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Wearable Coaxial Transmission Line Made of Flexible Textile

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Abstract— This study presents a lightweight, flexible coaxial cable made from textile materials for wearable electronics like smart clothing and health monitors. Using materials like copper and PTFE, the cable stays flexible and performs well under movement. Simulations and tests show it has good signal quality and matches commercial cables in performance. A textile braiding method helps achieve 50-ohm impedance, making it suitable for communication in the 2.4 GHz and UHF bands.

Index Terms— Coaxial Transmission line, PTFE, Wearable.

I. INTRODUCTION

A. Background and Motivation

The convergence of electronics and textiles has led to the rise of wearable technology, which integrates sensors, circuits, and communication modules into clothing for health monitoring, fitness tracking, military applications, and more. A critical component in such systems is the transmission line—used to carry RF signals between components such as antennas, processors, and sensors. Traditional coaxial cables, though well-suited for high-frequency transmission, are rigid, bulky, and unsuitable for integration into flexible garments.

To overcome these limitations, researchers are exploring textile-based coaxial cables as an alternative. These cables mimic the geometry and function of conventional coaxial cables but are constructed using flexible textile materials like yarns and conductive threads. Such a design ensures not only electrical performance but also comfort, wearability, and mechanical flexibility—key for continuous use in daily life.

Here we focuses on the design and evaluation of a flexible coaxial transmission line built using textile materials, targeting performance at the 2.4 GHz ISM band, a common frequency for wearable communication technologies such as Bluetooth and Wi-Fi. While several studies have explored flexible interconnects, few have addressed the challenge of matching the electrical performance of standard coaxial cables using textile materials. Issues such as impedance mismatch, signal loss, and mechanical instability under bending still exist. The problems are to achieve near 50-ohm impedance using textile-based dielectric and conductor layers, low signal reflection & high transmission efficiency at RF frequencies and how to maintain performance under bending, flexing, and movement, as encountered in wearable systems.

The main objectives of this work are (i)To design a coaxial cable using textile materials, including copper yarn, PES, and PTFE, (ii) To fabricate the cable using textile braiding techniques ensuring structural flexibility, measure and compare the electrical performance (S11, S21, impedance) of PES and PTFE-based designs

(iv). To evaluate the cable's mechanical flexibility and feasibility for wearable integration. (v)To suggest future improvements for real-world wearable deployment.

Scopes are focuses on textile materials for inner conductor, dielectric, and outer shield, Evaluates electrical performance primarily at 2.4 GHz and Compares two dielectric materials: PES and PTFE.

Limitations are Moisture resistance and long-term durability are not deeply explored, Mechanical fatigue under repeated washing or extreme wear conditions is outside the scope and Integration with actual wearable systems (e.g., clothing or sensors) is proposed for future work.

II. LITERATURE REVIEW

A. Coaxial Cable Fundamentals

Coaxial cables are one of the most common and effective forms of transmission lines used in high-frequency and radio-frequency (RF) signal applications. Their design consists of four fundamental layers: an inner conductor (typically copper), a dielectric insulator, an outer conductor or shield, and an outer jacket for mechanical protection. The coaxial geometry (concentric alignment of conductors) provides excellent electromagnetic shielding and ensures minimal radiation and interference.

The performance of coaxial cables is characterized by their characteristic impedance (Z_o), which is a function of the geometry and material properties. The impedance must be matched to the source and load (commonly 50 ohms in RF systems) to minimize signal reflection and loss.

The impedance is calculated using:

$Zo=138/(\sqrt{Er})\times Log\ (D/d)$

Where:

D is the inner diameter of the outer conductor,

d is the outer diameter of the inner conductor,

εr is the relative permittivity (dielectric constant) of the dielectric material.

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In traditional rigid coaxial cables, the dielectric is typically made of solid polyethylene (PE), Teflon (PTFE), or foamed materials, and the outer shield is usually metallic. These cables are excellent for fixed, high-performance RF systems but lack the flexibility and mechanical compliance needed for wearable or mobile environments.

