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Flexible Textile-based Coaxial Transmission Lines for Wearable Applications

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ABSTRACT Flexible and lightweight textile-based coaxial transmission lines for wearable applications are presented. In particular, textile yarns defined by copper (Cu), polyester (PES), and polytetrafluoroehtylene (PTFE) materials were used to design transmission line prototypes offering a 50-Ω characteristic impedance. These structures, which have the weight and texture of a cylindrical shoe lace, were also simulated and measured using a commercial simulator and results are in agreement. In addition, the textile cables were also studied in various straight, bent and wet conditions to ensure flexibility and durability whilst observing low reflection and insertion losses in these scenarios. In addition, the mass and DC losses of the fabricated cables were measured and are competitive when compared to a commercially available cable. To the best knowledge of the authors, this is the first implementation of simple RF/microwave coaxial cables whilst achieving a 50-Ω characteristic impedance, made possible by using purely wearable yarns and materials, whilst adopting a textile braiding process during manufacturing. Findings suggest that the reported textile-based cables are suitable for data connectivity between wearable devices in the UHF and the 2.4 GHz ISM frequency bands, for example, and can provide an alternative to more established strategies for wireless connectivity between body worn IoT devices and other related technologies.

INDEX TERMS Textile transmission line, coaxial cables, wearable devices.

I. INTRODUCTION

Wearable devices have been researched significantly for various applications in sectors such as healthcare, sports, defence and transportation. However, the majority of the published works in the literature are based on wearable antennas with a limited discussion on the required feeding network or interconnections. For radio frequency (RF) and microwave communications, a short feedline is generally required at both the receiver and transmitter because the connecting cable acts as a transmission line. Therefore the development of wearable-based transmission lines which are flexible, compact and robust are needed to compliment the existing devices and antennas that have been made wearable.

In this paper a flexible and wearable coaxial transmission line design using textile materials, making the structure have the consistency of a standard cylindrical shoelace, is proposed for broadband operation with a measured frequency range from DC to 6 GHz and with competitive losses to about 2.5 GHz (see Table 1). The developed textile cable is designed and fabricated for applications related to satellite, radio and Wi-Fi communications for example. In addition, the textile cable is also suitable for military, search and rescue operations, and other emergency services which require robust and secure RF/microwave connectivity. Basically the developed wearable transmission line can provide an alternative to more established wireless system approaches which utilize unbound RF signals for on the body communications

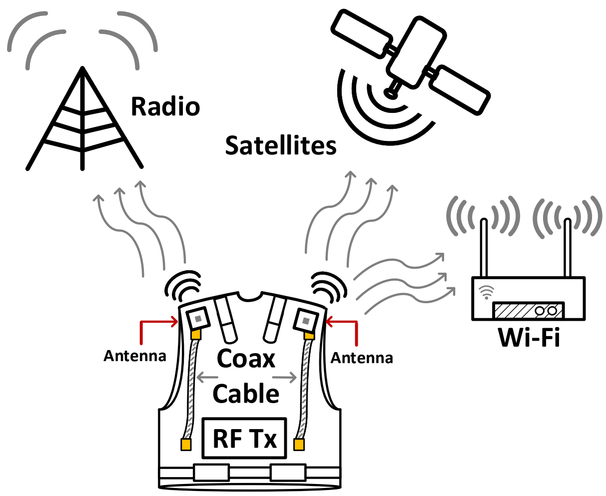

FIGURE 1. Illustration of the proposed textile-based RF cable connected to wearable devices and antennas which can all be integrated into clothing such as a conventional vest or jacket. If an RF transmitter T_x is made wearable, and the developed coaxial cable is connected to other antennas (placed at the shoulder, for example) the wearable and textile-based cable can support satellite communications and other wireless links.

between wearable electronic devices. Also, given the shielding effectiveness of the adopted coaxial line, the structure can potentially provide more secure data connectivity when compared to on-the-body wireless systems which might be more easily compromised. Regardless of these benefits and to our best knowledge, no similar textile-based and metallic fiber coaxial transmission line design has been reported in the literature. As described in the paper, such a wearable and low-loss transmission line should be light-weight and thin so it is comfortable while being worn. Flexibility and robustness are also some of the necessary characteristics, and since the developed coaxial transmission lines are to be worn, textile materials are preferred.

This combination of fabric mixed together with metal threads leads to the formation of a hybrid material, and the manufacturing of some basic guiding structures has been examined previously. Such a hybrid material, called PETEX in [1], was defined by the combination of fabric and copper wires. That work demonstrated two-wire and three-wire transmission lines which offered characteristic impedances in the range of 250-Ω and DC resistances of about 17.2 Ω/m. In [2], different multi-wire transmission lines were developed that were made from the polyester yarn twisted together with copper. Characteristic impedances above 100-Ω were reported with DC resistance values ranging from 7.31 Ω/m to 17.05 Ω/m depending on the configuration. As further described in the paper, our newly developed textile coaxial transmission lines offer maximum DC losses of 0.18 Ω/m. Moreover, the authors in [1] and [2] examined that indeed, the conductivity of the hybrid transmission line material increases due to higher proportions of metal filaments, which offers suitable electron mobility for current flow, and thus, decent RF performances can be obtained. More specifically, the authors in [1] and [2] commented that these wire-based transmission lines made using textile fabrics can be used for frequencies up to about 2 GHz.

The paper is outlined as follows. In Section II, the design motivation of the proposed textile-based coaxial cable prototype is described while also providing a literature review on previous reported flexible transmission lines. Section III briefly outlines the design approach for the new textile-based cables whilst simulations and measurements are compared in Section IV. Performance of the cables when bent and twisted for various cases is also reported, while ohmic losses at DC are also studied. A brief conclusion is also provided in Section V.

II. TEXTILE-BASED CABLE MOTIVATION

To improve upon the earlier micostrip and stripline textile-based prototypes present in the literature [1]–[4], we employ hybridized textile fabrics for the development of low-loss coaxial cables achieving characteristic impedances close to 50-Ω. Such transmission lines are suitable for connectivity with other RF devices, circuits, antennas, etc. for microwave applications. Also, previously reported microstrip-type textile structures offered characteristic impedances of 250-Ω [1] and 120-Ω [2], for example, which is not always useful for system integration and connectivity to other microwave devices, which typically require 50-Ω.

