JOURNAL OF NANO- AND ELECTRONIC PHYSICS
Vol. 17 No 6, 06034(9pp) (2025)
ЖУРНАЛ НАНО- ТА ЕЛЕКТРОННОЇ ФІЗИКИ
Том 17 № 6, 06034(9cc) (2025)

REGULAR ARTICLE

Design and Development of Low-Profile Flexible Antenna at 3.5 GHz using Different Substrate Materials for Smart Clothing and Wearable Communication

Md. Samiul Islam, Abu Zafor Md. Touhidul Islam*

Antenna Design Lab, Department of Electrical and Electronic Engineering, University of Rajshahi, Rajshahi-6205, Bangladesh

(Received 19 September 2025; revised manuscript received 17 December 2025; published online 19 December 2025)

This paper presents the design and performance analysis of low-profile flexible antenna at 3.5 GHz using various substrate materials such as FR4, Polyester and Cotton for smart clothing and wearable communication applications. The simulation has been performed using CST Microwave Studio software The miniaturized dimensions of the antenna is $30 \times 20 \times 0.8$ mm^3 and its performance improvement has been achieved through the incorporation of slotting and partial grounding techniques. The comparative performance analysis of three antennas by applying different substrates shows polyester textile-based antenna offers better performance. Therefore, the Rogers RT5880 substrate was chosen to be experimentally tested for antenna realization and validating the simulated results. Hence the well-suited textile material polyester is chosen for the proposed antenna realization at 3.5 GHz and experimental validation. The antenna operates over a wide frequency range of 3.11-4.27 GHz and satisfy the most popular lower 5G (3.33-4.2 GHz) and WiMAX (3.4-3.6 GHz) bands. Due to its low profile, compact size, cost effective and flexible structure, the proposed polyester-based textile antenna with satisfactory bandwidth, gain, efficiency, and omnidirectional radiation pattern, can suite on the surface of the human body and good nominate for smart clothing and wearable communication applications. Experimental results obtained from the fabricated prototype show good agreement with the simulation data.

Keywords: Polyester substrate, Flexible, Wireless broadband, Textile antenna, Smart clothing, Wearable technology.

DOI: 10.21272/jnep.17(6).06034 PACS number: 84.40.Ba

1. INTRODUCTION

The advancement of wearable technology has garnered substantial research interest, primarily due to the escalating demand for miniaturized, flexible, and high-performance electronic systems. Within these architectures, antennas constitute a fundamental subsystem, facilitating reliable wireless communication by enabling efficient transmission and reception of electromagnetic signals across various frequency bands. Wearable antennas have garnered considerable interest owing to their cost-effectiveness, lightweight nature, mechanical flexibility, and seamless integration into textile substrates [1]. Meanwhile, 5G communication systems – characterized by ultra-high data transmission rates – are rapidly evolving beyond conventional mobile applications, extending into domains such as the Industrial, Scientific, and Medical (ISM) band, where they support Wireless Body Area Networks (WBAN) [2]. Textile-based antennas have emerged as a predominant research focus within the domain of wearable technology [3]. Given that clothing is an essential aspect of daily life, integrating electronic components directly into garments presents a logical pathway toward the realization of smart clothing systems. The incorporation of wearable antennas into fabric not only facilitates seamless wireless communication but also enhances user comfort and mobility, thereby supporting unobtrusive and efficient connectivity in everyday environments [4]. Textile antennas are used for various applications including wireless information transmission [5], energy harvesting [6], medical and healthcare sectors, sports, fashion, and military [7-10].

In general, the primary design criterion for wearable antennas centers on the use of textile substrates that can be seamlessly integrated into smart garments. To ensure optimal performance, these fabric-based antennas must operate within the designated frequency bands, support adequate bandwidth, and exhibit omnidirectional radiation characteristics to maintain consistent connectivity regardless of body orientation [11]. Many wearable textile antennas based on different design topologies and exhibiting various radiation properties have been reported in the literature. Some of these antennas offer single-band operation in the ISM bands [12], Wi-MAX band [13], 5G application band [14], and WBAN application band [15]. Some of the wearable antenna designs are capable of providing dual-band such as Wi-MAX and WLAN bands [16], Wi-MAX and lower 5G bands [17], multi-band [18], and ultra-wideband operation [19].

