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Comparative Material Selection Framework for Wearable Microstrip Patch Antennas at 2.45 GHz

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ABSTRACT

The rapid growth of wireless body area networks, wearable healthcare systems, and Internet of Things devices has intensified demand for flexible antennas capable of maintaining stable electromagnetic performance under dynamic body-worn conditions. Existing wearable antenna studies optimize geometry but rarely provide systematic material-selection methodologies. This paper presents a comprehensive comparative assessment of nine substrate materials (PDMS, felt, cotton, denim, polyester, Kapton, Rogers RO3003, FR4, and paper) and four conductive materials (Zelt, Shieldit, Flectron, and copper) evaluated across electromagnetic, mechanical, environmental, and fabrication criteria for 2.45 GHz ISM-band wearable antenna applications. A weighted multi-criteria decision matrix was employed to rank material combinations. Results indicate that no single material simultaneously satisfies all wearable antenna requirements. PDMS emerged as the most balanced substrate, offering a moderate dielectric constant, low loss tangent, exceptional flexibility, minimal moisture absorption, and proven biocompatibility. Zelt conductive textile emerged as the preferred conductor, providing very low surface resistivity, mechanical flexibility, and corrosion resistance. The PDMS–Zelt combination achieved the highest weighted score of 4.85 out of 5.00 across all evaluated criteria. A quarter-wavelength resonator-loaded microstrip patch antenna operating at 2.45 GHz was adopted as an illustrative design example. A structured six-stage material-selection framework is further proposed to guide systematic substrate and conductive material decision-making in wearable antenna design, offering a practical alternative to conventional trial-and-error approaches.

Keywords: Wearable antennas, material-selection framework, PDMS, microstrip patch antenna, quarter-wavelength resonator

1. INTRODUCTION

Recent advances in wireless body area networks (WBANs), biomedical monitoring systems, sports tracking devices, and smart wearable electronics have accelerated the development of compact and flexible antennas capable of operating in close proximity to the human body. Wearable antennas constitute one of the most important components of these systems because they provide the wireless communication interface necessary for data transmission, sensing, and remote monitoring (Paracha et al., 2019; Kiourti & Nikita, 2012; Jiang et al., 2014).

Microstrip patch antennas (MPA) remain attractive for wearable applications due to their low profile, planar geometry, ease of fabrication, and compatibility with flexible materials. Unlike conventional rigid antennas fabricated on printed circuit board substrates, wearable antennas must maintain stable performance under repeated bending, stretching, and body movements. The selection of appropriate substrate and conductive materials becomes a fundamental design consideration (Mohamadzade et al., 2019).

The substrate material directly influences antenna dimensions, bandwidth, radiation efficiency, and mechanical flexibility through its dielectric constant and loss tangent. In addition, the conductive material determines conductor losses, gain, radiation efficiency, durability, and long-term reliability. Although numerous substrate materials such as felt, cotton, denim, polyester, Kapton polyimide, Rogers laminates, and PDMS have been investigated, there remains no consensus regarding the optimal material combination for wearable antenna applications (Sharma & Chung, 2023).

A review of recent literature reveals that most studies concentrate on the performance optimization of individual antenna designs rather than systematically comparing material alternatives. Consequently, researchers frequently select substrate and conductive materials based on availability rather than a comprehensive evaluation of their electrical and mechanical properties. This limitation becomes particularly significant when designing wearable antennas for the 2.45 GHz ISM band, where antenna bandwidth, and flexibility must be satisfied.

This paper presents a comprehensive assessment of wearable antenna materials through a comparative evaluation of commonly used substrate and conductive materials. Particular attention is given to the suitability of PDMS and Zelt relative to competing alternatives for wearable antenna applications. A $\lambda/4$ resonator-loaded microstrip patch antenna is employed as an illustrative design case study to demonstrate the applicability of the proposed approach. Furthermore, a structured material-selection framework is developed to support the systematic identification of suitable substrate–conductor combinations for wearable antenna design. The remainder of the paper is organized as follows: Section 2 reviews wearable antenna requirements, Sections 3 and 4 present comparative analyses of substrate and conductive materials, Section 5 presents the design case study, Section 6 introduces the proposed material-selection framework, Section 7 outlines future research directions, and Section 8 concludes the paper.

2. Material Requirements for Wearable Antennas

2.1 Substrate Material Requirements

The substrate provides both mechanical support and dielectric function in a microstrip antenna. For wearable applications, selection must address mechanical, environmental, and physiological requirements.

