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Exploring Polymer Substrates for CBSIW Antennas: Paper and Denim for Enhanced Gain and Bandwidth

M. Ravi Kishore[1,*], K.C.B. Rao[2]

Abstract

This paper presents a novel approach to antenna design by leveraging the unique properties of paper and Denim materials, both of which are polymers. This research underscores the potential of unconventional polymer materials like paper and jeans in antenna design, offering new avenues for the development of lightweight, flexible, and cost-effective communication devices for diverse wireless applications. The study focuses on the design and analysis of non-conventional substrate-based Circular Backed Substrate Integrated Waveguide (CBSIW) antennas. Specifically, two antennas, namely the Wearable Circular CBSIW antenna and Paper-based Circular CBSIW antenna, are designed and simulated using the HFSS simulator platform. These antennas are fabricated on Fabriano 5 paper and denim jeans substrates, respectively, and their performance characteristics are experimentally validated. The results demonstrate that the proposed multi-band paper-based antenna exhibits resonant frequencies at 2.4 GHz and 4.9 GHz with optimal bandwidths. Moreover, the denim-based antenna also shows promising performance. Notably, the peak gain of the proposed antennas reaches nearly 16 dB, indicating their suitability for various applications such as Wi-Fi, Bluetooth IIoT, Sub 6 GHz, and Intelligent Transport Systems.

Keywords: Polymer based substrates, Cellulose Fibre Based Paper Substrate, Synthetic Polymer Blended Denim Substrate, Cavity Backed Substrate Integrated Waveguide (CBSIW), Gain and Bandwidth of Antenna.

INTRODUCTION

Wearable antennas have emerged as a key enabler for various wireless communication applications, ranging from healthcare monitoring to industrial automation [1]. These antennas, integrated seamlessly into clothing and accessories, offer unobtrusive and convenient communication solutions for users. One crucial aspect in the development of wearable antennas is the selection of suitable substrates that provide both mechanical flexibility and electromagnetic performance [2, 3]. Figure 1 shows the compatibility of modern wireless communication technologies to wearable technology [4].

***Author for Correspondence**
M. Ravi Kishore
E-mail: mrkishore7709@gmail.com

[1]Research Scholar, Department of Electronics & Communication Engineering, Jawaharlal Nehru Technological University, Kakinada, Andhra Pradesh, India
[2]Professor, Department of Electronics & Communication Engineering, Jawaharlal Nehru Technological University, Gurajada, Vizianagaram, Andhra Pradesh, India

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In this context, denim, a ubiquitous textile material, presents an intriguing option for substrate material due to its unique combination of mechanical robustness and electrical properties. This paper aims to explore the design and analysis of wearable antennas utilizing denim as a substrate material, investigating their performance characteristics and potential applications.

Paper materials derived from cellulose fibres and denim materials blended with synthetic polymers present compelling alternatives as antenna substrates due to their distinctive blend of mechanical robustness, flexibility, and electromagnetic traits.

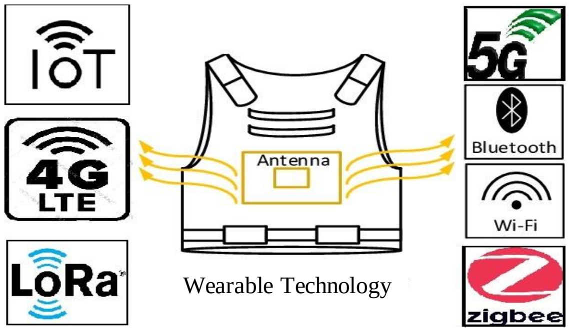

Figure 1. Wearable Technology.

By comprehending their attributes and aligning with antenna design prerequisites, both researchers and engineers can exploit the capabilities of paper and denim substrates to propel antenna technology forward across diverse domains such as wireless communication, IoT devices, and wearable electronics. Recent research efforts have focused on leveraging paper and textile materials for the development of wearable antennas, aiming to address the increasing demand for compact, lightweight, and conformal communication devices.

Research in the field of paper substrate-based antennas has progressed rapidly in recent years, driven by advancements in manufacturing techniques and the increasing demand for flexible and cost-effective communication solutions. Moro et al. [5] introduced the concept of plastic-based substrate integrated waveguide (SIW) components and antennas, highlighting the feasibility of using alternative materials for antenna fabrication. Moscato et al. [6] demonstrated the development of compact SIW components on paper substrates, showcasing the potential of paper-based antennas for microwave applications. Bozzi et al. [7] explored novel materials and fabrication technologies for SIW components, emphasizing the importance of eco-friendly materials for the Internet of Things (IoT) applications. Nauroze et al. [8] introduced inkjet-printed SIWs with “drill-less” vias on paper substrates, offering a cost-effective and scalable manufacturing solution for paper-based antennas. Tan and Poo [9] proposed a broadband concave paper antenna, highlighting the versatility of paper as a substrate material for antenna design. Prebianto and Futra [10] provided a comprehensive review of paper as a substrate for sensor applications, emphasizing its potential in various sensing applications. Le Dam et al. [11] developed a reconfigurable screen-printed patch antenna on paper for 4G and 5G applications, showcasing the adaptability of paper-based antennas to emerging wireless communication standards. Additionally, Moro et al. [12] and Bozzi et al. [13, 14] investigated inkjet-printed paper-based SIW components and antennas, demonstrating the feasibility of integrating paper substrates into complex innovative antenna designs. The recent research also focused on leveraging textile materials for the development of wearable antennas, aiming to address the increasing demand for compact, lightweight, and conformal communication devices. Moro et al. [15] introduced the concept of textile microwave components in substrate integrated waveguide (SIW) technology, highlighting the feasibility of integrating antennas into textile substrates for microwave applications. Bozzi et al. [16] further demonstrated innovative SIW components on paper, textile, and 3D-printed substrates, showcasing the potential of textile-based antennas for Internet of Things (IoT) applications. Various studies have explored the performance of wearable antennas in real-world scenarios. Castel et al. [17] investigated the capacity of broadband body-to-body channels between fire fighters wearing textile SIW antennas, highlighting the effectiveness of wearable antennas in challenging environments. Hong et al. [18, 19] proposed an all-textile SIW cavity-backed circular ring-slot antenna for wireless body area network (WBAN) applications, emphasizing the importance of antenna design for wearable communication systems. Despite the progress in wearable antenna research, several gaps remain in the existing literature. El gharbi et al. [20] analyzed the effects of the human body on the performance of wearable textile antennas, revealing the need for comprehensive understanding of the antenna-body interaction. Martinez et al. [21] emphasized the importance of compact, low-profile textile antennas with improved bandwidth for easy garment integration, pointing towards the necessity for antenna miniaturization and performance optimization. Pei's work in [22] presents a wearable EBG-backed belt antenna, while Celenk and Tokan propose an all-textile on-body antenna for military use [23]. Zhang et al. focus on a compact dual-band textile antenna design using metasurface technology [24]. These studies contribute to the growing field of wearable and textile antenna research.