In our developed coaxial cables, signal paths are also better shielded from exterior noise sources when compared to these previous textile-lines [1]–[4], mainly, due to the adopted coaxial cable configuration. This is because these previous transmission line structures, [1]–[4], were defined by parallel or multi-wire metallic-yarn (hybrid) traces which were exposed and not encapsulated. This is unlike the proposed coax textile-based transmission lines that are further developed and experimentally verified herein, mainly due to the coaxial configuration which naturally offers electromagnetic shielding. Moreover, to the best knowledge of the authors' no similiar textile coaxial line has been reported previously, whilst using the same low loss hybrid fabrics and metal threads for operation at RF/microwave frequencies.

It should be mentioned that some other types of transmission lines and connectors have also been designed for wearable applications in mind [3]–[10]. For example, flexible microstrip transmission lines have been presented in [3] for healthcare scenarios. Wearable striplines have also been been developed in [4]–[6] for GPS applications and ISM band frequencies. Furthermore, it needs to be stressed that the typical RF/microwave characteristics are not extensively reported in these previous works, making direct comparisons (in terms of loss, for example) to our newly proposed coaxial-like textile structures challenging.

TABLE 1. Comparison of Other Textile-based Transmission Lines Found in the Literature

Parameters	[1]	[2]	[3]	[4]	This Work
Transmission Line	Microstrip	Microstrip	Microstrip	Stripline	Coaxial
Impedance Ω	250	120	-	46 to 54	50
Material	PETEX	PES	PDMS	Silver Fabric	PES & PTFE
Structure Loss (at 0.5 GHz) dB/cm	-	0.05	0.03	0.01	0.01
Structure Loss (at 1.0 GHz) dB/cm	-	0.1	0.05	0.02	0.01
Structure Loss (at 2.5 GHz) dB/cm	-	1.2	0.15	0.05	0.1

In spite of this fact, various connectors for wearable devices have also been designed such as snap-on buttons, butterfly clasps, wing solutions as well as conductive epoxy (and also with limited RF metrics reported and complete structure characterization. Regardless, the motivation in those works was to connect wearable antennas with transmission lines [5]–[9]. In [8] for instance, Velcro was used to establish connections between the patch antenna and stripline. Recently, in [9] flexible coplanar waveguide transmission lines were also presented using polydimethylsiloxane (PDMS), whereas in [10], a flexible microstrip transmission line using PDMS material was developed for flexible RF devices.

Table 1 summarizes the advantages of our developed textile-based transmission lines as compared to other similiar designs found in the literature. For example, the characteristic impedance of the proposed textile-based transmission is lower than [1] and [2] being 50-Ω which is ideal for RF/microwave system integration. Also, the structure losses are lower for the examined textile-based cables as compared to [2], [3] and [4]. More specifically, as shown in Table 1, the textile-based transmission lines offer competitive losses with values of 0.01 dB/cm at 500 MHz and 0.1 GHz. Also, when compared to [1] and [2], high impedance values greater than 100-Ω were reported for the textile-based transmission lines considering microstrip topology. This was related to the thickness of the yarn used for the cables, fabrication tolerances, and the thickness of the employed metal for RF signal propagation.

It is also worth mentioning here, and as further described in the paper, that the proposed coaxial cables in this work are highly flexible and are very thin (having widths of about 0.3 cm) which make it easier to embed within a jacket or other clothing garments for example. This can support and enable discrete interconnections between various RF components whilst being comfortable and lightweight while being worn. Also, a maximum mass reduction of about 60% is observed when compared to a more standard coaxial cable.

In this paper the proposed textile-based transmission line follows the basic structure of the coaxial cable [11] and two different prototype lines were designed and fabricated for comparison. One using polyester (PES) as the dielectric cladding while the other employs polytetrafluroethylene (PTFE) due to its low dielectric loss values [11]. To the best knowledge of the author, no similar textile-based transmission line has been reported previously which adopts the classic coaxial cable configuration enabling a 50-Ω system impedance for microwave applications.

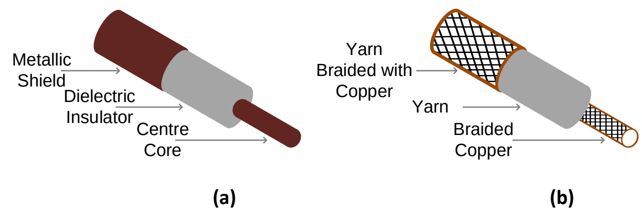

FIGURE 2. A comparison between the general topology of the (a) standard coaxial cable and (b) the proposed textile-based coaxial cable.

III. DESIGN OF THE TEXTILE-BASED COAXIAL CABLE

The developed textile-based coaxial cables follow the same physical structure as any standard commercially available coaxial cable (see Fig. 2(a)). A standard coaxial cable is constructed using three layers. Layer 1 is the inner conductor which is also known as the centre conductor or inner core. This inner (usually continuous) metal layer is surrounded by layer 2 which is a dielectric insulator, layer 3 is a metallic

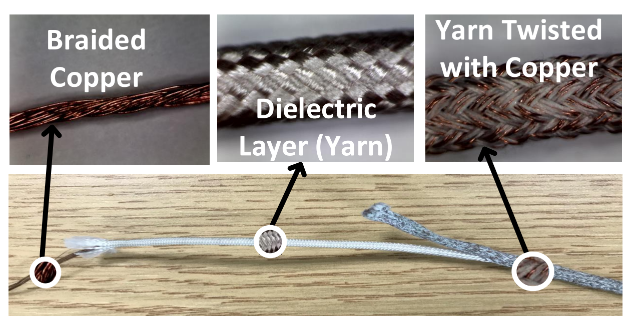

FIGURE 3. Textile-based coaxial cable showing an enlarged microscopic picture of each layer: the inner core is braided copper (layer 1), the dielectric insulator (layer 2), while the outer core is a dielectric yarn twisted with copper (layer 3). The selection of these materials and the braiding approach using hybrid yarns during manufacturing, makes the proposed textile-based transmission line structures have the consistency of a standard shoelace.

shield or mesh often called an outer conductor. Sometimes this outer layer is covered with a wrapping or outer jacket for electromagnetic shielding [11], [12].