The dielectric constant (εr) influences antenna dimensions and resonant behaviour. Higher εr reduces patch size but narrows bandwidth and increases surface-wave losses, while lower εr yields wider bandwidth and better radiation at the cost of larger dimensions (Balanis, 2016; Pozar, 2012). The loss tangent ($\tan\delta$) determines dielectric loss within the material; lower values improve radiation efficiency. Materials like Rogers laminates and Kapton polyimide offer low dielectric losses, whereas textile substrates typically exhibit higher losses due to fibrous structure and moisture absorption.

Mechanical flexibility is essential for body-worn antennas, which must endure repeated bending without significant resonant frequency shift. Rigid substrates such as FR4, despite widespread conventional use, are generally unsuitable for this purpose. Moisture resistance is equally important, as water absorption

alters dielectric properties and causes resonance detuning; substrates with low water absorption are preferred for long-term wearable deployment (Sharma & Chung, 2023; Kiourti et al., 2014; Chahat et al., 2013).

Table 1: Comparative Characteristics of Common Wearable Antenna Substrates

Material	Dielectric Constant (εr)	Loss Tangent	Flexibility	Moisture Resistance	Wearable Suitability
PDMS	2.67-3.80	0.01-0.04	Excellent	Excellent	Very High
Felt	1.20-1.45	0.02	Good	Poor	Moderate
Cotton	1.51	0.02	Good	Poor	Moderate
Denim	1.40-1.67	0.05	Good	Moderate	Moderate
Polyester	2.80	0.05	Good	Moderate	Moderate
Kapton	3.40-3.50	0.002-0.003	Very Good	Good	High
Rogers RO3003	3.00	0.001	Limited	Good	Moderate
FR4	4.40-4.70	0.018-0.020	Poor	Moderate	Low
Paper	1.50-3.00	0.07	Moderate	Very Poor	Low

2.2 Conductive Material Requirements

Conductive material forms the radiating patch, feed network, and ground plane of a patch antenna, critically determining radiation efficiency, gain, impedance, durability, and reliability. In wearable applications, conductors must simultaneously satisfy electrical performance and mechanical durability requirements under repeated bending, stretching, and environmental exposure.

Electrical conductivity is the primary parameter affecting antenna performance, as higher conductivity reduces ohmic losses, improving radiation efficiency and gain. Copper, with conductivity of approximately 5.8×10^7 S/m, serves as the benchmark conductor; however, its rigidity and susceptibility to mechanical fatigue under bending fundamentally limit its wearable suitability. Conductive textiles have emerged as flexible alternatives, offering sufficient conductivity for microwave operation.

Surface resistivity is equally critical, as lower values improve antenna efficiency and gain. The ideal wearable conductor should combine high electrical conductivity, low surface resistivity, excellent flexibility, and textile compatibility, while also satisfying long-term requirements of durability, washability, and environmental stability. These demands have motivated research into conductive fabrics such as Zelt, Shieldit, and Flectron, each exhibiting distinct performance trade-offs. Table 2 summarises their principal electrical and mechanical characteristics.

Table 2: Comparative Characteristics of Conductive Materials for Wearable Antenna Applications

Material	Conductivity (S/m)	Surface Resistivity (Ω/sq)	Flexibility	Durability	Wearable Suitability
Zelt	1×10^6	< 0.01	Excellent	High	Very High
Shieldit	1.18×10^5	< 0.10	Very Good	Good	High
Flectron	Up to 5.88×10^7	< 0.10	Good	Moderate	Moderate
Copper	5.8×10^7	≈ 0	Poor	High	Low

3. Comparative Assessment of Flexible Substrate Materials

3.1 Polydimethylsiloxane (PDMS)

PDMS is a silicone-based elastomer with excellent flexibility, low moisture absorption, biocompatibility, and stable dielectric properties (εr: 2.67–3.8; tanδ < 0.04) (Sharma & Chung, 2023). Its minimal moisture

absorption prevents perspiration-induced degradation, and its elasticity withstands repeated deformation. The moderate εr balances antenna compactness and bandwidth, making PDMS one of the most viable substrates for wearable communication systems (Simorangkir et al., 2018; Alemaryeen et al., 2020; Park et al., 2021).

3.2 Felt Fabric

Felt offers a low dielectric constant (εr: 1.20–1.45; tanδ is approximately 0.02), lightweight nature, and excellent wearer comfort, promoting wider bandwidth and strong fringing fields (Memon et al., 2021). Its softness enables easy garment integration. However, its porous structure absorbs moisture, shifting resonant frequency and causing performance instability. Thickness variations under bending further degrade electromagnetic consistency, limiting felt to comfort-oriented applications where long-term stability is not critical (Hertleer et al., 2009; Vallozzi et al., 2010; Rogier et al., 2015; Memon et al., 2015).