The literature review reveals several key research gaps in the field of wearable antennas using paper and textile substrates, including:

- Need for innovative substrate materials with enhanced mechanical flexibility and electromagnetic properties.
- Challenges in achieving compact and low-profile antenna designs with sufficient bandwidth of CBSIW antennas for practical applications.
- Lack of comprehensive studies on the gain performance of CBSIW wearable antennas under varying environmental conditions.

Based on the identified research gaps, this paper focuses on the design and analysis of wearable antennas using paper and denim as substrate materials. Paper and Denim are known for their versatility, presents a promising option for wearable antenna applications. Additionally, the utilization of denim and paper materials as substrate materials offer potential benefits such as cost-effectiveness, biodegradability, and aesthetic appeal. By investigating the electromagnetic properties and performance characteristics of paper and denim-based antennas, this paper aims to contribute novel designs of Cavity Backed Substrate integrated Waveguide (CBSIW) antennas with improved bandwidth and gain using polymer based substrates.

This paper is prearranged as follows. Section II illustrates the fundamental description of polymers and electromagnetic properties of Paper and denim substrates. Section III describes methodology followed for design of Cavity Backed Substrate Integrated Waveguide (CBSIW) on proposed polymer substrates. Section IV demonstrates the results elucidating antenna radiation characteristics and finally Section V is conclusion.

UNDERSTANDING POLYMERS AND ELECTROMAGNETIC TRAITS OF PAPER AND DENIM SUBSTRATES

The polymer material properties of paper and denim substrates play a significant role in their exposure to electromagnetic radiation. Understanding these properties is crucial for designing and optimizing antennas for various applications, from wearable electronics to IoT devices and beyond. Through careful selection and manipulation of substrate materials, antenna designers can unlock new possibilities for enhancing performance and functionality.

Polymers

Polymers, derived from the Greek words “poly” meaning many and “meros” meaning parts, are large molecules composed of repeating structural units called monomers [25, 26]. These versatile materials form the basis of a wide range of substances, from natural materials like proteins and cellulose to synthetic plastics and elastomers. The unique properties of polymers arise from the arrangement, size, and bonding characteristics of their molecular chains. Polymers play a crucial role in various industries, including manufacturing, medicine, electronics, and consumer goods. They offer benefits such as lightweight, durability, flexibility, and chemical resistance, making them indispensable in modern society [27–29]. Understanding the structure-property relationships of polymers enables scientists and engineers to tailor their characteristics for specific applications, driving innovation across diverse fields. Figure 2 shows the basic formation of Polymers of recurring chains of molecules [30].

Polymerization is the process of combining small molecules into long chains to form polymers [31] as shown in Figure 3. Polymer materials like paper and denim offer intriguing possibilities for antenna substrates due to their unique electromagnetic properties. Understanding how these materials interact with electromagnetic radiation is crucial for optimizing antenna performance.

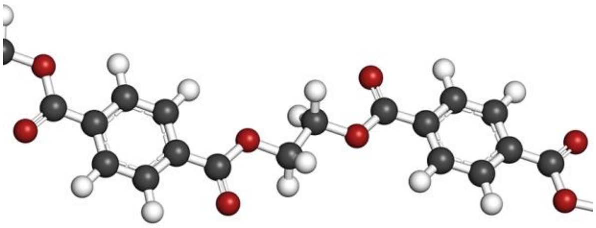

Figure 2. Polymers, synthetic or natural, consist of recurring chains of molecules.

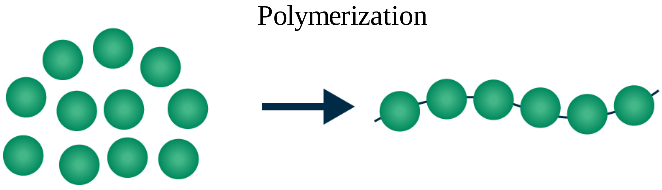

Figure 3. Polymerization.

Properties of Paper and Denim Polymers

At a fundamental level, both paper and denim are composed of long chains of organic molecules, forming polymers. These polymers possess specific dielectric properties that affect their interaction with electromagnetic fields. Dielectric properties such as permittivity and loss tangent determine how efficiently a material can store and release electrical energy when exposed to an electromagnetic field.

The literature in [32–41] encompasses various materials and composites studied for their effectiveness in electromagnetic properties of polymer based materials. Yoshida and Fujiwara (2003) investigated the electromagnetic wave absorption properties of textiles containing carbon microfibers. Nagasawa and Naito (2005) explored the EMI absorbing properties of carbon nanotube/thermoplastic polyurethane composites. Gupta and Dubey (2014) provided a comprehensive review of polymer composites for EMI shielding, highlighting their diverse properties and applications. Sadasivuni et al. (2014) discussed dielectric materials' role in EMI shielding, emphasizing their importance in electrical applications. Li et al. (2017) introduced flexible carbon aerogels with high EMI shielding effectiveness. Additionally, research has focused on advanced materials such as graphene/polymer nanocomposites (Kim et al., 2010) and natural fibers (Thomas et al., 2011) for their potential in EMI shielding applications. Furthermore, efforts have been made to explore cellulose nanofibril-polymer nanocomposites (Biswas et al., 2019) and natural polymer-based nanocomposites (Shanmugam et al., 2020) for their efficacy in EMI shielding. Moreover, Kim and Kim (2018) reviewed the utilization of paper-based electronics in biomedical applications, highlighting their significance in wearable and implantable devices. These studies collectively contribute to advancing the field of EMI shielding materials and technologies.