The coaxial cable made from these textile materials is shown in Fig. 2(b) and has three layers. Layer 1 is the inner layer that is purely a metallic braid using about 50 tightly packed pieces of copper yarn (0.5 mm diameter), this ensures a high degree of flexibility. Layer 2 is a dielectric insulator enclosing the inner conductor and is a flexible material using textiles while layer 3 is a hybrid mesh of copper and an insulating material. These different layers are shown in Fig. 3 for the fabricated textile cables. The thickness of the outer layer was defined by the braiding technique and employed hybrid metal-insulator yarn whilst being limited by the braiding machinery. Efforts were also made to ensure a coaxial structure that was as thin as possible.

To realize the insulating layers, polyester (PES) and polytetrafluroethylene (PTFE) materials were employed. These materials are durable, resistant to shrinking, offer fast drying times when compared to other fabrics, are light weight and have a low dielectric constant [13]. It should also be mentioned that we have adopted a braiding technique instead of weaving in order to get a strong and flexible physical structure for the inner core. Moreover, the choice of the textile material for implementation of the cables is another factor to consider. Generally, any device for wearable applications should offer flexible properties, needs to be durable, and robust after any deformation. Also the employed material should be lightweight, not bulky, and preferably low-cost.

The characteristic impedance (Z_o) is an important parameter that needs to be carefully considered prior to designing the textile cable, as it determines the transmission line matching to other RF/microwave devices. As is well known for a lossless or low loss coaxial cable, Z_o is purely a function of the inductance and capacitance disturbed along the transmission line length and can be calculated [11]:

$$Z_o = \frac{138}{\sqrt{\epsilon_r}} \times \log(\frac{D}{d}) \quad (1)$$

where, ϵ_r is the relative permittivity of the dielectric insulator, D is the outer core diameter and d is inner core diameter. Therefore the characteristic impedance of coaxial transmission lines depends on D, d and ϵ_r. Moreover, the coaxial cables manufactured in this paper were designed to offer a 50-Ω characteristic impedance.

The attenuation constant or loss factor, denoted as α, is another important parameter for coaxial cables. As the signal propagates, there can be a loss of power that can arise from several factors and this loss is present on all practical transmission lines [14]. Also, as it is well-known, low-loss α values can define conditions for low-loss transmission lines. This attenuation is usually specified in terms of a loss factor, normally in decibels over a given length; i.e. dB/m or dB/cm. Also, such attenuation is dependent on

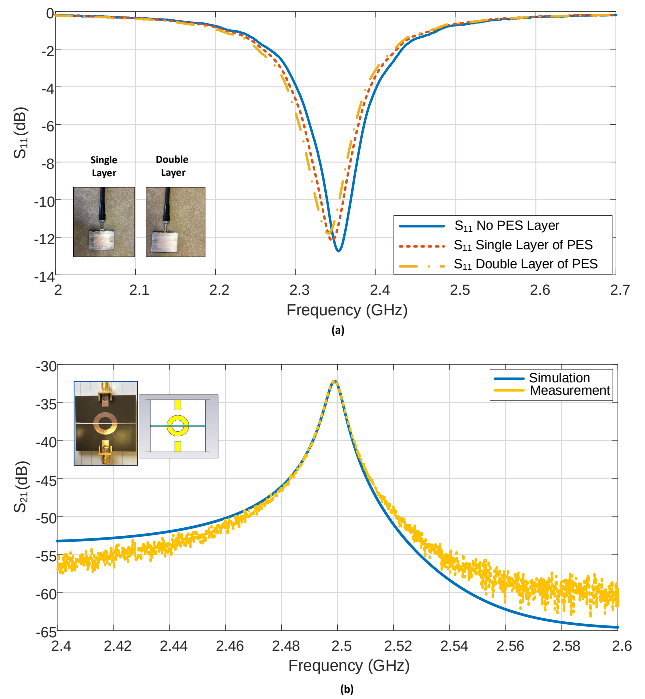

FIGURE 4. Electrical characterization of PES (a) using a microstrip patch antenna and (b) a ring resonator. The experimental results were compared to simulations to identify ε_r.

the three main parameters: resistive loss, dielectric loss and radiated loss [15]. When implementing these textile-based cables efforts were also made to minimize losses in terms of selecting commercially available materials with the least amount of conductor and dielectric loss.

IV. ASSEMBLY OF THE TEXTILE CABLES

The first step in the construction of the cables is to electrically characterize the insulating yarns; i.e. the raw PES and PTFE textile material in terms of the relative dielectric constant ε_r. Different methods have been reported in the literature for such textile material characterization which include free-space methods [16], transmission-line methods [17], as well as near-field sensors [18], and resonant cavities [19]. These four methods are also further described in [20].

A. ELECTRICAL CHARACTERIZATION

To electrically characterize the employed textile yarns, two resonant type PCBs were developed to extract ε_r and $\tan\delta$: (1) measurements using a microstrip patch antenna which operated at 2.35 GHz (and covered by a thin layer of the yarn under investigation), and (2), using a planar microstrip ring resonator loaded with yarn which resonated at about at 2.5 GHz. These methods were employed as they are cost-effective and are fairly accurate to determine ε_r [20] in that a shift in the resonant frequency can be observed as compared to a non-loaded scenario. Both approaches were used to characterize the PES and PTFE yarns.

These two techniques, with results at 2.35 GHz and 2.5 GHz respectively, were used so that the measured shift in

TABLE 2. PES and PTFE Yarns Relative Permittivity (ϵ_r) and Loss Tangent ($\tan\delta$) Estimations using Two Different Electrical Characterization Approaches

Approach	Textile Material	ϵ_r	tanδ
Mircostrip Patch Antenna	PES	2.0	0.035
	PTFE	2.1	0.001
Microstrip Ring Resonator	PES	2.1	0.030
	PTFE	2.2	0.001

frequency can be compared to an equivalent CST full-wave simulation model providing some confidence in the extracted ε_r and $\tan\delta$. Values can be found in Table 2 and these are in general agreement with values as found in the literature [11]. However, it should be noted that the PES-textile experiments showed much higher levels for $\tan\delta$ when compared to the PTFE material. Regardless, $\tan\delta$ for the PTFE study was in close agreement with [11], for example, with ε_r typically in the range of 2.0 to 2.1 and with $\tan\delta \leq 0.001$. It can also be observed that the values of both PES and PTFE yarns are almost the same for both methods suggesting consistency in the investigations.