However, key challenges in designing textile

* Correspondence e-mail: touhid.eee@ru.ac.bd

antennas for smart clothing include maintaining antenna performance and reliability while ensuring flexibility, comfort and washability. To mitigate these challenges, researchers are exploring various approaches such as optimizing material selection and antenna geometry for various body movements, utilizing advanced fabrication techniques, specific absorption rate (SAR) concerns, and so on [20, 21]. One of the critical challenges in wearable antenna design is ensuring consistent performance across diverse environmental conditions. Factors such as ambient temperature, relative humidity, proximity to the human body or adjacent garments, and repeated exposure to washing cycles can significantly influence the antenna's gain and overall electromagnetic behavior [22]. These variables introduce dynamic changes in the dielectric properties of textile substrates, necessitating robust design strategies to maintain reliable wireless communication under real-world usage scenarios. Although the stated antennas showed promising results for wearable applications, for most of the cases, they have larger sizes, narrow bandwidths, expensive substrates, and so on. Therefore, continuous advances in research are now focused on wideband, low-cost, and tiny antennas for wearable applications. Moreover, there's a noticeable gap in studies focusing on textile antenna designs specifically for the 3.5 GHz band, particularly for broadband wireless communication. Existing research primarily concentrates on other 5G frequencies like (2.4-2.484 GHz), WiMAX (2-11 GHz), and other WLAN bands. The 3.5 GHz band is relevant for various applications including telemedicine, mobile m-health (mobile health), and e-health, making it a crucial area for further investigation. While very few research exists on textile antenna design at 3.5 GHz [11, 23-25], a comprehensive study covering all aspects is currently lacking.

This study presents design and comparative performance analysis a low-profile small size flexible textile antenna 3.5 GHz band using various substrate materials (a standard FR-4, and various textile materials like polyester and cotton) for smart clothing and wireless wearable communication applications. The design utilizes a set of three substates. The performance of the antennas with various substrate materials is evaluated, but the low-cost well-suited polyester textile is finally selected as substrate for the proposed antenna design, implementation and experimental validation

The rest of the paper is arranged as follows. The antenna design approach is discussed in Section 2. Section 3 presents the results and discussion, including simulation and experimental results under the free space conditions. A comparison of the proposed antenna's performance with previously reported designs is given in Section 3. Finally, key findings of the research are listed in Section 4.

2. METHODOLOGY AND PARAMETRIC INVESTIGATION

The proposed antenna's design, simulation, parametric investigation, and numerical analysis are carried out in Computer Simulation Technology (CST) studio suite under the free space condition. The prototype is then fabricated and the performance metrics are measured in the laboratory using the Vector Network Analyzer (VNA). The initial antenna prototype was developed on a conventional FR4 substrate to establish baseline performance metrics. To evaluate its suitability for wearable applications, the design was subsequently adapted using textile-based materials such as polyester and cotton – both commonly employed in garment manufacturing. This transition enables a comparative analysis of electromagnetic behavior across rigid and flexible substrates, thereby assessing the antenna's functional compatibility with smart clothing environments.

Figure 1 describes the construction of the proposed antenna designed to resonate at 3.5 GHz, and shows both the front view (Fig. 1(a)) and bank view (Fig. 1(b)). The design employs a microstrip feed line to deliver power to the radiating patch element of the antenna. Initially, the antenna size has been estimated for 3.5 GHz using the following set of basic equations. After that, the antenna design is optimized to a net size of 30 × 20 × 0.8 mm^3 to attain the miniaturized structure. A set of rectangular slots to the patch plane and partial grounding structure are added to improve impedance matching and effectiveness of the antenna.

$$\text{Width of the patch, } W_p = \frac{c_0}{2f_r}\sqrt{\frac{2}{\epsilon_r+1}} \tag{1}$$

Where c_0 – light speed in free space, f_r – resonance frequency, ϵ_r – substrate dielectric constant.

$$\text{Length, } L = 0.412h\frac{(\epsilon_{reff}+0.3)\ (\frac{W_p}{h}+0.264)}{(\epsilon_{reff}-0.258)\ (\frac{W_p}{h}+0.8)} \tag{2}$$

$$\text{Where } \epsilon_{reff} = \frac{\epsilon_r+1}{2}+\frac{\epsilon_r-1}{2}\left[1+12\frac{h}{W}\right]^{-\frac{1}{2}} \tag{3}$$