Cellulose Fibre Based Paper Substrate: Paper is primarily composed of cellulose fibers, which are a type of polymer. The cellulose polymer chain structure [42] is shown in the Figure 4. These fibers can provide good dielectric properties and can be engineered to have specific electrical characteristics suitable for antenna substrates. However, paper may not be as durable or water-resistant as other polymer substrates.

The dielectric properties of paper material are influenced by factors such as fiber composition, density, and moisture content. Generally, paper has a relatively low permittivity compared to other common substrates like FR4 or Rogers materials. This lower permittivity results in a slower propagation velocity of electromagnetic waves through the material. Additionally, the loss tangent of paper is typically higher compared to synthetic substrates, leading to increased absorption of electromagnetic energy. These properties make paper suitable for applications where moderate bandwidth and impedance matching are essential. Fabriano 5 paper [43,44] is one of the high-quality, versatile substrates usable in antenna shown in Figure 5. Fabriano 5 paper possesses electromagnetic properties conducive to diverse applications. Its composition and structure influence its interaction with electromagnetic waves, making it suitable for RFID tags, electromagnetic shielding, and even antennas. The paper's conductivity, dielectric constant, and magnetic permeability contribute to its efficacy in such electromagnetic functionalities, enhancing its utility across various domains.

Key Properties of Paper as a Polymer

Paper is primarily composed of cellulose fibers, which are a type of polymer. Cellulose is a long-chain polymer made up of repeating units of glucose molecules. Here are some key properties of paper as a polymer:

Hydrophilic Nature: Cellulose fibers have hydrophilic properties, meaning they have a strong affinity for water. This property can affect the absorption and release of moisture by paper, making it susceptible to changes in humidity and environmental conditions.

Mechanical Strength: Cellulose fibers provide paper with excellent mechanical strength, allowing it to withstand tensile, compressive, and bending forces. The arrangement of cellulose fibers in paper contributes to its overall strength and durability.

Flexibility: Despite its strength, paper remains flexible and can be easily folded, bent, or manipulated into various shapes. This flexibility makes paper suitable for a wide range of applications, from packaging materials to printing substrates.

Dielectric Properties: Cellulose has relatively low dielectric constants, which can vary depending on factors such as moisture content and density. This property makes paper suitable for electrical insulation applications and as a substrate material for antennas and electronic devices.

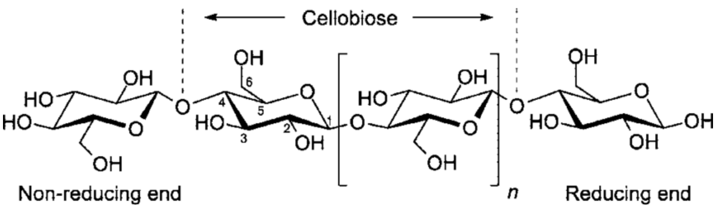

Figure 4. Cellulose Polymer Chain Structure.

Figure 5. Fabriano 5 Paper Substrate.

Biodegradability: One of the most notable properties of paper is its biodegradability. Being derived from natural cellulose fibers, paper can be broken down by microorganisms over time, making it an environmentally friendly material compared to many synthetic polymers.

Porosity: Paper is inherently porous, with gaps and voids between cellulose fibers. This porosity can influence properties such as absorption, permeability, and airflow through the material.

Surface Chemistry: The surface of paper can be modified through treatments or coatings to enhance its properties, such as water resistance, printability, or adhesion.

Overall, the polymer properties of cellulose in paper contribute to its versatility, making it a widely used material in various industries, including packaging, printing, textiles, and electronics.

Electromagnetic Properties of Paper Substrate

Paper, as a substrate for antennas, offers a unique set of electromagnetic properties that can influence antenna performance. Here's an overview:

Low Cost: Paper is an inexpensive and widely available substrate, making it attractive for low-cost antenna fabrication, especially for disposable or temporary applications.

Lightweight: Paper is lightweight compared to traditional substrates like FR4 or ceramics, which can be advantageous for applications where weight is a concern, such as in lightweight or portable devices.

Flexibility: Depending on the thickness and type of paper, it can offer flexibility, allowing for conformal or curved antenna designs. This flexibility can be beneficial for integrating antennas into irregularly shaped objects or structures.

Biodegradability: Paper is biodegradable and environmentally friendly, making it suitable for disposable or eco-friendly applications where sustainability is a consideration.

Absorption: Paper has a tendency to absorb moisture, which can help mitigate impedance variations due to changes in environmental conditions, particularly in humid environments.

Dielectric Constant and Loss Tangent: The dielectric constant and loss tangent of paper can vary depending on factors such as moisture content, type of paper, and manufacturing process. In general, paper tends to have a relatively high dielectric constant and loss tangent compared to other RF substrates, which can lead to increased losses and reduced antenna efficiency, especially at higher frequencies.

Thickness Variability: Paper thickness may not be uniform across the substrate, leading to variations in the antenna's impedance and performance. This variability can be challenging to control during fabrication and may require additional measures to ensure consistent performance.

Surface Roughness: The surface of paper may exhibit irregularities and roughness, which can affect the antenna's radiation pattern and impedance matching. Surface treatment or coating may be necessary to minimize these effects.

Environmental Sensitivity: Paper is sensitive to environmental factors such as humidity, temperature, and moisture, which can impact its dielectric properties and, consequently, the antenna's performance. Careful design considerations and environmental testing may be required to account for these effects.