3.3 Cotton Fabric Cotton offers low dielectric constants (around 1.5), low dielectric loss, comfort, breathability, and fabrication versatility. However, its high moisture absorption significantly alters impedance matching, bandwidth, resonant frequency, and radiation efficiency under realistic conditions. Repeated washing also degrades its structural properties. Although cotton remains suitable for low-cost wearable prototypes, its susceptibility to environmental influences makes it less attractive than polymer-based alternatives such as PDMS (Soh et al., 2015).

3.4 Denim

Denim provides dielectric constants of 1.40-1.67, good dimensional stability, and mechanical durability, offering improved fabrication robustness over cotton and felt (Manikonda et al., 2018). Its low dielectric constant supports wider bandwidth, though its relatively high tanδ introduces dielectric losses. Like other textiles, moisture absorption remains a vulnerability. Although denim provides a practical balance between mechanical durability and electromagnetic performance, it cannot match the environmental stability and moisture resistance offered by polymer substrates such as PDMS (See et al., 2012).

3.5 Polyester Fabric

Polyester, with dielectric constant around 2.8, and loss tangent around 0.05, offers better dimensional stability and moisture resistance than natural textiles. It also provides resistance to wrinkling, stretching, and mechanical deformation. These characteristics contribute to more stable antenna performance under repeated use. However, its relatively high dielectric loss and narrower bandwidth potential are drawbacks. While superior to natural fibers in environmental robustness, polyester still falls short of PDMS in dielectric stability and biocompatibility, making it suitable for moderate-performance, cost-sensitive wearable applications (Tak et al., 2017).

3.6 Kapton Polyimide

Kapton offers an exceptionally low tanδ (0.002-0.003), εr of 3.4-3.5, and outstanding thermal and mechanical stability, yielding excellent radiation efficiency. However, its limited commercial thickness (0.1-0.2 mm) restricts bandwidth. Although Kapton provides exceptional electromagnetic performance and mechanical reliability, its limited thickness options and reduced elasticity make it less suitable than PDMS for highly conformal body-worn applications (Yan et al., 2018).

3.7 Rogers RO3003

Rogers RO3003 (εr around 3.0; tanδ around 0.001) delivers exceptional electromagnetic performance, including high radiation efficiency and stable impedance matching, making it a common research benchmark. However, its semi-rigid structure cannot withstand repeated bending, and its high cost limits scalability for wearable deployment. This reduces its practical suitability beyond laboratory reference use.

3.8 FR4

FR4 remains the most widely used substrate in conventional antenna and printed circuit board applications because of its low cost, global availability, and ease of fabrication. The dielectric constant of FR4 typically ranges from 4.4 to 4.7, while loss tangent values vary between 0.018 and 0.020. FR4 enables antenna miniaturization but suffers from narrow bandwidth, increased surface-wave losses, and

mechanical rigidity. While useful as a benchmarking substrate, it is unsuitable for practical conformal wearable systems.

3.9 Paper-Based Substrates

Paper substrates suit low-cost, disposable wireless sensing due to inkjet-printing compatibility, but exhibit unstable dielectric properties under humidity, high dielectric losses, and poor mechanical durability. These limitations make paper generally unsuitable for long-term wearable antenna applications. The comparative evaluation reveals that no single substrate simultaneously maximizes all performance metrics. Textile materials such as felt, cotton, denim, and polyester provide excellent wearer comfort and low fabrication cost but suffer from moisture sensitivity and inconsistent dielectric behavior. Rogers RO3003 and Kapton offer superior electromagnetic performance but are constrained by cost, rigidity, or limited flexibility.

Among the investigated materials, PDMS provides the most balanced combination of electrical, mechanical, and environmental properties. Its moderate dielectric constant supports practical antenna dimensions while maintaining acceptable bandwidth performance. Furthermore, its flexibility, moisture resistance, biocompatibility, and long-term dielectric stability make it attractive for wearable antenna applications operating in realistic environments. Hence PDMS emerges as the most favourable substrate material for advanced wearable microstrip antenna designs operating at 2.45 GHz.

4. Comparative Assessment of Conductive Materials for Wearable Antennas

4.1 Zelt Conductive Textile

Zelt is a copper-tin-plated nylon textile with surface resistivity below 0.01 Ω/sq and conductivity about 10^6 S/m (Sankaralingam & Gupta, 2010). Its nylon backing enables stable electrical performance under repeated bending without conductive layer cracking, while the copper-tin coating provides corrosion resistance against moisture and perspiration. Despite lower conductivity than bulk copper, its very low surface resistivity supports efficient current distribution, yielding superior radiation efficiency over competing conductive textiles.

It is also fabrication-versatile, supporting cutting, laminating, stitching, and bonding onto flexible substrates using relatively simple manufacturing procedures. This versatility facilitates rapid prototyping and scalable wearable antenna production. Limitations include higher cost and unavoidable conductor losses relative to copper, but Zelt remains the most attractive conductive materials for wearable antennas (Rao et al., 2005).