Results in Fig. 4(a) and (b) are reported for the PES ε_r material extraction considering a patch antenna and the ring resonator method, respectively. The S_{11} was measured with no PES material and then with different layers of PES material with measurable thicknesses (0.3 cm for the single-layer test and 0.6 cm for the double-layer testing). Very similar results were observed for the PTFE material and all property extraction results are not fully reported due to brevity. For the ring resonator study, the textile material was passed through the gap between the two rings and S_{21} was measured. In particular, a single-layer of yarn was positioned between the gap which was 0.3 cm thick. Likewise, the measurements were repeated for the PTFE material. This information provides important knowledge when designing the transmission lines and to motivate design efforts for achieving characteristic impedance values of 50-Ω.

B. CABLE PROTOTYPING

During the braiding process to assemble the cables, the diameter of the fibers for the inner copper layer was known and was fixed to be 0.5 mm. Then based on the extracted values of the relative dielectric constant for PES and PTFE (see Table 2), the dielectric layer was braided onto the inner core using a textile braiding machine by J&D Wilkie Ltd.

TABLE 3. Calculated Impedance of the Fabricated Prototypes

Parameter	PES	PTFE
d (mm)	0.50	0.55
D (mm)	1.85	2.36
Impedance Z_o, (Ω)	53.47	54.20

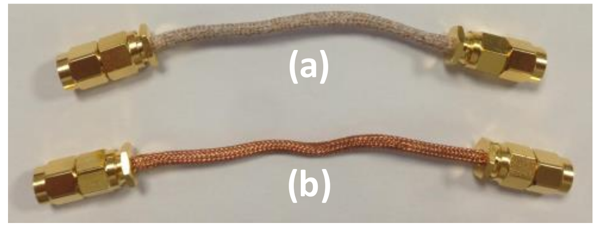

FIGURE 5. Fabricated textile coaxial cable (a) PES and (b) PTFE prototypes.

Best possible efforts were ensured such that the thickness of this layer followed Eq. (1) such that a 50-Ω characteristic impedance was achieved as per design. As outlined in Table 3 impedance values deviated by about 4-Ω or less. It should be mentioned that these impedance values were calculated by following Eq. (1) and by physically measuring the thickness of the textile fiber layers using a digital computer-based microscope during the braiding and manufacturing process. This ensured that the correct dimensions of the various yarn layers were achieved as per design.

Two fabricated prototypes of the textile-based coaxial cables, polyester (PES) and polytetrafluroethylene (PTFE), with connectors are shown in Fig. 5 (a) and (b). Each cable had a length of several meters but then reduced to 10 cm (and SMA connectors were added on both ends) for RF/microwave measurements. As briefly mentioned earlier, the prototypes were made using an inner conductor (layer 1) composed of pure braided copper (Cu) threads. The dielectric insulator for the PES cable (layer 2) was manufactured using PES threading (100%) while the outer conductor (layer 3) was made using a hybrid PES yarn twisted with Cu. In particular, a composition of 6% PES and 94% Cu. On the other hand, the PTFE cable prototype was also manufactured using a pure dielectric (PTFE) as layer 2, while the outer conductor (layer 3) was a pure, copper-based yarn (100% Cu). A table outlining the yarn materials adopted for the prototypes is in Table 4.

The difference in layer 3 for the PES cable was due to the capability of the braiding process, in that the PES layer could not easily be woven to a pure copper yarn as in the PTFE cable. This is why layer 3 for the PES cable was composed with a small amount of PES; i.e. 6%. This was to ensure that a proper layering of the yarns was achieved, and, with no air gaps between layers. This realized a continuous and uniform cross-section for the cables. Moreover, these yarn compositions for the two prototypes were needed such that the cable layers could be properly braided together to form a continuous cable whilst maintaining the aforementioned radial dimensions to ensure a 50-Ω characteristic impedance.

In order to mount or affix the cable prototypes to a conventional SMA connector for RF/microwave measurements, the following steps were taken. The inner most layer of the textile cable, defined by the copper threads, was soldered to the inner side of the connector, then the outer core of the cable was manually pressed firmly into place. This was made possible by the design of the connector. Basically the inner connection was made by soldering the inner connector fitting, while the outer layer was made firm in-place by compression. Finally, the outer nut was fastened to keep the cable set in place. This was repeated on both cable ends and for all prototypes for consistancy.

The calculated values of the characteristic impedances for both PES and PTFE cables are about 6% and 8% higher than 50-Ω, respectively, by Eq. (1) and when using measured diameters of the layers for the cables. This is related to the achievable tolerance during cable manufacturing in that the dimensions of the inner and outer core was measured to be about $\pm$0.4 mm. Also, the braiding technique used for the manufacturing of the yarn also introduced some minor variation in the diameter of the fabricated cables. However, these minor tolerances due to the practicalities of the cable assembly, did not appear to have a significant effect on the performance of the proposed textile-based coaxial cables in terms of reflection and insertion losses. This was because 5 prototype samples of the same length ($\approx$ 10 cm) and RF connector type were assembled (as in Fig. 5) and measured. These samples showed little difference in terms of variations in the reflection coefficient and insertion loss with respect to the frequency, likely due to the noted tolerancing size.