Limited Frequency Range: Due to its relatively high dielectric constant and loss tangent, paper may not be suitable for high-frequency applications where low loss and precise impedance control are critical. Overall, while paper offers advantages such as low cost, lightweight, and flexibility, its electromagnetic properties, including dielectric constant, loss tangent, and environmental sensitivity, can pose challenges for antenna designers. Understanding these properties and their implications is essential for designing paper-based antennas that meet the desired performance requirements for specific applications.

Synthetic Polymer Blended Denim Substrate

Denim is made from cotton, which is also a polymer. Cotton fibers provide mechanical strength and flexibility, making denim a versatile material for various applications. The composition of Synthetic Polymer Blended Denim [45] is shown in Figure 6 and 7. When treated or coated with appropriate substances, denim can exhibit desirable dielectric properties, making it suitable for antenna substrates. Additionally, denim's widespread availability and low cost make it an attractive option for certain antenna applications.

On the other hand, denim, being a textile material, exhibits more complex dielectric behavior due to its fibrous structure. The permittivity of denim varies depending on factors such as fabric weave, yarn composition, and thickness. Generally, denim has a higher permittivity compared to paper, allowing for faster wave propagation. However, the fibrous nature of denim also introduces higher losses due to dielectric and conductor losses within the fabric structure. This can lead to greater absorption and attenuation of electromagnetic waves, affecting the overall efficiency of the antenna.

Key Properties of Denim as a Polymer

Jeans, as in denim fabric used for making jeans, is typically made from cotton fibres, which are woven together to form a sturdy and durable material. However, to enhance certain properties or introduce specific characteristics, denim can also be blended with other types of fibres, including synthetic polymers. Here's a general overview of the properties of denim when blended with synthetic polymers:

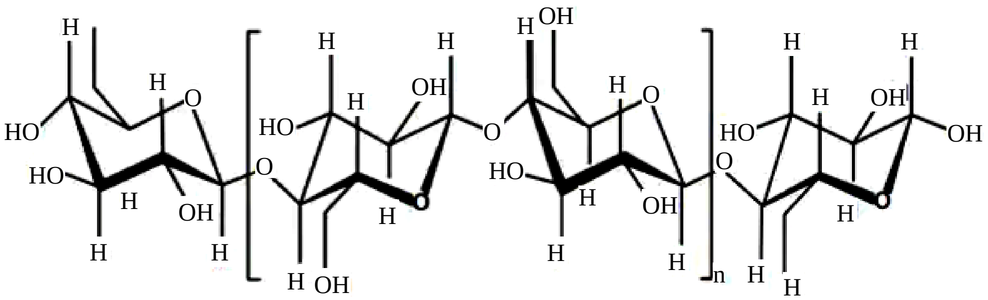

Figure 6. Synthetic Polymer Blended Denim.

Figure 7. Denim Jeans Substrate.

Strength and Durability: Synthetic polymers like polyester or nylon can be blended with cotton to increase the strength and durability of denim fabric. This makes the jeans more resistant to wear and tear, resulting in a longer lifespan for the garment.

Wrinkle Resistance: Synthetic polymers are often more resistant to wrinkling compared to natural fibres like cotton. Blending cotton with polyester, for example, can help reduce wrinkling in denim fabric, making the jeans easier to care for and maintain their appearance over time.

Stretch and Elasticity: Some synthetic polymers, such as spandex (also known as Lycra or elastane), are highly elastic and can be blended with cotton to add stretchiness to denim fabric. This enhances the comfort and flexibility of the jeans, allowing for greater freedom of movement.

Moisture Management: Certain synthetic polymers have moisture-wicking properties that help draw moisture away from the skin, keeping the wearer dry and comfortable. Blending these polymers with cotton denim can improve the fabric's moisture management capabilities, making the jeans suitable for active wear or warm weather conditions.

Colourfastness: Synthetic polymers are often more resistant to fading than natural fibres. Blending cotton with polyester, for instance, can help improve the colourfastness of denim fabric, ensuring that the jeans retain their color vibrancy even after multiple washes.

Shrink Resistance: Synthetic polymers can also help reduce the tendency of denim fabric to shrink when washed. Blending cotton with polyester or other shrink-resistant polymers can minimize shrinkage, allowing the jeans to maintain their original size and shape.

Overall, blending denim with synthetic polymers can impart a variety of desirable properties to jeans, including increased strength, durability, stretch, wrinkle resistance, moisture management, colourfastness, and shrink resistance. These properties make synthetic polymer-blended denim an attractive choice for manufacturing high-quality, comfortable, and long-lasting jeans.

Electromagnetic Properties of Paper Substrate: In recent years, the field of antenna design has witnessed a growing interest in unconventional substrate materials to meet the evolving demands of modern communication systems. Traditional substrates like fiberglass and ceramics offer well-established properties but may lack versatility or cost-effectiveness in certain applications. This has led researchers to explore alternative materials, including synthetic polymer-blended denim, traditionally known for its use in garment manufacturing, particularly in jeans production.

Denim, a sturdy and durable fabric typically made from cotton fibers, has garnered attention for its potential as an antenna substrate when blended with synthetic polymers such as polyester, nylon, or elastane. This paper aims to review the electromagnetic properties of synthetic polymer-blended denim and explore its usability as an antenna substrate in various antenna design considerations.

Properties of Synthetic Polymer-Blended Denim

Strength and Durability: Synthetic polymers enhance the strength and durability of denim, making it suitable for supporting antenna structures and withstanding environmental factors.

Stretch and Elasticity: Incorporating elastane or similar polymers adds stretchiness to denim, facilitating flexibility in antenna design and deployment.

Substrate Dielectric Properties: The dielectric constant and loss tangent of synthetic polymer-blended denim influence antenna impedance matching and radiation efficiency.

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Mechanical Stability: The structural integrity of denim substrates ensures antenna robustness and longevity in diverse operating environments.

Moisture Management: Certain synthetic polymers offer moisture-wicking properties, maintaining antenna integrity in humid or wet conditions.

Colourfastness: Synthetic polymers improve colour retention in denim, preserving antenna aesthetics and visibility.