4.2 Shieldit

Shieldit (conductivity of 1.18×10^5 S/m; surface resistivity < 0.1 Ω/sq) features an adhesive backing enabling direct attachment to textile and polymer substrates without additional bonding, making it fabrication-friendly. It tolerates moderate bending and has been used in dual-band, multiband, and body-worn antenna designs. However, its conductivity is lower than Zelt, increasing conductor losses and reducing radiation efficiency. Moisture exposure and mechanical stress can also degrade adhesive and conductive integrity over time, making its overall electrical performance generally inferior to Zelt.

4.3 Flectron Conductive Fabric

Flectron is a copper-plated textile capable of achieving near-metallic conductivity levels, enabling competitive gain and radiation performance in wearable antenna designs. However, its conductivity varies considerably with weave orientation and manufacturing conditions. Repeated bending degrades conductive pathways, increasing resistive losses over time. While Flectron can provide satisfactory performance for specific wearable antenna applications, its long-term reliability and consistency are often considered less favorable than those of Zelt (Chen et al., 2017; Bhattacharjee et al., 2022).

4.4 Copper as Reference Conductor Copper with conductivity of about 5.8×10^7 S/m is the benchmark antenna conductor, offering negligible ohmic losses, high radiation efficiency, and predictable microwave performance. However, its rigidity renders it unsuitable for repeated bending, with mechanical fatigue leading to cracking and conductor failure. Additional drawbacks include increased weight, reduced wearer comfort, and fabrication complexity in garment integration. Despite superior electrical

performance, copper is generally impractical for wearable antennas, where conductive textiles offer a better balance of electrical and mechanical properties.

Copper offers the highest conductivity but lacks flexibility; Shieldit provides good flexibility and fabrication ease but lower conductivity; and Flectron delivers competitive conductivity but with greater performance variability and reduced long-term consistency.

Zelt demonstrates the most balanced combination of electrical and mechanical properties. Its low surface resistivity supports efficient current distribution, its flexible nylon-based structure withstands repeated bending, and its copper-tin construction provides superior corrosion resistance over competing conductive textiles. Since wearable antenna design demands an optimal balance of conductivity, flexibility, durability, and fabrication practicality rather than maximum conductivity alone, Zelt is selected as the preferred conductive material.

4.5. Quantitative Material Selection

A weighted multi-criteria decision matrix was developed to evaluate candidate substrate-conductor combinations across five criteria: RF performance, flexibility, moisture and environmental stability, wearability and comfort, and fabrication practicality (Ouyang & Chappell, 2005; Sankaralingam & Gupta, 2010; Mohamadzade et al., 2019; Xu et al., 2020; Memon et al., 2021). Criteria were weighted by relative importance, and each combination scored 1-5 (for Poor, Fair, Good, Very Good and Excellent respectively) per criterion. The weighted score was computed as:

Each material combination was assigned a score between 1 and 5, where:

$$Ws = \sum_{i=1}^{n}(W_i \; X \; S_i) \; .. \quad . \quad . \quad . \quad (8)$$

Where W_s is a weighted score, W_i is a weighting factor, S_i is a performance score.

Table 4 presents the criteria and weights, while Table 5 presents the full evaluation results.

Table 4: Weighted Material Selection Criteria

Criterion	**Description**	**Weight (%)**
Electromagnetic Performance	Dielectric properties, conductivity, radiation efficiency, gain potential	30
Mechanical Flexibility	Resistance to bending, deformation, and fatigue	25
Moisture and Environmental Stability	Resistance to humidity, perspiration, and environmental degradation	15
Wearability and Comfort	User comfort, conformability, biocompatibility	15
Fabrication Practicality	Ease of manufacturing, integration, and reproducibility	15
Total		**100**

Table 5: Weighted Evaluation of Material Combinations

Material Combination	RF Performance (30)	Flexibility (25)	Moisture Stability (15)	Wearability (15)	Fabrication (15)	Total Score
PDMS–Zelt	5	5	5	5	4	4.85
PDMS–Shieldit	4	5	5	5	5	4.65
Kapton–Copper	5	3	5	3	4	4.05
Rogers–Copper	5	1	5	1	4	3.60
Denim–Copper	3	3	3	3	4	3.15
Cotton–Zelt	3	4	2	4	4	3.40
Felt–Shieldit	3	4	2	4	4	3.40
FR4–Copper	3	1	3	1	5	2.60

PDMS-Zelt achieved the highest overall score (4.85/5.00), reflecting its balanced satisfaction of all key requirements. Rogers-Copper scored well electromagnetically but exhibits poor flexibility and wearability. Textile combinations (Cotton–Zelt, Felt–Shieldit) offered good flexibility but failed for moisture sensitivity and dielectric instability. PDMS–Shieldit scored competitively (4.65) but ranked lower due to reduced conductivity relative to Zelt.