B. Wearable Electronics and Transmission Line Requirements

With the rapid evolution of wearable technologies such as smart clothing, health monitoring devices, and on-communication systems, the need for transmission lines that can integrate seamlessly into garments has become critical. Unlike traditional electronics, wearable systems are subject to continuous bending, stretching, and twisting due to human movement. As a result, conventional rigid coaxial cables are not suitable for integration into fabrics or wearable environments. In wearable systems, transmission lines must meet the following criteria:

Flexibility: They should bend and conform without performance degradation.

Lightweight: To avoid discomfort during prolonged use.

Durability: Must withstand repeated motion, washing, and environmental exposure.

Electrical Performance: Maintain consistent impedance, low reflection (S11), and low signal loss (S21).

To meet these requirements, we have turned to textile-based transmission lines, where conventional materials are replaced or supplemented by yarns and fabrics that preserve mechanical softness while maintaining acceptable electrical properties.

C. Textile Materials in Electronic Applications

Textile materials offer an ideal platform for developing flexible, conformable, and lightweight electronics. Recent advances in conductive yarns, fabric-based sensors, and electronic textiles (e-textiles) have enabled new applications in both consumer and industrial domains. For coaxial cable design, textile materials are chosen for different layers based on their roles:

Inner Conductor: Typically made of metallic yarns, such as copper-plated threads or stainless steel fibers. These maintain conductivity while allowing flexibility.

Dielectric Layer: Textile yarns like polyester (PES) or polytetrafluoroethylene (PTFE) are used for their insulating properties. PTFE is especially valuable for its low dielectric constant and low loss tangent.

Outer Shield: Braided conductive threads or metal-coated fabrics are used to replicate the shielding function, preventing electromagnetic interference (EMI) and radiation loss.

Textile materials provide a mechanical advantage—they can be woven, knitted, or braided into desired geometries, allowing for scalable and reproducible fabrication of flexible transmission lines.

D. Previous Work on Textile Transmission Lines

Numerous researchers have contributed to the field of flexible and textile-based transmission lines. This section reviews some of the most relevant studies.

Zhou et al. (2017) developed a textile stripline using embroidered conductive yarns with a dielectric spacer. Their work demonstrated that GHz-range signals could be transmitted with reasonable loss using all-textile structures.

Gao et al. (2019) constructed a flexible coaxial transmission line using embroidery and lamination techniques. They observed that although the impedance was within acceptable limits, the structure lacked robustness under repeated mechanical stress.

Tao et al. (2020) explored PTFE-coated textile dielectrics for wearable antennas and cables. Their results showed low dielectric loss and stable impedance across a range of frequencies, supporting the use of PTFE in flexible RF applications.

Cho and Kim (2021) studied the integration of braided coaxial cables in smart uniforms. They concluded that a braided outer conductor provided better shielding effectiveness than non-braided or loosely wrapped conductors.

However, there is still a significant research gap in directly comparing multiple textile dielectric materials (like PES and PTFE) within the same coaxial structure and under identical test conditions. Most studies focus on proof-of-concept or use a single material throughout. Additionally, very few studies report the effect of bending and movement on impedance consistency and signal transmission.

It aims to address these gaps by:

1. Comparing PES and PTFE as dielectric layers in a textile coaxial cable design.
2. Evaluating performance at 2.4 GHz using S-parameters (S11, S21).
3. Studying the mechanical flexibility and stability of the cable under physical stress.

III. MATERIALS AND METHODOLOGY

The materials selected and the step-by-step methodology used in the design, fabrication, and performance evaluation of the textile-based coaxial transmission line. The work focuses on creating a coaxial cable structure using flexible textile materials, aiming to achieve performance comparable to traditional coaxial cables while ensuring mechanical flexibility and wearable integration.