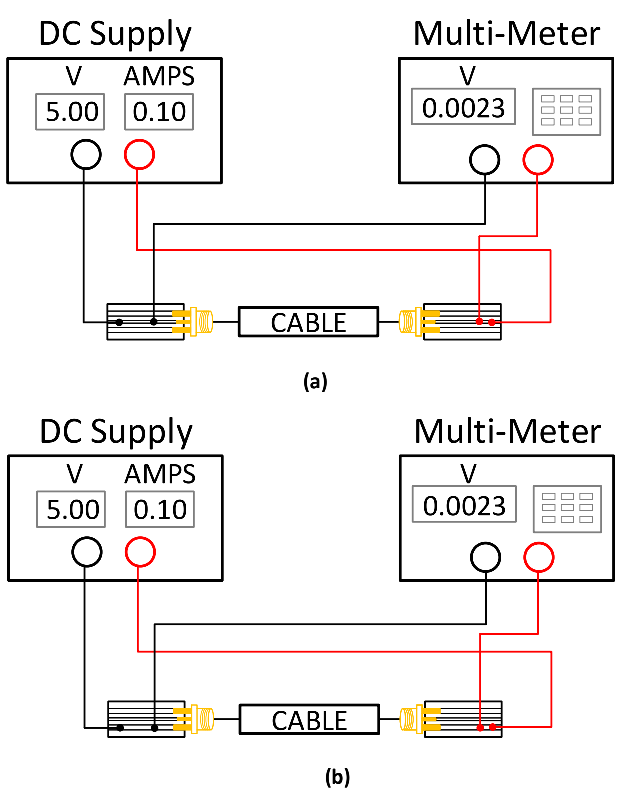

FIGURE 6. **Experimental set up to characterize the DC properties of the manufactured textile cable prototypes. (a) DC analysis setup for the inner conductor and (b) DC analysis setup for the outer conductor.**

TABLE 4. **Textile Cable Composition**

Cables	Inner Conductor (Layer 1)	Dielectric (Layer 2)	Outer Conductor (Layer 3)
PES Prototype	Braided Threads (Pure Cu)	100% PES Threading	Hybrid Yarn 6% PES, 94% Cu
PTFE Prototype	Braided Threads (Pure Cu)	100% PTFE Threading	Pure Yarn 100% Cu

TABLE 5. **DC Resistive Losses: Inner Conductor**

Cables	Measured Voltage [V]	Resistance (Ω)	Length [cm]	Ohmic Losses [Ω/m]
PES Prototype	0.0019	0.019	10.6	0.18
PTFE Prototype	0.0017	0.017	11.2	0.15

TABLE 6. **DC Resistive Losses: Outer Core**

Cables	Measured Voltage [V]	Resistance (Ω)	Length [cm]	Ohmic Losses [Ω/m]
PES Prototype	0.0076	0.076	10.6	0.716
PTFE Prototype	0.0011	0.011	11.2	0.097

C. DC LOSS STUDIES

A Kelvin four-wire resistance measurement method [21] was adopted to study the DC characteristics of the fabricated coaxial cable prototypes. This method was used as it eliminates any effect of the fixture resistance and can obtain a precise resistance value for the DUT. Figures 6 (a) and (b) shows measurement setups for the inner and outer cores, respectively. Also, to check that the setup was working accurately the ohmic losses of the inner conductor for a four-inch commercial cable (086-4SM+ from Mini-Circuits) was measured. From the datasheet provided by the supplier of the commercial cable, the ohmic loss of the inner conductor was stated to be 212.6 mΩ/m and the value acquired from our measurement setup was 214.6 mΩ/m. This gave us the confidence that our measurement setup was working as expected and that results for the proposed cables were representative. The comparison of the measured DC resistive loss for the inner conductor of the textile cable prototypes is reported in Table 5. The results show the PTFE prototype has a slightly lower ohmic loss as compared to the polyester prototype.

Table 6 lists DC resistive losses for the outer conductor of the textile cables as well. The PES cable has reduced DC losses as compared to the PTFE cable due to the higher conductivity and thickness of the material used for the outer conductor. This is because copper has a large conductivity due to its high current density [22]. So for example, a thin copper wire has a large resistance while a thick copper wire will have a smaller resistance. The PTFE cable has copper as its outer conductor increasing the effective conductivity, but the outer conductor of the PTFE cable is thinner as compared to the polyester prototype which will allow less current flow contributing to the increase in the observed DC resistance. The ohmic loss per meter for all cables are on the order of 0.1 Ω/m or less when considering the outer core.

The mass of the fabricated braided cables was also measured and compared with a commercial cable. Table 7 shows the results from the mass measurements. It was found that the PES textile-based cable has approximately 60% lower mass per meter as compared to a commercial cable (086-4SM+ from Mini-Circuits). It should also be mentioned that the RF connectors were disconnected from the fabricated cables when this mass per unit length measurement was carried out. This was completed to ensure a fair comparison, with no connectors, for the proposed textile-cable study as well as the commercial cable.

D. GENERAL DISCUSSIONS

By employing these textile materials for the proposed coaxial transmission lines, which included some thin copper filaments, all parts of the cables were made lightweight and as flexible as possible considering the aforementioned wearable applications. In addition, these cable prototypes were manufactured for further microwave testing with the support of J&D Wilkie Ltd, a textile-based company in Kirriemuir, Scotland. The copper wires for the inner core were supplied from Wagner Textile in Ibbenburen, Germany (their yarn reference was Coopra Wire considering DIN packaging). The PES (1100 dtex) and PTFE (550 dtex) dielectric layers were textile yarns which are readily available from multiple textile suppliers. Also, the third layer was made possible by using spun yarns (Polirom) was from Technofilati Srl in Italy. Here dtex is common measurement unit that indicates the linear mass of yarn in decigrams, per 10,000 meters.

V. SIMULATIONS AND MEASUREMENTS

A. REFLECTION AND TRANSMISSION COEFFICIENTS

The simulation software AWR from National Instruments was used for the simulation of the cables. The measured dimensions of the transmission lines were introduced into the simulator to study the performance of the cables. This gave a simulated impedance of about 55-Ω for both cables confirming the measured dimensions for the characteristic impedance as in Table 3. The S-parameters of the two fabricated cable prototypes were also measured using a N5225A Keysight VNA. The measurement setup is shown in Fig. 7. The comparison of the measured S_{11} magnitude for the prototypes is shown in Fig. 8. The -10 dB impedance matching bandwidth for the PES cable is up to about 4 GHz and beyond that the matching of the prototype is still below -7 dB. On the other hand, the PTFE cable has similar matching up to 6 GHz.