Wrinkle Resistance: Blending denim with synthetic polymers reduces wrinkling, ensuring consistent antenna performance over time.

Shrink Resistance: Denim blended with shrink-resistant polymers maintains dimensional stability, crucial for antenna precision and performance.

Usability in Antenna Design

Fabrication Compatibility: Synthetic polymer-blended denim's compatibility with conventional fabrication techniques enables cost-effective antenna manufacturing processes.

Flexibility in Form Factor: The flexibility and stretchability of denim substrates facilitate innovative antenna form factors, supporting conformal, wearable, or deployable designs.

Environmental Considerations: Sustainable production practices and recyclability make synthetic polymer-blended denim an eco-friendly choice for antenna substrates.

When exposed to electromagnetic radiation, both paper and denim substrates exhibit interaction mechanisms such as reflection, transmission, and absorption. Reflection occurs when electromagnetic waves encounter a change in impedance at the interface between the substrate and air or another medium. The amount of reflection depends on the impedance mismatch and the angle of incidence. Transmission occurs when electromagnetic waves pass through the substrate with minimal attenuation. Absorption, on the other hand, occurs when electromagnetic energy is converted into heat within the substrate material.

The electromagnetic properties of paper and denim substrates directly impact antenna performance parameters such as gain, bandwidth, and radiation pattern. By carefully selecting and engineering these substrates, antenna designers can tailor these properties to meet specific application requirements. For example, the slower wave propagation in paper may be advantageous for achieving wideband performance, while the higher permittivity of denim could be utilized to enhance antenna efficiency.

The Importance of Gain and Bandwidth

For denim and paper-based substrates in substrate integrated waveguide (SIW) antennas, the importance of gain and bandwidth remains significant, albeit with some unique considerations.

Gain: Gain measures the antenna's ability to direct electromagnetic energy in a particular direction compared to an ideal isotropic radiator. In the case of denim and paper substrates, which are relatively lossy compared to traditional substrates like FR4 or Rogers materials, achieving high gain becomes crucial to compensate for the substrate losses. High gain helps improve the antenna's performance by enhancing signal strength and extending communication range. Antenna engineers working with denim and paper substrates may employ design techniques such as optimizing the SIW structure, incorporating efficient feeding mechanisms, and carefully selecting radiating elements to maximize gain while mitigating substrate losses.

Bandwidth: Bandwidth refers to the range of frequencies over which the antenna can operate effectively. In the context of denim and paper substrates, which may have higher dielectric losses compared to conventional substrates, ensuring sufficient bandwidth is essential to maintain reliable communication performance. Wide bandwidth enables the antenna to accommodate various frequency bands and adapt to different operating environments and communication standards. Antenna designers may employ strategies such as impedance matching techniques, bandwidth enhancement structures, and careful substrate selection to achieve the desired bandwidth while accounting for the substrate's electrical properties and limitations.

In summary, for SIW antennas on denim and paper-based substrates, optimizing gain and bandwidth becomes crucial to compensate for substrate losses and ensure reliable communication performance. Antenna engineers need to carefully consider design strategies that enhance gain and broaden bandwidth while accommodating the unique characteristics of the chosen substrate materials.

METHODOLOGY

The design approach for the proposed wearable Textile and Paper based CBSIW antennas adhere to precise mathematical formulation and the established design principles of basic CBSIW structures. The key dimensions of any SIW structure are intricately linked to both the operational frequency and the effective dielectric constant of the substrate material employed [44–48].

Achieving a circular SIW cavity structure involves strategically inserting cylindrical-shaped air-filled vias into the substrate with optimal spacing. The mitigation of energy loss from the structure's sidewalls is contingent upon factors such as the diameter and spacing of these vias. In this instance, Denim jeans Textile material and paper material, characterized by a dielectric constants of 1.6 and 2.25 respectively, serve as the substrates for the two proposed SIW antennas. Additionally, two slots with optimized dimensions are strategically integrated atop the cavity to elicit the desired radiation characteristics. The proposed antennas are simulated in High Frequency Structure Simulator (HFSS) software.

HFSS Software

High Frequency Structure Simulator (HFSS) software plays a pivotal role in antenna design by providing engineers with a powerful tool to simulate, analyze, and optimize the performance of various antenna configurations across a wide range of frequencies. HFSS utilizes finite element method (FEM) and finite element-boundary integral (FEBI) techniques to accurately model electromagnetic fields and interactions within complex structures.

Engineers can design antennas with precise control over parameters such as dimensions, materials, and operating frequencies. The software enables users to simulate antenna behaviour under different conditions, including radiation patterns, impedance matching, and bandwidth analysis. By visualizing electromagnetic fields and currents, engineers can identify potential issues and refine antenna designs for optimal performance.

HFSS streamlines parametric studies, enabling engineers to efficiently navigate extensive design spaces. Optimization algorithms automate the iterative refinement of antenna designs, aligning them with specified performance criteria like gain, directivity, and efficiency. This accelerates the development process, enhancing productivity and enabling the creation of optimized antenna systems with greater precision.

Design Equation

The design of Wearable Circular CBSIW antenna follows the following equations of circular cavity resonators of resonating frequency

$$f_r = \frac{c}{2\pi\sqrt{\varepsilon_r}}\left(\frac{P_{nm}}{r}\right) \quad (1)$$

Where f_r is resonant frequency, c is velocity of light $3 \times 10^8 m/s$, P_{nm} represents the eigen value to be determined depending on the mode, $\boldsymbol{\varepsilon_r}$ represents the dielectric constant of the substrate, and $\boldsymbol{r}$ represents the radius of the circular cavity.