ϵ_{reff} – effective dielectric constant, h – substrate thickness.

$$\text{Effective length, } L_{eff} = \frac{c_0}{2f_r\sqrt{\epsilon_{reff}}} \tag{4}$$

$$\text{Patch length, } L_p = L_{eff} - 2\Delta L \tag{5}$$

The optimized parameters of the projected antenna are shown in Table 1. The patch is placed on the top surface of the textile substrate. The optimized size of the patch is 12.65 mm × 14.64 mm. The antenna comprises a right-angle triangular slot ($p = q = 3$ mm, $r = 4.24$ mm) and rectangular slots ($Li_1 = 12.75$ mm, $Li_2 = 8.75$ mm, $W_1 = 2$ mm). A microstrip feedline having a dimension of 15 mm × 2.58 mm is used to excite the patch.

Table 1 – Optimized values of design parameters of the projected antenna

Parameters	Values (mm)
Substrate Width, *Ws*	20
Substrate Length, *Ls*	30
Feed Line Length, *Lf*	15
Feed Line Width, *Wf*	2.58
Patch Length, *Lp*	12.65
Patch Width, *Wp*	14.64
Ground Width, *Wg*	20
Ground Length, *Lg*	14
Substrate Height, *h*	0.8

Li_1	12.5
Li_2	8.75
W_1	2.0
p	3.0
q	3.0
r	4.24

Initially, the antenna is designed on a standard FR-4 substrate. Next, the same antenna is designed using two widely used textile materials polyester and cotton as substrates. The dielectric constant, loss tangent and thickness of FR4 are chosen as 4.3, 0.015, and 0.8 mm, respectively. The used cotton fabric has a dielectric constant 1.3, loss tangent 0.033, thickness 0.8 mm, while the 0.8 mm thick polyester textile material with a dielectric constant of 1.9 and loss tangent of 0.0045 is used as the third substrate. The patch, feed line, and ground plane are made from conductive copper tape whose thickness is 0.035 mm. The three antennas are simulated and their performance metrics are compared. As polyester-based antenna shows much better performance than others and offer advantages like cost effectiveness, durability, dimensional stability, and resistance to environmental factors, polyester textile is finally selected for designing the proposed textile antenna.

Copper tape is popular for use on polyester-based antennas due to its excellent conductivity and flexibility. It allows for the creation of conductive pathways for radio frequency signals, while the polyester substrate provides a lightweight and flexible base. This combination is ideal for wearable or flexible antenna applications where conformability and portability are important.

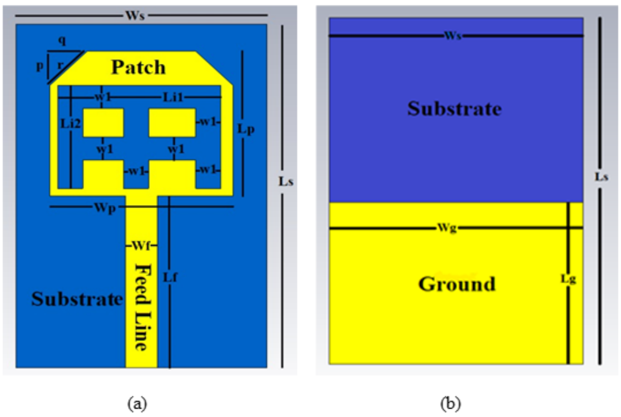


Fig. 1 – Proposed antenna (a) front view (b) back view

The various design steps (denoted as Step 1, 2, 3, 4, and Final Step) of the proposed antenna are shown in Fig. 2(a), and the reflection coefficient (S11) at various stages of the implementation is shown in Fig. 2(b). Partial ground is used in each Step. The use of slots in subsequent five design steps improve S11 of the antenna and widen the bandwidth at the expected frequency. For the proposed design (Final step), the S11 reaches a minimum value of – 60.73 dB at the deaired resonant frequency of 3.5 GHz. Lower values of reflection coefficient indicate better impedance matching (less reflection, more power delivered), while a broader bandwidth with low reflection indicating the antenna can operate efficiently across more channels, and is well-suited for real-world deployment in wireless communication systems.