The quantitative assessment confirms the comparative analysis conclusions: PDMS–Zelt provides the most balanced combination of electromagnetic performance, flexibility, environmental robustness, wearability, and fabrication practicality for 2.45 GHz wearable antenna applications.

Note: Scores were derived from material characteristics reported in wearable antenna literature and are intended as a comparative design-support tool, not direct experimental measurements.

5. PDMS–Zelt Antenna Design Case Study

The comparative assessment presented in Sections 3 and 4 revealed that no single substrate or conductive material simultaneously satisfies all wearable antenna requirements. Material selection demands a balanced evaluation of electromagnetic performance, mechanical flexibility, environmental robustness, fabrication practicality, and long-term reliability. Therefore, the PDMS–Zelt combination was selected as an illustrative design platform for the proposed material-selection framework.

5.1 Antenna Configuration

To certify the material-selection methodology, a quarter-wavelength resonator-loaded rectangular microstrip patch antenna operating at 2.45 GHz was adopted as the wearable antenna design example. The design employs PDMS as the dielectric substrate and Zelt conductive textile for the radiating patch, feed structure, and ground plane, with two quarter-wavelength resonators positioned adjacent to the feed line. The PDMS substrate parameters are $\varepsilon r = 2.7$, $\tan\delta = 0.02$, and thickness $h = 2.5$ mm. Zelt was modelled with conductivity $\sigma = 1 \times 10^6$ S/m, thickness of 0.063 mm, and surface resistivity = 0.01 Ω/sq.

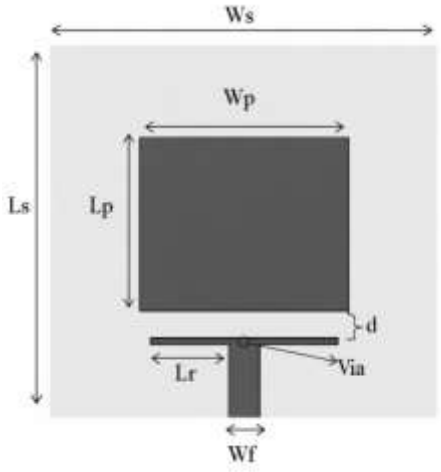

Figure 1: Antenna Geometry

5.2 Design Procedure

Design began with calculating a rectangular microstrip patch at 2.45 GHz using the following design equations (1-7) (Balanis, 2016) for patch width, effective dielectric constant and patch length.

$$Wp = \frac{c_o}{2f_r}\sqrt{\frac{2}{1+\varepsilon_r}} \quad . \quad . \quad . \quad . \quad (1)$$

$$Lp = \frac{c_o}{2f_r\sqrt{\varepsilon_{ep}}} - 2\Delta L \quad . \quad . \quad . \quad . \quad (2)$$

$$Lr = \frac{c_o}{f_r\sqrt{\varepsilon_{er}}} \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Where Wp is patch width, Lp is patch length, ΔL is the change in patch's length due to fringing effect given by equation (4):

$$\Delta L = 0.412h\frac{(\varepsilon_{ep}+0.3)(\frac{Wp}{h}+0.264)}{(\varepsilon_{ep}-0.258)(\frac{Wp}{h}+0.8)} \quad . \quad . \quad (4)$$

ε_{ep} and *h* are the effective permittivity for the patch and Substrate thickness respectively. ε_{ep} can be calculated using equation (5)

$$\varepsilon_{ep} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}[1+\frac{12h}{Wp}]^{-1/2} \quad . \quad . \quad . \quad (5)$$

The PDMS substrate is backed by a full ground plane of zelt material, so that both the ground and substrate has the same dimensions of length (Ls) and Width (Ws) given by:

$$Ls = 6*h + L_p + L_f \quad . \quad . \quad . \quad . \quad . \quad (6)$$

$$Ws = 6*h + W_p \quad . \quad . \quad . \quad . \quad . \quad (7)$$

The resonators were positioned at an optimized coupling distance (d) from the radiating patch to generate a secondary resonance merging with the primary resonance into a single wider operating band. Final dimensions were obtained through parametric full-wave electromagnetic simulation and presented in Table 3.