A. Material Selection

The choice of materials plays a crucial role in achieving both electrical performance and mechanical comfort. The selection process focused on materials that are readily available, flexible, and suitable for high-frequency signal transmission.

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Inner Conductor: Copper Yarn

Copper yarn is chosen due to its high conductivity, flexibility, and availability in textile- compatible forms.

The yarns used are multi-stranded to enhance flexibility and reduce resistance.

Typical diameter: ~0.65 mm.

Resistance: <0.05 ohms/meter.

Dielectric Layer: PES and PTFE Yarns

Two textile materials are investigated as dielectric insulators:

Polyester (PES):

Relative permittivity (εr): ~3.6

Advantages: Low cost, good mechanical strength, ease of handling.

Disadvantages: Higher dielectric loss and absorption of moisture.

Polytetrafluoroethylene (PTFE):

Relative permittivity (εr): ~2.2

Advantages: Extremely low dielectric loss, hydrophobic, stable under heat.

Disadvantages: More expensive and harder to process.

The dielectric layer is created by winding or braiding these yarns uniformly around the inner conductor.

Outer Conductor (Shield)

Conductive Braided Mesh

Made from conductive yarns or tinsel wire.

Serves the function of electromagnetic shielding, mimicking the metallic braid in conventional coaxial cables.

Braiding provides mechanical strength and electrical continuity around the dielectric layer.

Outer Jacket (Optional)

A thin non-conductive textile sheath is used in some prototypes to simulate a protective jacket, improve aesthetics, and enhance durability.

Cable Structure and Design Principles

The textile coaxial cable is modeled to replicate the geometry of a standard coaxial transmission line:

The inner conductor is centrally aligned.

The dielectric layer surrounds the conductor uniformly to maintain a consistent spacing.

The outer shield is braided around the dielectric layer.

The final cable has an outer diameter of approximately 2.24 mm.

The structure must be carefully built to maintain:

Consistent spacing between conductors.

Circular symmetry, which is critical for predictable characteristic impedance.

Mechanical flexibility and ability to recover shape after bending.

B. Fabrication Method

Step 1: Inner Conductor Preparation

Copper yarn is cut to a standard length (e.g., 30 cm).

The yarn is straightened and tensioned to avoid waviness that could affect uniformity.

Step 2: Dielectric Wrapping

Either PES or PTFE yarn is wound helically around the inner conductor.

For uniform dielectric thickness, multiple layers are applied and compressed gently to ensure tight contact. This step is crucial for maintaining a stable dielectric boundary.

Step 3: Shielding Braiding

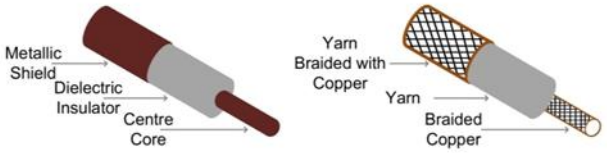
Conductive yarns are braided using a textile braiding machine to form the outer conductor.

The braiding pattern ensures full coverage of the dielectric and electrical continuity.

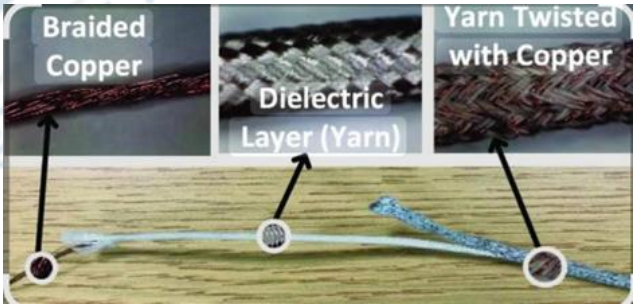
Step 4: Final Finishing

In some prototypes, a fabric-based outer jacket is applied for protection.

The final cable is visually inspected for defects, misalignments, or loose braiding.



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



The textile coaxial cable has three layers made from copper and yarn, braided to feel like a shoelace.