TABLE 7. Mass Per Meter of the Textile-Based Coaxial Transmission Line as Compared to a Standard Cable (086-4SM+)

Cable Type	Cable Length (m)	Total Mass (g)	Mass per meter (g/m)
PES	2.62	25.97	9.91
PTFE	1.80	22.48	12.49
086-4SM+	0.11	1.86	16.92

The measured S_{21} magnitude for both cables is compared in Fig. 9. The S_{21} of the PES cable is above -2 dB up to 3.5 GHz whereas the PTFE cable is above -2 dB up to 5.5 GHz. In comparison, the measured S_{21} of the polyester cable was above -2 dB up to 4 GHz and -2 dB for the PTFE cable up to 6 GHz. This makes sense since it is generally well known that PTFE is a low loss material that is typically employed in the design of planar antennas and microwave circuits [11].

The simulated and measured reflection coefficients and insertion phases of the fabricated cable prototypes are shown in Fig. 10 by considering the 10 cm length of the cables, the relevant dimensions, and the relevant materials whilst adopting a low-loss transmission model with the AWR simulator. As can be observed in Fig. 10 the simulated insertion phase of the fabricated cables are in agreement with the measurements along with similar values for the reflection coefficient. It should be noted that there is a minor discrepancy between the measured and simulated reflection coefficients which are likely related to fabrication tolerances and the noted losses in the cables as described next. However, all reflection coefficient values show similar results; i.e. $S_{11} \leq$ -10 dB for the measurements and simulations with insertion phase values in good agreement.

It is worth mentioning that the S-parameter simulations for the textile cables were completed up to 6 GHz (see Fig. 10). In particular, simulations were completed by using values for the extracted relative dielectric and loss tangent as outlined in Table 2. It is also worth mentioning that theses narrowband

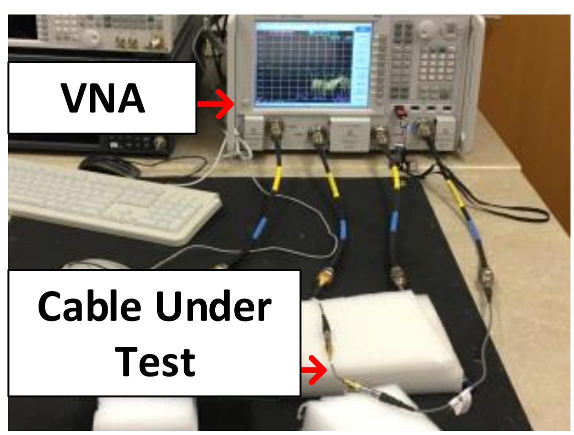

FIGURE 7. Measurement setup for S_{11} and S_{21} for the textile-based coaxial cables.

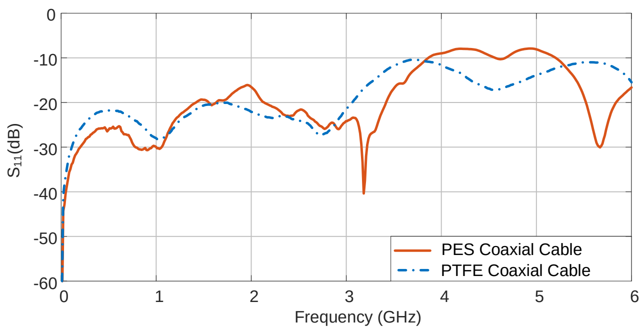

FIGURE 8. **Measured S_{11} for the two textile-based coaxial cables (see Fig. 5).**

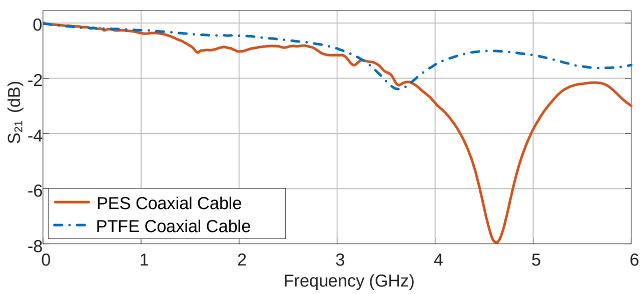

FIGURE 9. **Measured S_{21} for the two textile-based coaxial cables (see Fig. 5).**

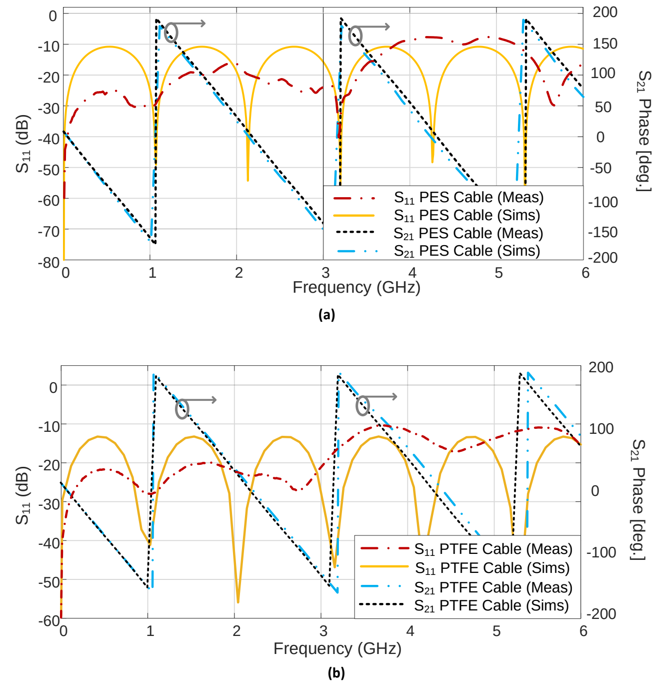

FIGURE 10. **Simulations and measurements of the textile coaxial cables. (a) PES coaxial cable, and (b) PTFE coaxial cable. Left axis: S_{11} comparison of the simulated textile coaxial cables with measurements. Right axis: S_{21} (insertion phase) comparison.**

findings (at about 2.45 GHz) were used to estimate the relative permittivity and loss tangent over a larger frequency range for the developed textile cable prototypes. However, as can be observed in 10, good agreement is achieved between the simulations and the measurements of the textile cables, in particular, for the insertion phase up to 6 GHz which is related to the relative permittivity, ε_r. Given these observations it can be summarized that the extracted estimations of the electric material properties, for the materials which realized the textile cables (as outlined in Section IV.A.), appear stable over the investigated and intended frequency range.