Table 3: Optimized PDMS–Zelt Antenna Dimensions

Parameter	Description	Value (mm)
L_p	Patch Length	34.3
W_p	Patch Width	44.0
W_f	Feed Width	6.53
L_r	λ/4 Resonator Length	20.3
D	Coupling Distance	2.6
H	Substrate Thickness	2.5
L_s	Substrate Length	70
W_s	Substrate Width	60

5.3 Simulation Results

Reflection Coefficient and Impedance Bandwidth

The proposed quarter-wavelength resonator-loaded patch antenna achieves an impedance bandwidth of 230 MHz (2.34 - 2.57 GHz) at the -10 dB return loss threshold, corresponding to a fractional bandwidth of 9.4%. The dual resonant modes, generated by the radiating patch and the coupled resonators merge into a single wideband response centred at 2.45 GHz, as depicted in Figure 2.

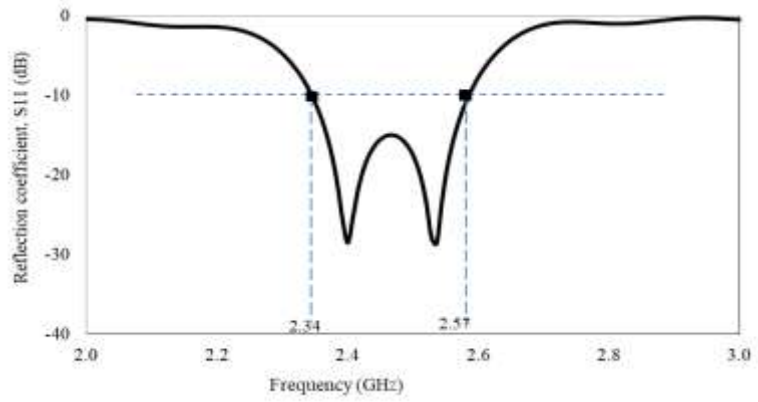

Figure 2: Reflection Coefficients (S11) plot

Radiation Pattern and Gain

The antenna exhibits a simulated directivity of 6.85 dB and a realised gain of 4.03 dBi at 2.45 GHz, with predominantly broadside radiation consistent with standard microstrip patch behaviour, as shown in Figure 3.

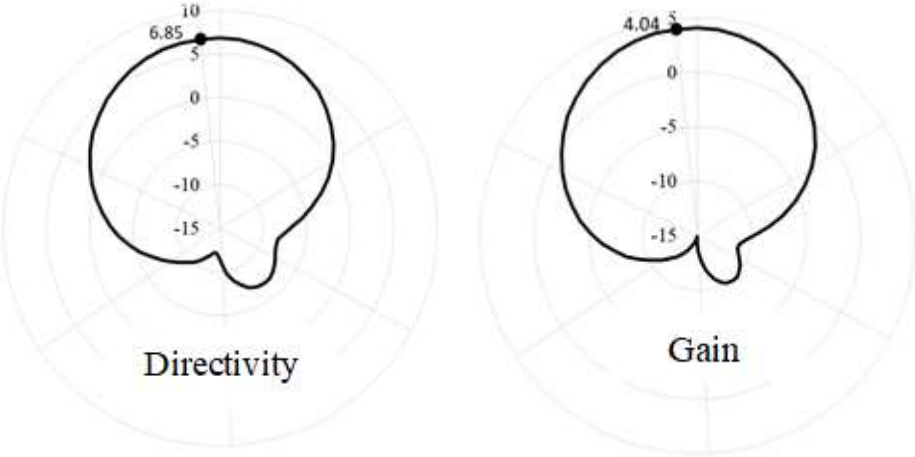

Figure 3: Radiation pattern of the designed antenna for Directivity and Gain.

Radiation Efficiency

A radiation efficiency of 52% is achieved at 2.45 GHz, coinciding with the peak gain frequency. The moderate efficiency reflects conductor and dielectric losses inherent to the Zelt conductive textile and PDMS substrate combination, and is consistent with values reported for flexible conductive textile-based wearable antennas in the literature.

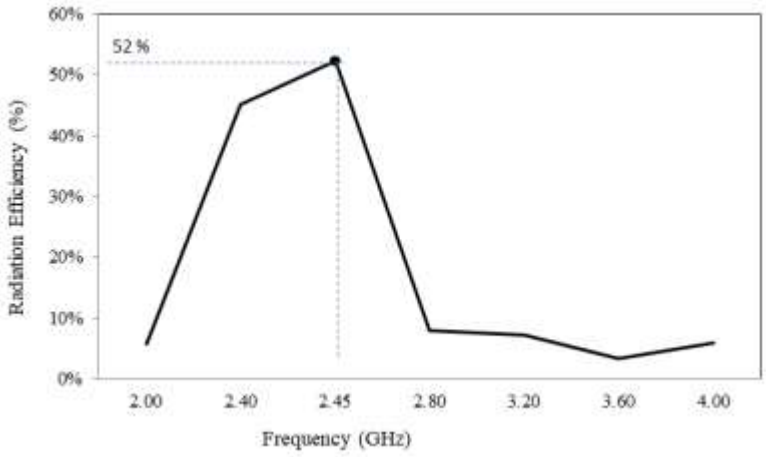

Figure 4.6: Radiation efficiency of the proposed antenna design without EBG.