Design Steps

Using the equation provided above, the design of the proposed antennas was executed on HFSS platform as illustrated in Figures 8 and 9. The steps are as follows:

1. Compute the cavity radius based on the prescribed mode.
2. Calculate the patch dimensions for the given dielectric constant. For Fabriano 5 substrate (ε_r = 2.25) and for Denim jeans substrate (ε_r = 1.6).
3. Determine the dimensions of the Vias, Ground, and Substrate to match the cavity size.
4. Place the necessary number of vias on the substrate with pre-determined dimensions.
5. Integrate two semi-concentric circular/rectangular shaped slots on the patch with optimized dimensions to induce multiple resonant frequencies.
6. Install the coaxial feed cable back into the cavity at an optimized location.
7. Configure the Analysis Setup and Frequency sweep as per requirements.
8. Conduct a validation check and proceed to Analyze all.
9. Evaluate the results, including 2-D and 3-D radiation patterns, return losses, gain, efficiency, etc.

Fabrication and Testing of Proposed Antennas

Fabricating antennas on denim and paper substrates involves several key steps. Firstly, the substrate is prepared by cleaning and possibly coating it to enhance its electrical properties. Next, conductive materials like copper or silver are patterned onto the substrate using techniques such as printing, etching, or deposition, forming the antenna's radiating elements and feed structures. Additional components such as matching networks or baluns may be integrated as needed. Finally, the fabricated antenna is assembled and tested for performance. The lightweight and flexible nature of denim and paper substrates offers advantages for applications requiring conformal or low-cost antenna designs. The fabricated prototypes of the proposed antennas are shown in Figure 10.

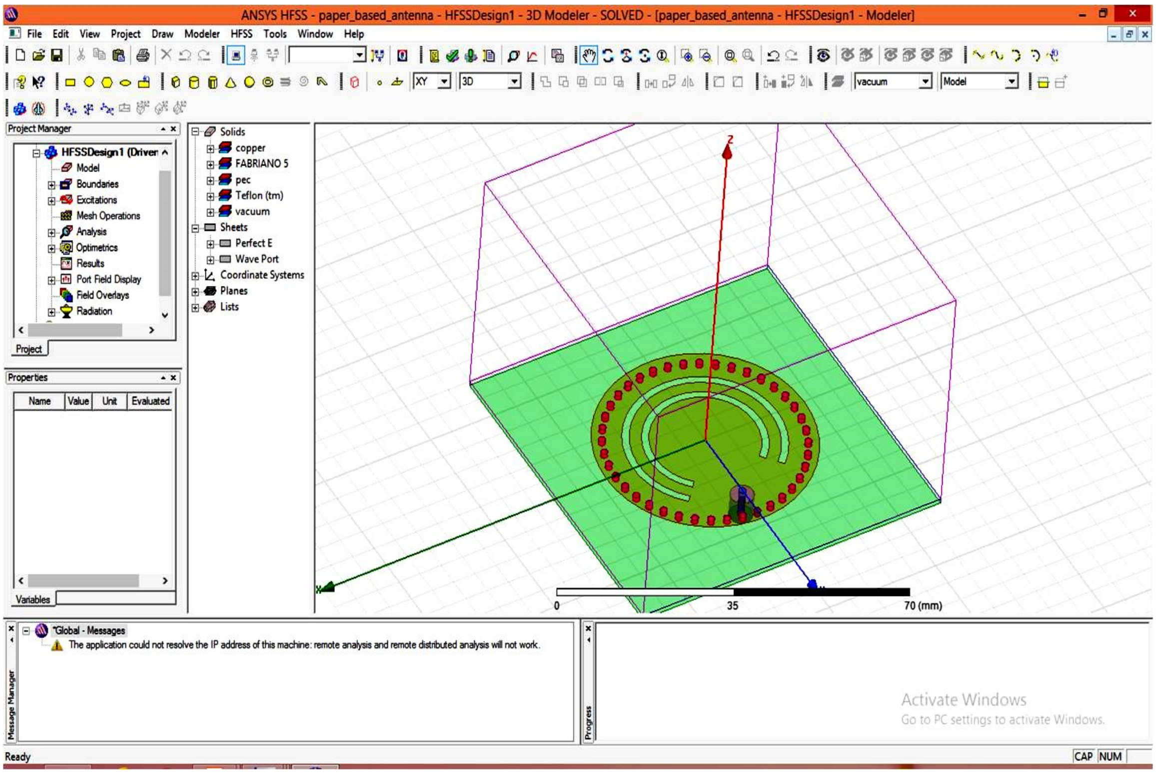

Figure 8. Proposed Paper Substrate based Antenna design in HFSS Software.

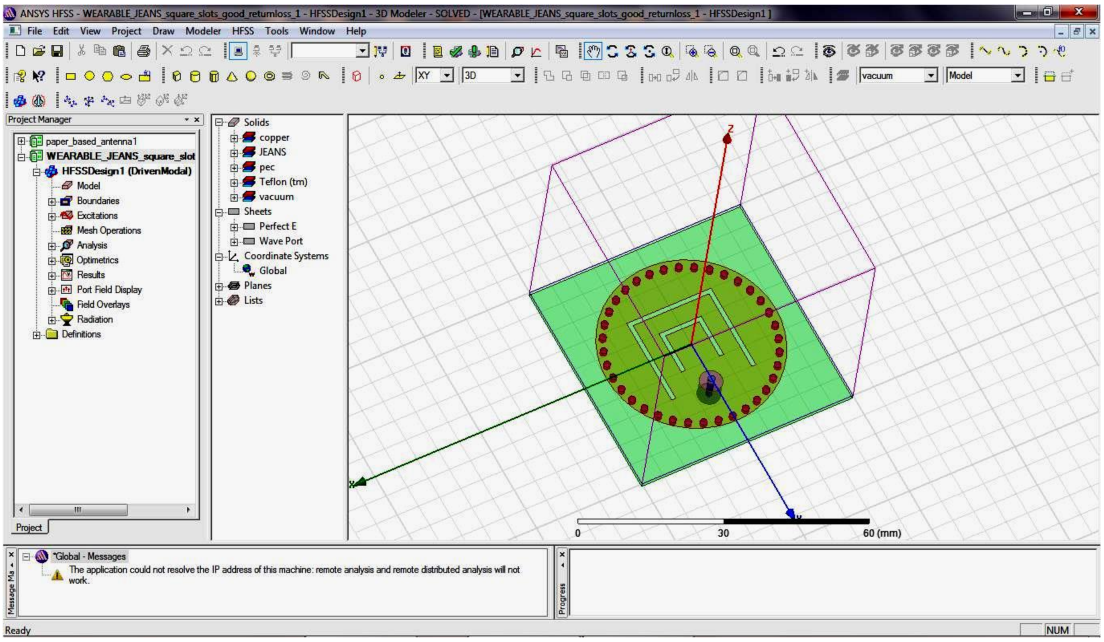

Figure 9. Proposed Denim Substrate based Antenna design in HFSS Software.

