (d.c) is applied. Frequency factor is not taken into account.
Transmission line	Ref. [16]	Reliability is limited to low frequency (MHz). Accuracy at GHz is not studied. Post-processing is needed to obtain σ.
Transmission line with improved formula	Equation (8), (9)	More reliable and straightforward, with reliability range validated for 500MHz to 5GHz. Effects of frequency and loss properties are clarified.

V. IMPLEMENTATION OF THE METHOD IN THE E-TEXTILE ANTENNA DESIGN

The characterization process was then repeated at 1.575 GHz and the calculated σ of the self-made e-textile was used in the design of a basic rectangular planar antenna, as illustrated in figure 20. In order to demonstrate the applicability of the technique for an actual antenna, the antenna was developed from e-textile as the radiating element and polyester fabric as the non-conductive element or substrate. The dimensions of the antennas are shown in Table 5. The antenna was designed at 1.575 GHz for future integration with wearable GPS tracking devices.

Figure 21 shows the measured and simulated return loss data of the antenna. From the graph, it can be seen that the antenna resonates at the targeted frequency of 1.575GHz with good return loss performance. A slight difference is shown between the simulation and measurement, which is expected due to the manual cutting of fabric during fabrication, which has resulted in inaccurate dimension of the

TABLE 5. Dimensions and design parameters of a rectangular E-textile antenna.

Layer	Parameters	Dimensions/ Details
Radiating element	Length, L_p	79 mm
	Width, W_p	74 mm
	Thickness, t	0.48 mm
Non-radiating element	Length, L_s	105 mm
	Width, W_s	93 mm
	Loss tangent, $tan\ \delta$	0.031
	Dielectric constant, ε_r	1.36

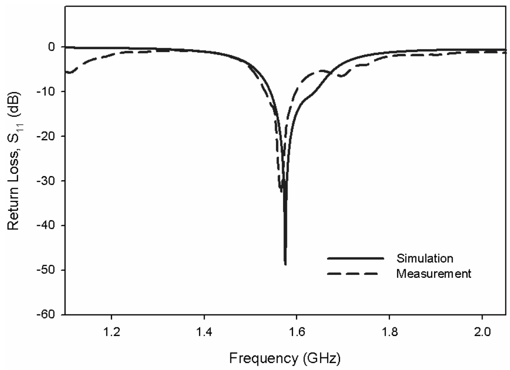
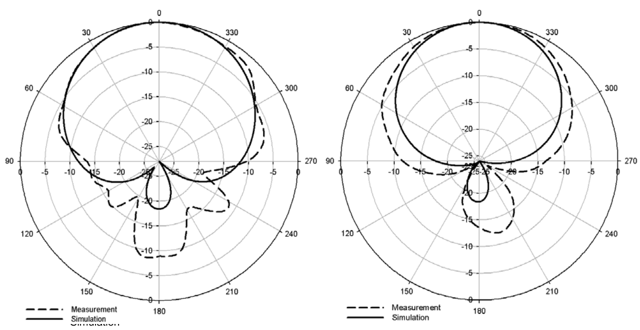


FIGURE 21. The measured and simulated data of return loss, S_{11} of the rectangular electro-textile planar antenna.



(a) (b)

FIGURE 22. The measured and simulated radiation pattern of the rectangular electro-textile planar antenna; (a) E-plane, (b) H-plane.

fabricated antenna. Nevertheless, frequency shift or detuning effect does not happen in this measurement. This scenario can be directly associated with Figure 1, which indicates that there are no frequency shift occurred when different σ values are used. The value of σ shall give more significant impact on the transmission performance as illustrated in Figure 2 previously, which can be directly translated to antenna gain parameter in the measurement. Figure 22 shows the radiation pattern of the antenna in the E-plane and H-plane. Good agreement is obtained between the simulation and measurement, which indicates that the parameters used in the simulation were accurate. There were only small differences observed in the gain values. The gain was 0.7 dB in simulation and reduced to 0.61 dB during measurement.

VI. CONCLUSION

Based on the analysis done in this paper, and the comprehensive and critical discussion on the results, the reliability of the proposed technique for characterizing the main electrical property of the electro-textile material was validated through both simulation and lab measurement. Accuracy assessment has been performed for many types of conductive and non-conductive materials, dielectric substrates of different loss properties, and also the main important element is the applicability and consistency of the technique over wider range of frequencies. The threshold range of $\sigma = \sim 10^7$ S/m was found to be valid, even though the frequency was increased up to 7.5 GHz. However, in this paper, due to the complexity of the fabrication at higher frequency, the lab works were limited until up to 5 GHz. Although there is a defined threshold range, this method is very suitable for electro-textile material due to its known low-to-medium conductivity characteristic. Therefore, to sum up, the 2-port transmission line technique is very accurate and practical in determining the σ of a new conductive textile intended for RF application, including at GHz operation.

ACKNOWLEDGMENT

Authors would also like to thank all researchers of Antenna Research Centre, Faculty of Electrical Engineering, Universiti Teknologi MARA, Shah Alam, Selangor, Malaysia specifically Muhammad Shakir for his great assistance during fabrication and Textile Research Group, Faculty of Applied Sciences, Universiti Teknologi MARA, Shah Alam, Selangor, Malaysia for supporting this project.

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