6. Proposed Material Selection Framework for Wearable Antennas

6.1 Motivation for a Material Selection Framework

A recurring challenge in wearable antenna design is the lack of systematic material selection methodology; choices are often driven by availability or fabrication convenience rather than structured performance evaluation. As demonstrated in Sections 3 and 4, no single material optimally satisfies all wearable requirements simultaneously. Rogers RO3003 excels electromagnetically but lacks flexibility; textiles offer comfort but suffer moisture sensitivity; copper provides outstanding conductivity but is

insufficiently flexible, etc. A structured framework is therefore proposed, integrating electromagnetic, mechanical, environmental, and fabrication considerations to guide systematic substrate–conductor selection.

Stage 1: Mechanical Screening

Materials are first evaluated for mechanical suitability, since flexibility and durability are primary wearable requirements. Criteria include flexibility, elasticity, bending tolerance, stretchability, fatigue resistance, and user comfort. Rigid materials are eliminated: FR4 is excluded; Rogers are downgraded. PDMS, felt, cotton, polyester, denim, and Kapton proceed to Stage 2.

Stage 2: Dielectric Screening

Remaining substrates are assessed on dielectric constant (εr), loss tangent (tanδ), and dielectric stability. High εr reduces antenna size but narrows bandwidth; low tanδ improves efficiency and gain. Stability under humidity, temperature, deformation, and perspiration is critical. Cotton and felt are penalised for moisture sensitivity; denim receives a moderate rating; PDMS, Kapton, and Rogers rate highest for dielectric stability. Poor performers are eliminated.

Stage 3: Environmental and Biocompatibility Assessment

Substrates are evaluated for moisture resistance, chemical stability against sweat and detergents, and biocompatibility for skin-contact applications. PDMS rates highest due to low moisture absorption and established biocompatibility; Kapton rates favourably for chemical stability; textile materials are generally penalised for moisture absorption. This stage further narrows the selection pool.

Stage 4: Conductive Material Screening

Conductive materials are evaluated on electrical conductivity, surface resistivity, flexibility, durability, and fabrication compatibility. Copper scores highest electrically but poorly mechanically; Shieldit offers moderate performance; Flectron exhibits variability; Zelt achieves the most balanced overall rating across electrical and mechanical criteria, emerging as the preferred conductive material for wearable applications.

Stage 5: Antenna Performance Optimization

With materials selected, antenna geometry is optimized against key performance indicators: impedance bandwidth, radiation efficiency, gain, and frequency stability under bending, stretching, and environmental exposure. Additional application-specific criteria may include SAR compliance, miniaturization, multiband operation, and polarization requirements.

6.2 Proposed Material Selection Decision Model

The framework follows a sequential six-step process: Determine flexibility requirements → Evaluate substrate dielectric characteristics → Assess moisture resistance and biocompatibility → Evaluate conductive material performance → Optimize antenna geometry → Validate through simulation and measurement → Final Selection: PDMS Substrate + Zelt Conductive Textile. This structured approach minimises subjective decision-making and improves design consistency across wearable antenna development.

Figure 2: Proposed material-selection framework for wearable microstrip patch antennas.

6.3 Framework Validation

From an initial pool of nine substrates and four conductive materials, successive screening stages systematically eliminated candidates exhibiting poor flexibility, dielectric instability, moisture sensitivity, or inadequate conductivity. The final PDMS–Zelt selection emerged from a comprehensive assessment spanning dielectric properties, mechanical flexibility, moisture resistance, biocompatibility, conductivity, fabrication practicality, and long-term reliability, not electromagnetic performance alone. The successful design of PDMS–Zelt quarter-wavelength resonator antenna validates the framework's effectiveness.

7. Future Research Directions

The rapid evolution of wearable communication systems, flexible electronics, and wireless healthcare technologies continues to create new challenges and opportunities for wearable antenna development. Although the comparative analysis presented in this study identified PDMS and Zelt as highly suitable materials for current 2.45 GHz wearable antenna applications, ongoing advancements in materials science and manufacturing technologies are expected to expand the range of available substrate and conductive materials. Hence, future research should focus on exploring emerging materials and fabrication approaches capable of further enhancing wearable antenna performance.