The losses within the cables is likely related due to the differences in the yarn pitches (i.e. the spacing between the yarn meshes) between the different layers (see Fig. 2) during the hybridization of the textile and metal materials which can create an unwanted airgap. This occurred during the braiding process and can occur during the machining of the yarns themselves employed for the different layers. Also, the losses could be related to any fabrication imperfections during the manufacturing of the used yarns (as mentioned previously when assessing the tolerance dimensions for the characteristic impedance) as well as any dielectric and conductor losses of the textile materials. Also as shown in Fig. 9 at about 4.5 GHz, the insertion loss of the PES cable increases. This might be related to the yarn mesh. In particular, with an increase in frequency the yarn mesh could be comparable to the shorter wavelengths defining unwanted leakage losses. Regardless of these practicalities, the intended frequency range is from DC to about 2.5 GHz, mainly that, the proposed textile-based transmission lines may be suitable for wearable applications and were short-interconnections are required between different radiating and non-radiating devices on the human body (about 2.5 GHz and below), for example. Basically that, the observed losses might be acceptable. Also, to the authors best knowledge, no similar implementations of simple coaxial cables, manufactured using purely wearable yarns, has been designed for a 50-Ω characteristic impedance and when considering RF/microwave frequencies of operation.

When comparing the S-parameters of the 50-Ω commercial cable having a length of 10 cm (086-4SM+ from Mini-Circuits, see Table 7), reflection coefficient values were well below -40 dB whilst the insertion losses were 0.1 dB at 2.45 GHz (all results not reported for brevity). These results are expected for a commercial cable standard, however, the reflection coefficient and insertion loss for the proposed textile-based structure is still competitive; i.e. $S_{11} \leq$ -20 dB and $S_{21} \leq$ -0.5 dB, respectively, for the common 10 cm length when considering the PTFE design at 2.4 GHz. It should also be mentioned that textile-based cables offer improved bending quality as described next. In particular, the commercial cable (which was not a semi-rigid design) could not easily achieve a 180° bend as well as the examined loop-like structure (see Fig. 11) for the 10 cm length. This comparison highlights the benefits of the proposed textile-based transmission line prototype in terms of its flexibility when compared to a standard commercially available cable.

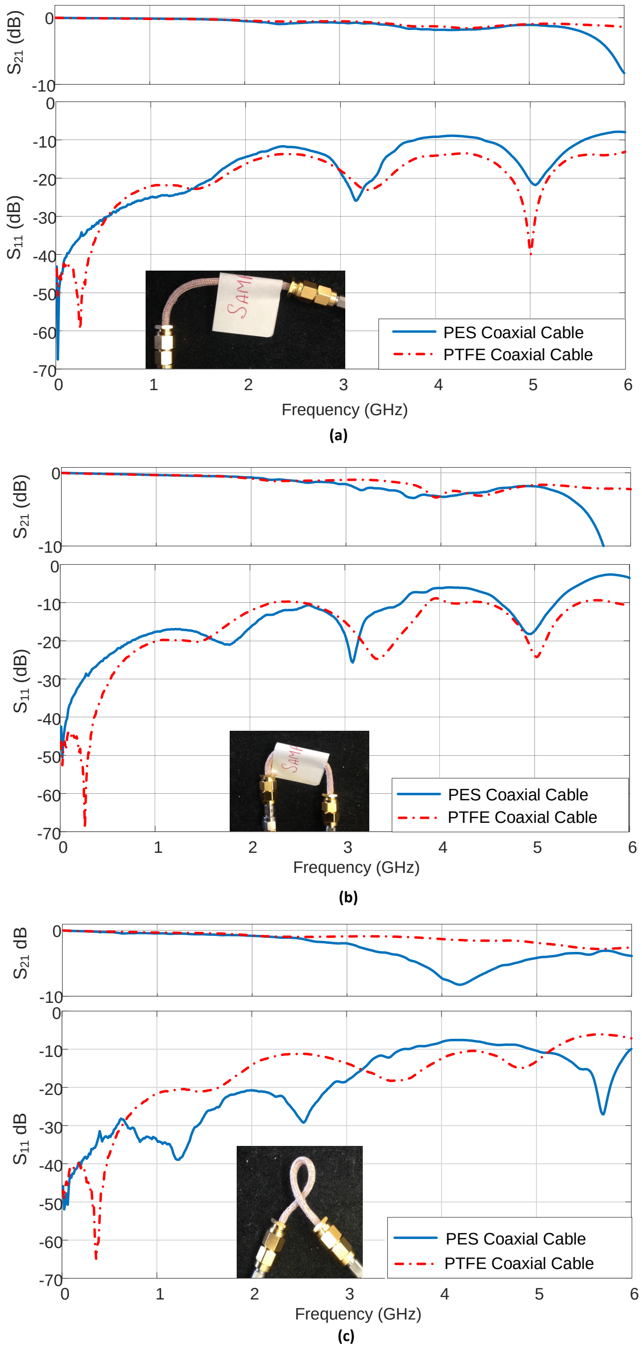

FIGURE 11. Bending tests of the cables demonstrating robustness: (a) 90° bend, (b) 180° bend, and, (c) the loop-like structure.

B. ROBUSTNESS TESTING

1) BENDING EXPERIMENTS

The performance of the textile cable prototypes under various bent conditions is another factor when considering the aforementioned wearable applications. It also demonstrates the physical robustness of the cables. To evaluate said performance, three different tests were performed. First, the cable was bent 90°, second, it was bent to 180° and lastly, it was bent to its maximum tolerance by forming a loop-like structure (similar to a knot). The S_{11} and S_{21} of the coaxial was measured for all the three cases. Figures 11(a), (b) and (c) shows the S_{11} and S_{21} for these scenarios.