A parametric investigation showing how changing the ground length (L_g) affects the impedance matching and resonant frequency of an antenna is presented in Fig. 3. Each colored line represents the S11 for a different Lg from 12 to 30 mm. As L_g decreases, the resonant frequency shifts. With increasing L_g from 12 mm, the reflection coefficient is decreasing and it achieves minimum at 14 mm, then again it is increasing. Poor matching observed around 3.5 GHz at L_g = 30 mm and best matching at L_g = 14 mm. The purple curve (L_g = 14 mm) has the sharpest dip (~ – 63 dB) near 3.5 GHz. It demonstrates that L_g = 14 mm offers the best performance near 3.5 GHz, making it optimal among the tested values.

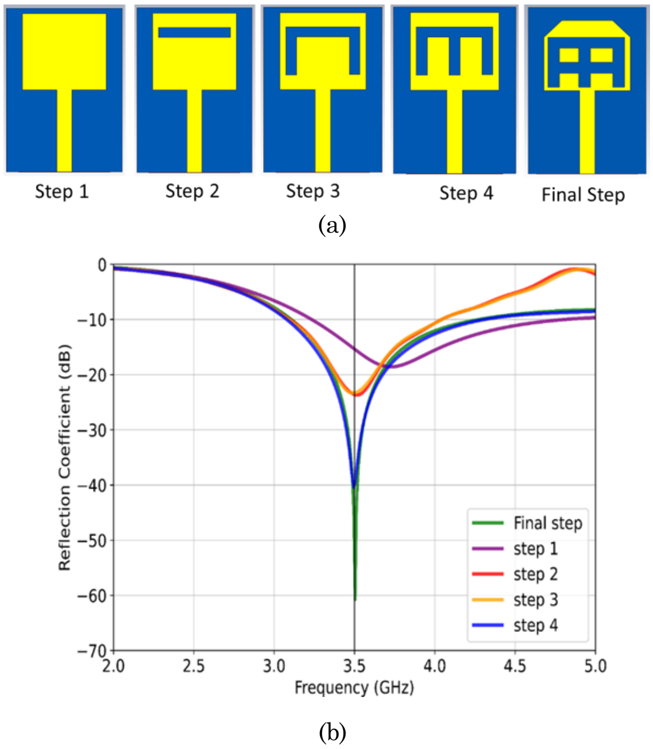


Fig. 2 – (a) Development stages of the proposed antenna, (b) Reflection coefficient versus frequency

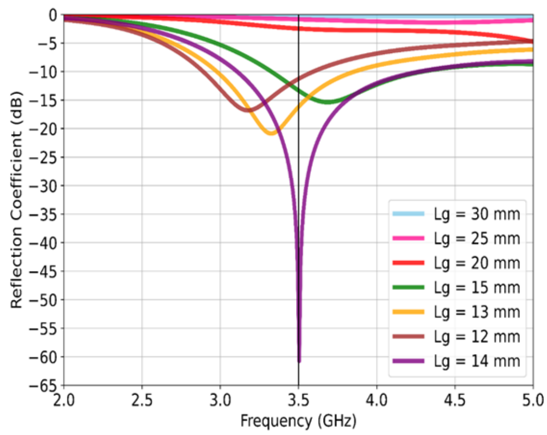


Fig. 3 –Effect of change of Ground length on the reflection coefficient

3. RESULTS AND DISCUSSION

The simulation results of the designed antennas on various substrates including FR4 and textile materials Polyester and Cotton are presented, analysed and compared for selection of well-suited substrate in Section 3.1. The simulation results of the proposed polyester-based antenna are compared with the earlier works in Section 3.2. Section 3.3 presents the experimental results of the fabricated antenna.

3.1 Simulation Results

(a) Reflection Coefficient (S11)

Figure 4 shows the variation in reflection coefficient (return loss or S11) with frequency, in the range of 2.5 to 5.0 GHz, of the antennas built on FR-4, polyester, and cotton substrates. The FR-4 based antenna resonates at a frequency of 3.52 GHz. At the target operating frequency, the antenna exhibits a return loss of – 30.48 dB, indicating effective impedance matching. When implemented on a polyester substrate, the resonance frequency shifts to 3.52 GHz, accompanied by a significantly improved return loss of – 60.73 dB. Similarly, the cotton-based variant demonstrates a resonance frequency of 3.50 GHz with a return loss of – 47.13 dB, further validating the suitability of textile materials for wearable antenna applications. All presented antennas show a deep notch (minimum return loss) around 3.5 GHz, indicating that the antenna is resonant at this frequency. Polyester based antenna shows deepest notch, around – 60 dB, excellent impedance matching and minimal reflection. The width of the notch indicates how wide the frequency range is where the antenna performs well. FR-4 based antenna appears to have a narrower but deeper notch, while antennas with Cotton and Polyester have slightly wider notches, which specifies that Polyester based antenna offers the best impedance matching and widest usable bandwidth.