7.1 Emerging Flexible Substrate Materials

Three elastomeric materials show strong potential beyond PDMS. Ecoflex offers greater elasticity and stretchability, making it attractive for e-skin and direct skin-attachment applications, though its lower stiffness introduces fabrication and dimensional stability challenges. Dragon Skin silicone similarly provides excellent flexibility, durability, and environmental resistance. TPU has gained traction due to its compatibility with commercial 3D printing, enabling rapid fabrication of customised wearable antenna structures and positioning it as a practical emerging alternative to conventional elastomeric substrates.

7.2 Advanced Conductive Materials

Graphene-coated textiles and graphene-based inks offer high flexibility, low weight, and corrosion resistance, but challenges in large-scale manufacturing, conductivity consistency, and cost must be resolved before they can replace conventional conductive textiles (Gao et al., 2021). Silver nanoparticle inks enable direct printing of antenna structures via inkjet, screen-printing, or aerosol-jet technologies, offering precise patterning and rapid prototyping, though long-term durability under bending and environmental exposure requires further investigation (Li et al., 2021). Conductive polymer composites represent a third direction, combining conductivity with inherent polymer flexibility and potentially eliminating the need for separate conductive textile layers entirely.

7.3 Additive Manufacturing and 3D Printing

Conventional fabrication methods such as manual cutting, bonding, embroidery, and lamination, introduce dimensional inconsistencies and manufacturing variability. 3D printing offers rapid prototyping, customisation, reduced material waste, and repeatable accuracy. Emerging multi-material printing further enables simultaneous fabrication of dielectric and conductive components. Future research should explore integrating PDMS-like materials, conductive inks, and printable conductive polymers within unified additive manufacturing workflows (Wang et al., 2022; Liu et al., 2019).

7.4 Artificial Intelligence-Assisted Material Selection

AI and machine learning offer significant potential for wearable antenna material selection, moving beyond manual evaluation of dielectric properties, conductivity, flexibility, and fabrication constraints. Key applications include predicting material properties, estimating antenna performance prior to fabrication, and simultaneously optimising bandwidth, gain, efficiency, flexibility, and cost. Integration of AI-assisted tools with electromagnetic simulation platforms could substantially accelerate antenna development cycles (Zhang et al., 2021).

7.5 Sustainable and Environmentally Friendly Wearable Antennas

Environmental sustainability is an emerging consideration in wearable antenna design. Candidate materials include cellulose-based substrates, biodegradable polymers, paper-based electronics, and eco-friendly conductive composites. Most currently exhibit inferior electromagnetic performance relative to PDMS and established conductive textiles, but continued advancement may yield viable sustainable alternatives. Balancing sustainability with antenna performance represents a key future research challenge (Zhao et al., 2023).

7.6 Towards Next-Generation Wearable Antenna Platforms

The future of wearable antennas lies in converging advanced materials, intelligent design, and innovative manufacturing. Emerging substrates such as Ecoflex, Dragon Skin, and TPU may deliver enhanced flexibility, while graphene-based conductors and conductive inks may improve integration. Additive manufacturing and AI-assisted optimisation are expected to reduce design complexity and accelerate development, potentially enabling antennas that are lighter, thinner, more comfortable, more reliable, environmentally sustainable, and tightly integrated with smart textiles and healthcare systems. Although PDMS and Zelt remain the most suitable established combination, future material developments may surpass their performance. The proposed material-selection framework is sufficiently adaptable to accommodate these emerging materials, ensuring its continued relevance in future wearable antenna research.

8. CONCLUSION

This paper presented a systematic comparative assessment of substrate and conductive materials for wearable microstrip patch antenna design at 2.45 GHz. The analysis confirmed that no single material simultaneously satisfies all wearable antenna requirements. Among the nine substrate materials evaluated, PDMS demonstrated the most balanced performance, combining moderate dielectric constant, low loss tangent, exceptional flexibility, minimal moisture absorption, chemical stability, and biocompatibility. For the four conductive materials assessed, Zelt provided the most favourable combination of low surface resistivity, mechanical flexibility, corrosion resistance, and fabrication compatibility, consistently outperforming Shieldit, Flectron, and copper when electromagnetic and mechanical criteria were jointly considered. The PDMS–Zelt combination was simulated using a quarter-wavelength resonator-loaded microstrip patch antenna at 2.45 GHz. The quantitative decision matrix in Section 5 demonstrated PDMS–Zelt as the highest-ranked material combination with an overall score of 4.85 out of 5.00. The principal contribution of this work is a structured six-stage material-selection framework that provides an objective and repeatable methodology for material decision-making in early-stage wearable antenna development. The findings establish that material selection is as critical to wearable antenna performance as antenna geometry itself. The proposed framework is sufficiently general to accommodate emerging materials such as Ecoflex, TPU, graphene-based conductors, and conductive inks, ensuring its continued relevance as wearable antenna technology advances.

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