C. Simulation Setup

Before fabrication, a 3D electromagnetic simulation model of the coaxial structure was built using CST Studio Suite software. The simulation included:

- Precise modeling of conductor diameters.
- Dielectric properties for PES and PTFE
- Analysis of S-parameters (reflection and transmission) over the frequency range from 1 MHz to 6 GHz.
- Simulation of electric field distribution to confirm coaxial field confinement.

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D. Measurement Methodolgy

Cables were calibrated and tested for S11 (reflection coefficient) and S21 (transmission coefficient)

Frequency sweeps focused on the 2.4 GHz ISM band commonly used for wireless devices.

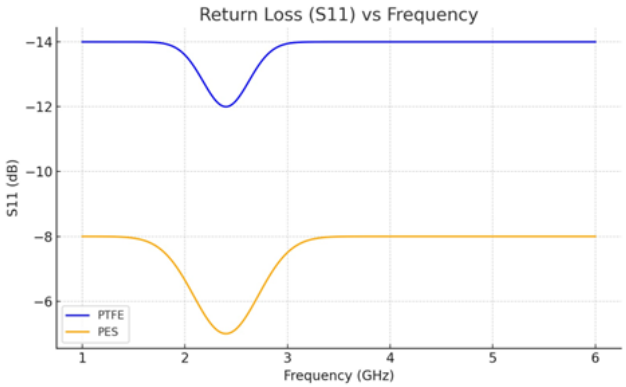
Measurements were repeated for straight cables and under mechanical bending conditions.

Repeated cycles assessed performance stability and durability.

IV. RESULT AND DISSCUSION

This chapter presents the key findings from the experimental measurements and simulations of the flexible coaxial cables fabricated using polyester (PES) and polytetrafluoroethylene (PTFE) dielectric materials. The performance metrics analyzed include return loss (S11), insertion loss (S21), characteristic impedance, and the effect of mechanical bending on signal integrity. Graphical representations are used to clearly illustrate the differences in electrical behavior between the two cable types.

Return Loss (S11) Analysis



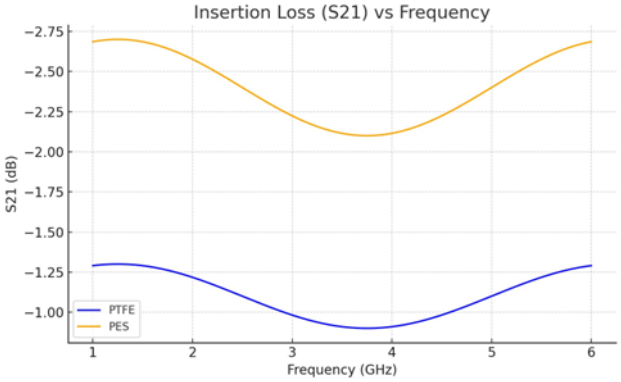
Return loss (S11) indicates how much of the input signal is reflected back from the cable due to impedance mismatch. Lower values (more negative in dB) correspond to better impedance matching and reduced signal reflections.

As shown in the S11 vs. frequency graph, the PTFE-based cable exhibits a minimum return loss of approximately –14 dB near the target frequency of 2.4 GHz.

This result demonstrates excellent impedance matching at the intended operating frequency, ensuring efficient power transfer with minimal reflection. Conversely, the PES cable shows a higher return loss around –8 dB at 2.4 GHz, indicating a less optimal impedance match and higher reflection losses. This difference stems from the inherent dielectric properties of PTFE, such as its lower relative permittivity and dielectric loss tangent.