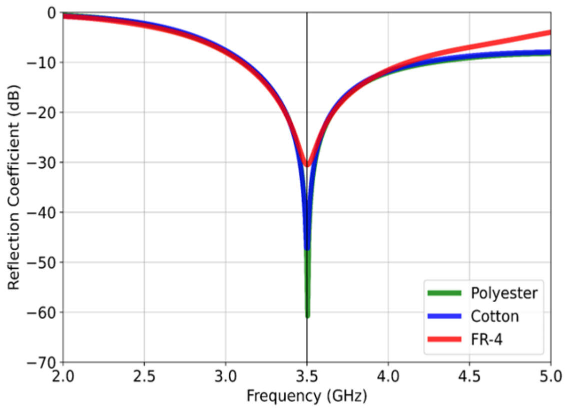


Fig. 4 – Antenna reflection coefficient versus frequency

(b) Voltage Standing Wave Ratio (VSWR)

The plot in Fig. 5 compares the Voltage Standing Wave Ratio (VSWR) of antennas made with FR-4, Polyester, and Cotton across a frequency range of 2.0 to 5.0 GHz. All three curves dip sharply around 3.5 GHz where VSWR is close to 1.0, indicating maximum power transfer and efficient energy transfer. Polyester based antenna achieves the lowest VSWR (1.001) near resonance, which is very close to the ideal value and indicating best impedance matching. Antenna with Cotton substrate has slightly higher VSWR (1.008) than Polyester, but still well below 2.0, while FR-4 based antenna has the highest VSWR (1.06) among the three, suggesting less efficient matching.

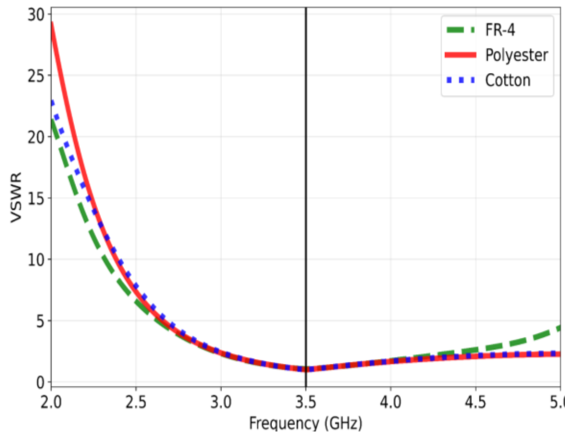


Fig. 5 – VSWR versus frequency

(c) Efficiency

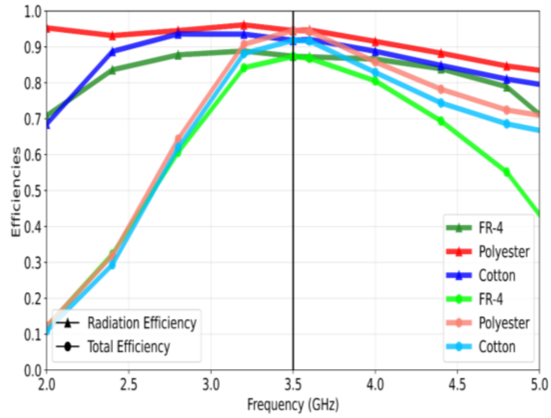


Fig. 6 – Antenna efficiency versus frequency

Figure 6 compares Radiation Efficiency and Total Efficiency versus frequency of antennas made with FR-4, Polyester, and Cotton in the operating range of 2.0 to 5.0 GHz. Efficiency increases with frequency from 2.0 GHz to ~ 3.5 GHz, then gradually declines. Peak efficiency occurs near 3.5 GHz. Antennas with Polyester and Cotton maintain higher efficiency across the band. FR-4 based antenna shows a sharper decline in both radiation and total efficiency beyond 4 GHz. FR-4, while widely used in PCB-based antennas, suffers from higher dielectric losses and impedance mismatch, reducing its efficiency. Polyester based antenna is the most efficient both in terms of radiation (94.54 %) and total efficiency (94.52 %) of the antenna.