For the 90° bend case, the measured S_{11} for the polyester cable is below -10 dB up to 3.5 GHz and the measured S_{21} is above -2 dB up to 3.5 GHz. A similar behavior can be noticed for the 180° bend and the loop-like scenario for the polyester cable. In comparison with the PTFE cable, $S_{11} \leq$ -10 dB for the following cases: 90°, 180° and the loop-like knot test. The PTFE prototype also shows very consistent performance up to 3.8 GHz with S_{21} above -2 dB and being between -2 dB and -3.5 dB up to 6 GHz. Similar performance is noticed for the PTFE prototype for the 180° bend case and the loop-like condition. It is worth mentioning here that the bending tests were performed multiple times (about 50) for 5 different samples and the performance of the cables was still consistent for all cases.

From these studies, it can be summarized that the proposed textile cables can yield low-loss performances for straight as well as the various bending and twisting scenarios. For example, in all cases the measured insertion losses are about 1 dB and 0.5 dB for the PES and PTFE cables, respectively.

2) WET TESTING

To further study the robustness of the PTFE prototype, a wet test was performed as reported in Fig. 12. This measurement was done considering the scenario where the cable is being worn by the user. This measurement test considered two conditions: completely wet and 24 hours later. It should be mentioned that after this 24 hour period, the cable appeared dry. Moreover, a completely wet condition can be considered when the cable is in contact with water either partially or completely, for example, due to rain or human sweat. This study also investigates the resiliency of the material after being made wet and then dried, which is similar to a washing scenario.

Insertion loss measurements were more than 8 dB up to 1 GHz for the 10 cm cable implying that the performance of the cable was not very efficient when it is wet (see Fig. 12(a)). However, these loss conditions are mitigated (once dry) maintaining similar results as in the standard testing case after 24 hours and when the cables were dry (see Fig. 9). The reason for the poor performance of the cable when wet is due to the higher dielectric constant and losses in water; i.e. ϵ_r can be more than 50 and $\tan\delta$ can be greater than 0.1 at 3 GHz [11], for example. Regardless, when designing wearable electronic systems which support such short textile-based transmission lines (as the proposed), transmit power levels could be made to accommodate for these possible insertion losses in the worst case and when operating under wet conditions. Also, such low-loss textile transmission lines could be made short to overcome the noted performances degradations when wet.

VI. CONCLUSION

The design of simple textile-based coaxial cables has been presented for wearable applications. The developed pro-

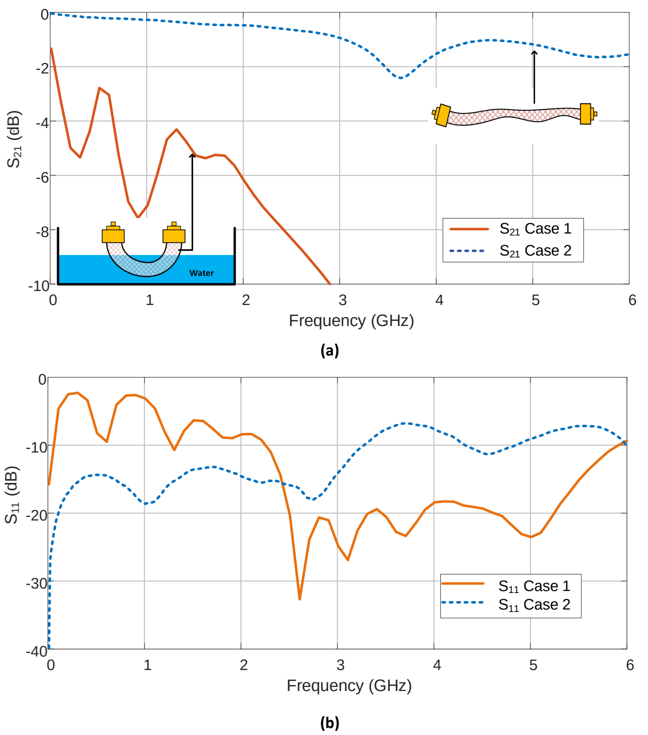

FIGURE 12. Measured S_{21} of the fabricated PTFE textile-based coaxial cable for wet and dry conditions, cases 1 and 2, respectively. Measured S_{11} for both cases. Once the cable dried after 24 hours, results are similar to Figs. 8 and 9.

totypes were manufactured from copper, PES, and PTFE hybrid yarns and these transmission line structures were simulated and measured whilst considering a 50-Ω characteristic impedance in the initial design stages. These lightweight structures offer low reflection coefficient and insertion loss values in the UHF and the 2.4 GHz ISM bands. It should be highlighted that the material selection and manufacturing process for the proposed cables, makes the coaxial lines have the texture and weight of a standard shoelace.

Measurements of the transmission line prototypes in terms of mass were also compared to a standard co-axial cable (see Table III). It can be observed that about a 40% and 30% reduction in mass is achieved for the PES and PTFE prototypes, respectively, when compared to a more standard and commercially available coaxial cable. Bending and twisting tests were also reported demonstrating the robustness of the cables. In addition, a DC analysis study was performed on the fabricated prototypes and the ohmic losses of the inner and outer conductors were measured and compared. Results which are at most 0.18 Ω/m (see Table III), and are significantly less than the values reported in [1] and [2] which range from 7.3 Ω/m to 17.2 Ω/m depending on the transmission line configuration. Also, in future work, to improve cable performance during humid and wet conditions, an exterior hydrophobic layer can be introduced to better encapsulate the braided yarn and copper textile materials. The motivation for this is to make the developed cables more resilient to wetness and other humid conditions.

As further discussed in our paper, the proposed textile-based coaxial cables offers a new and innovative approach when connecting wearable devices, in particular, when durable, lightweight, and flexible transmission lines are required. Moreover, to the authors best knowledge, this is the first implementation of textile-based transmission lines which achieve characteristic impedances very close to 50-Ω. This makes the developed structures suitable for standard microwave systems as well as conventional connectivity to other RF devices. These features can support robust and new communication systems which are designed to be wearable.

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