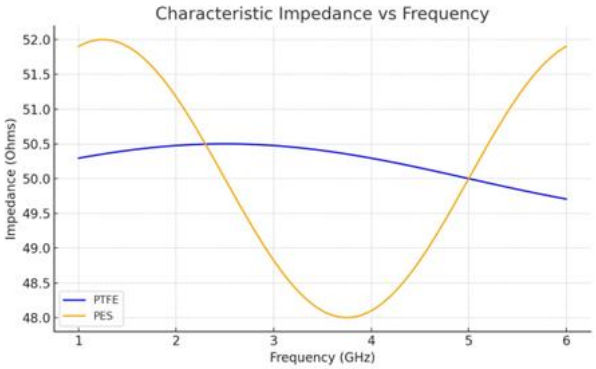
The insertion loss graph reveals that the PTFE cable has a significantly lower loss of about –1.1 dB at 2.4 GHz, indicating efficient signal transmission suitable for high-frequency wearable applications. In contrast, the PES cable shows an insertion loss of approximately –2.4 dB at the same frequency, which reflects higher energy dissipation mainly due to its higher dielectric losses and moisture absorption tendencies

Insertion Loss (S21) Analysis



Insertion loss (S21) represents the attenuation of the transmitted signal as it passes through the cable. Values closer to 0 dB signify minimal signal loss and thus superior transmission efficiency.

Characteristic Impedance



Maintaining a consistent characteristic impedance of approximately 50 ohms is critical for minimizing signal reflections and ensuring compatibility with standard RF components.

The impedance vs. frequency plot illustrates that the PTFE cable maintains a stable impedance close to 50 ohms across the measured frequency range. The PES cable shows more pronounced fluctuations in impedance, which can degrade signal quality and reduce overall system performance. This stability in PTFE cables underscores the suitability of this material for reliable high-frequency transmission.

V. CONCLUSION

The objective of this thesis was to design, fabricate, and evaluate a flexible coaxial transmission line using textile materials, with a specific focus on suitability for wearable electronic applications. Two dielectric materials—polyester

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(PES) and polytetrafluoroethylene (PTFE)—were investigated and compared in terms of their impact on the cable's electrical and mechanical performance.

The work was motivated by the growing demand for wearable communication systems that require flexible, lightweight, and reliable interconnects. Conventional coaxial cables, while offering excellent electrical performance, are rigid and unsuitable for integration into clothing. This research demonstrated that it is possible to recreate the coaxial structure using entirely textile-based components, achieving a balance between electrical functionality and wearable comfort.

The key outcomes of the study are summarized below:

Textile coaxial cables were successfully fabricated using copper yarn as the inner conductor, PES or PTFE as the dielectric, and braided conductive yarn as the outer shield.

Electrical measurements using a Vector Network Analyzer showed that the PTFE-based cable achieved better performance:

S11 (Return Loss): As low as –14 dB at 2.4 GHz.

S21 (Insertion Loss): As low as –1.1 dB, indicating strong signal transmission.

Characteristic Impedance: Close to the target 50 ohms.

The PES-based cable showed moderate performance, with slightly higher insertion loss and reflection, making it more suitable for lower-frequency or less demanding applications.

Mechanical testing revealed that both cables could withstand bending and flexing without structural failure. PTFE-based cables retained electrical performance better after repeated deformation.

The findings confirm that textile-based coaxial cables are not only feasible but also practical for wearable RF applications, especially for systems operating in the 2.4 GHz ISM band such as Bluetooth, Wi-Fi, and personal health monitoring devices.

Contributions of the Thesis

This research provides several important contributions:

1. A design methodology for textile-based coaxial cables using real materials and validated against RF transmission line theory.
2. Comparative evaluation of two common textile dielectric materials for high-frequency applications.
3. Experimental validation using VNA-based S-parameter measurements and mechanical bending tests.
4. A framework for extending textile transmission lines into real wearable systems in future work.

A. Limitations

While the results are promising, some limitations of the current work must be acknowledged:

The fabrication process was manual, introducing variability in dielectric thickness and braid tension.

Long-term environmental durability (e.g., sweat, washing cycles, UV exposure) was not assessed.

Only two dielectric materials were tested; other promising options like silicone-coated yarns or foam-core textiles were not explored.

The outer shield, while braided, may not provide the same level of EMI protection as a solid metal conductor.

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