(d) Gain

Figure 7 shows how the antenna gain varies with frequency for three different substrate materials (FR-4, Polyester, and Cotton) based antennas. Gain increases steadily from 2.0 GHz to 5.0 GHz for all three materials.

This suggests that the antenna becomes more directional and efficient at higher frequencies. Polyester based antenna consistently shows the highest gain (2.59 dB) across all frequencies. Antenna with Cotton substrate shows slightly lower gain than Polyester but higher than FR-4 based antennas. FR-4 based antenna has the lowest gain, indicating less effective radiation.

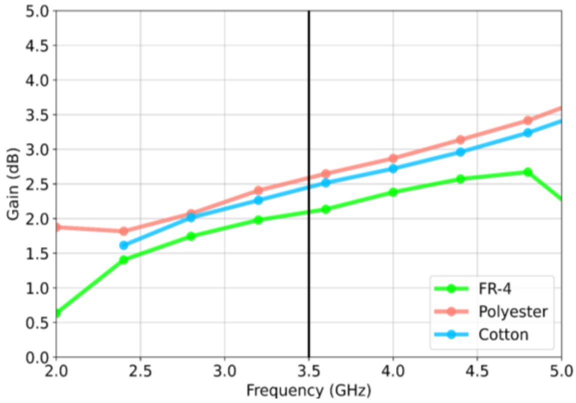


Fig. 7 – Antenna gain versus frequency

(e) Directivity

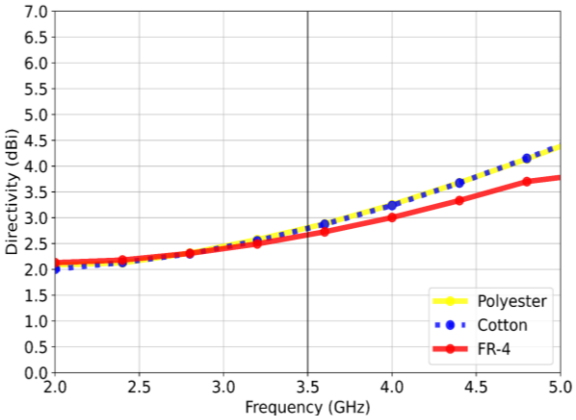


Fig. 8 – Antenna directivity versus frequency

The plot in Fig. 8 shows how antenna directivity varies with frequency for three antennas based on substrate materials Polyester, Cotton, and FR-4. Directivity increases steadily from 2.0 GHz to 5.0 GHz for all substrates, which indicates that the antennas become more directional at higher frequencies. Cotton based antenna shows slightly higher directivity than Polyester and FR-4 based antenna at most frequencies. Antenna directivity with Polyester substrate closely follows Cotton based antenna, with nearly identical performance, making it a strong candidate for flexible antennas. FR-4 based antenna consistently has the lowest directivity.

A comparison of the numerical performance metrics of three antennas designed on standard substrate material FR-4, and textile materials Polyester and Cotton is presented in Table 2. Antennas with Polyester and FR-4 show excellent refection coefficient (very negative values), indicating strong impedance matching. Cotton based antenna has a weaker return loss (S11), suggesting more reflected power and less efficient matching. The VSWR of all antennas are close to the ideal value of 1.0, meaning efficient power transfer. Polyester based antenna leads both the cotton and FR-4 based antennas with over 94 % total and radiation efficiency. Antenna with Polyester textile offers the widest bandwidth (1.17 GHz) than FR-4 and Cotton, supporting a broader range of operating frequencies. Polyester based antenna again leads with the highest gain, meaning stronger signal transmission. These results implies that Polyester based antenna consistently outperforms the other antennas with FR4 and Cotton materials across nearly all key metrics: superior impedance matching (lowest S parameter), highest efficiency and gain, widest bandwidth and strongest directivity, which making it the most suitable choice for flexible antenna design in wearable communication applications. Henceforth the proposed antenna is designed with polyester textile and results will be presented only for polyester-based antenna.