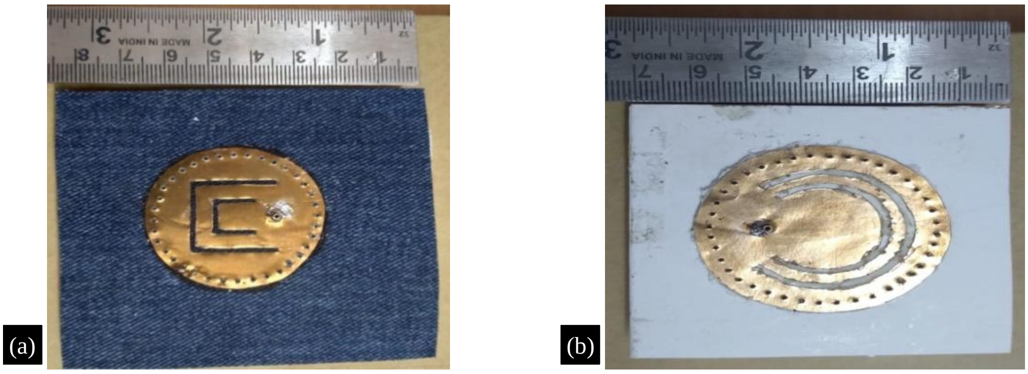

Figure 10. Fabricated prototypes of Antennas (a) Denim based antenna (b) Paper based antenna.

Validation of Antennas using Anechoic Chamber & Vector Network Analyzer (VNA): The purpose of antenna measurements using a Vector Network Analyzer (VNA) and an anechoic chamber is to characterize the performance of antennas in controlled environments [49, 50].

The VNA measures parameters like return loss, impedance, and radiation patterns across various frequencies. An anechoic chamber provides an isolated space free from external interference, enabling precise measurements of antenna radiation patterns and efficiency. The process involves connecting the antenna to the VNA, scanning frequencies while recording data, and analyzing the results to evaluate antenna performance in terms of gain, bandwidth, and impedance matching. The testing of proposed antennas are shown in Figure 11.

RESULTS & DISCUSSION

According to the methods suggested in section III, the proposed antennas were simulated on HFSS platform. The proposed Cavity Backed Substrate Integrated Waveguide (CBSIW) based antennas were fabricated on Denim and Fabriano 5 substrates. The testing for return losses have been done on Vector Network Analyzer and the radiation pattern and gain values in anechoic chamber.

The analysis of the designed antennas focuses on parameters such as return loss, bandwidth, gain, and radiation pattern. Figures 12, 13, 14 and 15 display the results of reflection and radiation

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characteristics. The findings demonstrate that the proposed multi-band antennas, constructed with Denim and Paper substrates, resonate effectively at frequencies of 2.4 GHz, 4.9 GHz, 8 GHz, and 8.2 GHz with optimal bandwidths. Peak gains for the Denim and Paper-based antennas are approximately 19 dBi and 18.15 dBi, respectively. The comparison of performance characteristics of antennas with standard references are shown in Table 1.

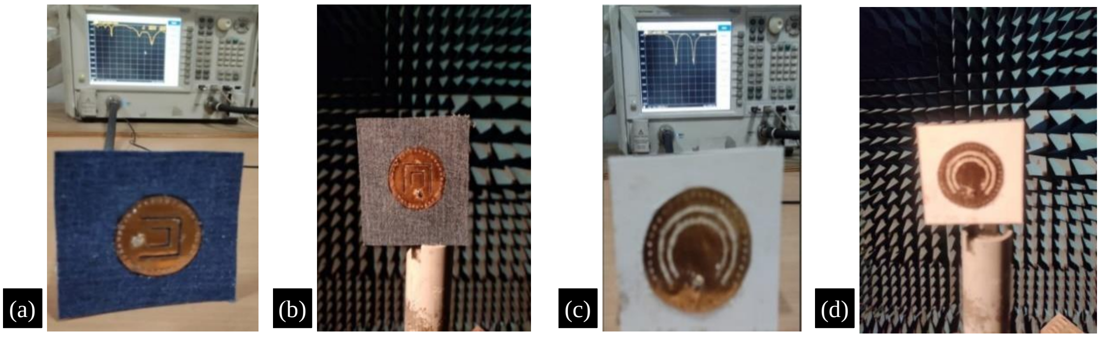

Figure 11. Testing of CBSIW antennas (a) & (b) Testing of Denim based antenna on VNA& Anechoic Chamber (c) & (d) Testing of Paper based antenna on VNA & Anechoic chamber.

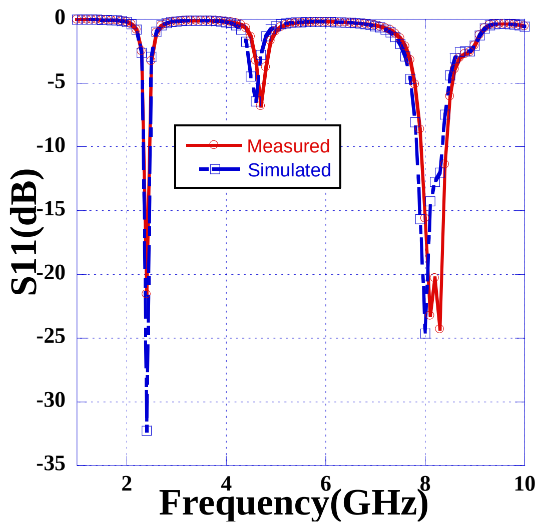

Figure 12. Reflection Characteristics of Wearable CBSIW Antenna.