Table 2 – Antenna's performance for using various substrate materials

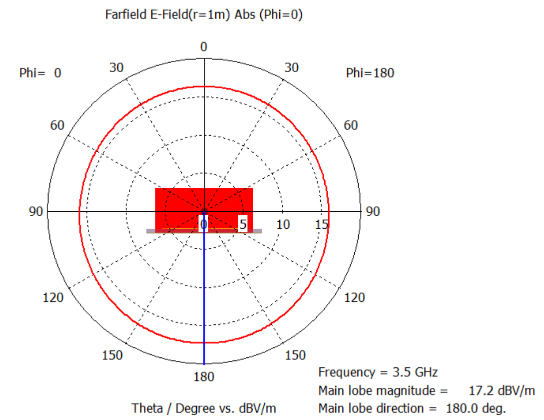
Material	S11 (dB)	VSWR	Efficiency (%)		Bandwidth (GHz)	Gain (dB)	Directivity (dBi)
			Total	Radiation			
Polyester	-60.73	1.001	94.52	94.54	1.17	2.59	2.83
FR-4	-30.48	1.060	87.32	87.39	1.02	2.10	2.69
Cotton	-47.13	1.008	91.82	91.83	1.10	2.45	2.82

(f) Radiation Pattern

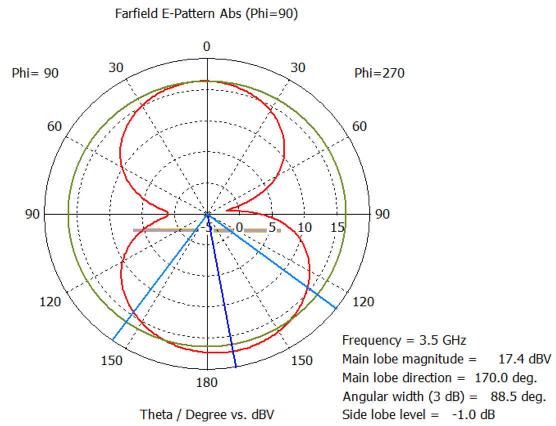
The 2D and 3D radiation patterns of the proposed polyester-based textile antenna in free space measured at 3.5 GHz are depicted in Fig. 9. The polar plot of Fig. 9(a) showing the far-field electric field (E-field) distribution of the antenna at a distance of 1 meter, in the phi = 0° plane. The main lobe magnitude (peak electric field strength) and direction are 17.2 dBV/m and 180°, respectively, showing the antenna radiates most strongly toward 180° and contributes to better signal strength and range.

The polar plot of Fig. 9(b) showing the E-field radiation pattern of the antenna at 3.5 GHz, in the phi = 90° plane. The antenna radiates strongest signal of magnitude 17.4 dBV/m in the 170.0° direction. Aangular width (beamwidth) of the main lobe is 88.5°, measured between points where the field strength drops by 3 dB from the peak. The wide beamwidth (88.5°) suggests it covers a broad area in that direction. The side lobe level of − 1.0 dB indicates moderate side radiation.

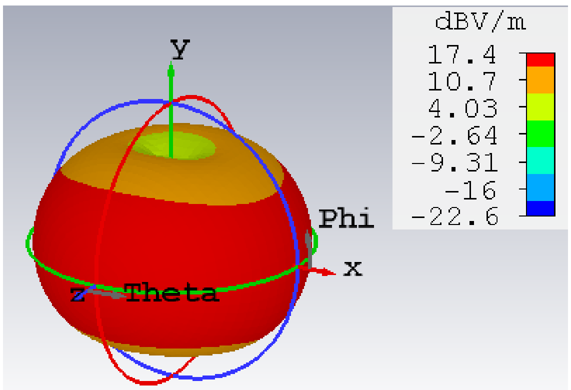
The 3D far-field radiation pattern of Fig. 9(c) showing how the antenna radiates electromagnetic energy in space at 3.5 GHz. The pattern resembles a flattened sphere, indicating omnidirectional behaviour in the horizontal plane (around the Z-axis). There is a null or low radiation along the vertical (Y-axis), suggesting minimal radiation directly above or below the antenna. Red and orange zones represent the strongest radiation, with field strengths around 17.4 dBV/m. Green to blue zones indicate weaker radiation, dropping to − 22.6 dBV/m in the null regions. The pattern is symmetric around the Phi (azimuthal) axis, confirming omnidirectional horizontal coverage. This antenna is likely designed for broad horizontal coverage, making it ideal for applications in wireless broadband technology.