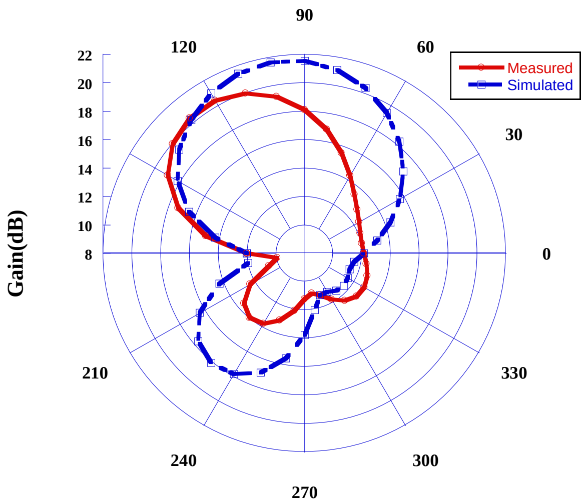

Figure 13. Radiation pattern of Wearable CBSIW Antenna.

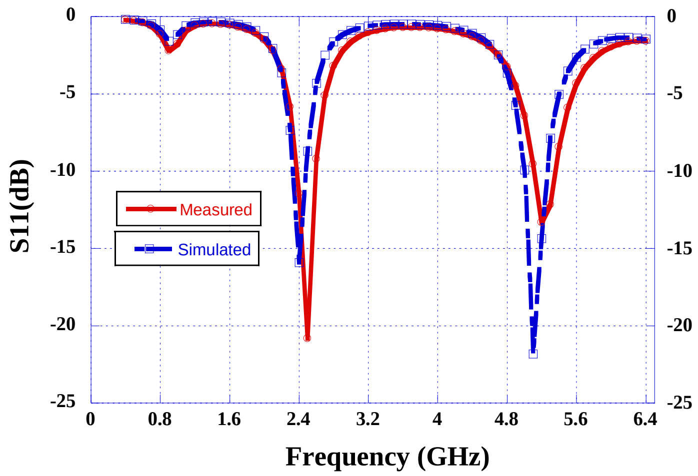

Figure 14. Reflection Characteristics of Paper based CBSIW Antenna.

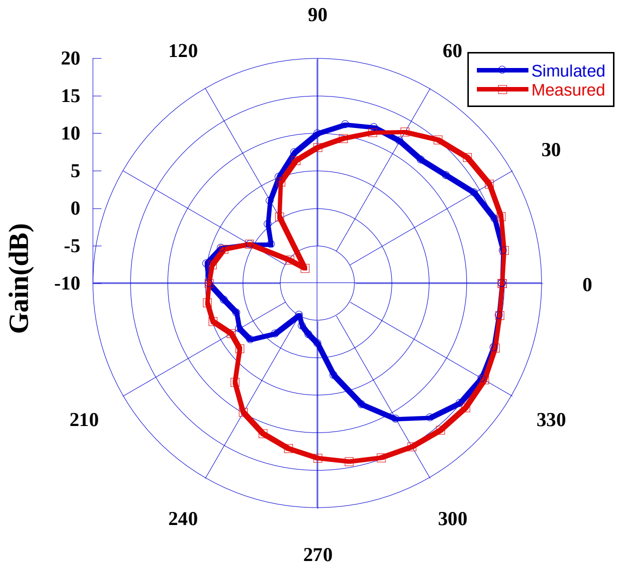

Figure 15. Radiation pattern of Paper based CBSIW Antenna.

Table 1. Comparison table for Non-Conventional Substrate based antenna.

Antenna References	Substrate Material	Dielectric Constant (εr)	Band width (%)	Gain (dBi)	Return loss (dB)	Efficiency (%)	Size
Y. Hong, J. Tak and J. Choi [17]	Fabric	32.7	6	3.12	-34	37.7	75 × 42
Martinez *et al* [20]	embroidered Textile	1.7	3.26	5.5	-30	79	53 × 53
R. Pei[22]	Leather	2	4.44	7.94	-40	84.11	104 × 78
E. Çelenk and N. T. Tokan[23]	Military textile	1.4	26	5.2	-35	79.2	55 × 40
K. Zhang, P. J. Soh and S. Yan[24]	Felt material	1.3	22.5	7.4	-34	42	44.1 × 44.1
Proposed Paper based Antenna	Fabriano 5	2.25	14	18.15	-22	69	70 × 70
Proposed Wearable Antenna	Denim Jeans	1.6	12	19	-32	72	85 × 85

The Table 1 compares various non-conventional substrate-based antennas, detailing their references, substrate materials, dielectric constants (εr), bandwidths (%), gains (dBi), return losses (dB), efficiencies (%), and sizes. Antenna substrates range from fabric, embroidered textile, leather, military textile, to felt material. The proposed antennas utilize Fabriano 5 paper and denim jeans substrates. Results showcase differences in performance metrics such as bandwidth, gain, return loss, and efficiency, with the proposed antennas.

CONCLUSION

This paper delves into the design and analysis of unconventional substrate-based CBSIW antennas. Specifically, it explores two antenna designs: the Wearable Circular CBSIW antenna and the Paper-based Circular CBSIW antenna, which are simulated using the HFSS simulator platform. Fabrication of these antennas is carried out on Fabriano 5 (paper-based) and Denim jeans (textile-based) substrates, with experimental validation conducted to assess their performance characteristics including Gain and Bandwidth. Results show that the Synthetic polymer-blended denim and Cellulose Fiber Based Paper offer promising alternatives as antenna substrates with promising gain and optimum bandwidth, leveraging its unique combination of mechanical strength, flexibility, and electromagnetic properties. By understanding its characteristics and considering antenna design requirements, researchers and engineers can harness the potential of denim-based substrates to advance antenna technology in various applications, including wireless communication, IoT devices, and wearable electronics.

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