(a)



(b)



(c)

Fig. 9 – Radiation patterns of the proposed polyester-based antenna: (a) and (b) 2D, (c) 3D.

(g) Surface Current Distribution

Figure 10 shows the surface current distribution of the proposed polymer-based antenna at 3.5 GHz. It illustrates how electric current flows across the surface of the antenna when it's excited at a frequency of 3.5 GHz. Highest current density up to 85.3 A/m and lowest current density near 0 A/m are observed. Maximum current is concentrated near the feed region. The current flows upward and spreads across the structure, exciting different parts of the antenna.

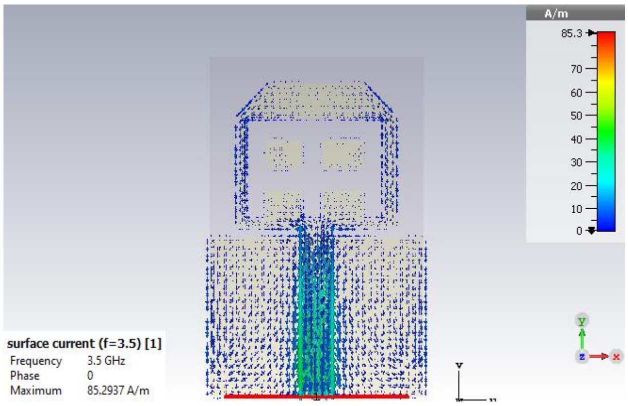


Fig. 10 – Surface current distribution of the proposed antenna

(h) Power Flow Pattern

The power flow pattern of the proposed polymer-based antenna operating at 3.5 GHz is depicted in Fig. 11. It illustrates how electromagnetic energy propagates away from the antenna structure. The highest power flow up to 539,523 V·A/m^2 and lowest power flow near zero are observed. The antenna is efficiently radiating energy upward, suggesting a directional radiation pattern. The high concentration of power vectors near the feed and central axis confirms strong coupling and effective energy transfer.

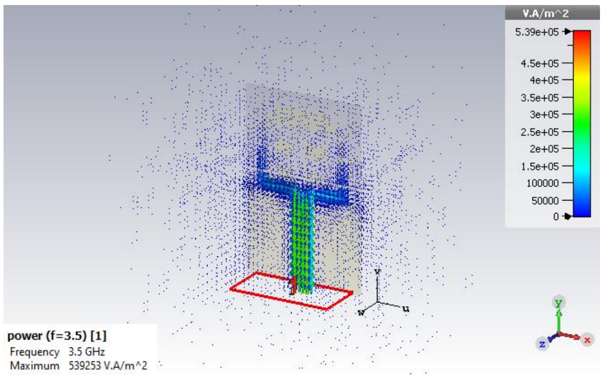


Fig. 11 – Power flow pattern

3.2 Comparative Performance Analysis

A comparative performance analysis between the proposed polyester-based antenna and the several reference antennas is given in Table 3. This work uses low-permittivity textile material polyester ($\varepsilon_r = 1.9$) – same as [25], which helps in maintaining flexibility and mechanical durability. The proposed antenna is smallest in size (30 × 20 × 0.8 mm^3), has the widest frequency range (3.11-4.12 GHz) and largest bandwidth (1.17 GHz) suitable for wearable applications. The bandwidth of the proposed antenna covers the most popular lower 5G (3.33-4.2 GHz) and WiMAX (3.4-3.6 GHz) band. This work and [24] show very good impedance matching (≈ – 40 dB), indicating minimal return loss. The proposed design has the best VSWR (1.001), almost ideal (1.0), moderate gain (2.59 dB) balanced for omnidirectional use, and highest efficiency (94.52 %), which means most of the input power is radiated. The proposed antenna is the smallest (enhancing wearability and integration), offers moderate gain (balancing performance and compactness), and design simplicity (uses a rectangular patch that is easy to fabricate and simulate).

Table 3 – Performance Comparison of the proposed polymer-based antenna with the previous work

Parameter	Reference No.				
	[11]	**[23]**	**[24]**	**[25]**	**This Work**
Antenna Size [L×W×h] mm^3	30×30×1.6	40×40×0.44	35×25×2	55×46×1.5	30×20×0.8
Substrate Material/ Permittivity	Jeans/Denim/ 1.7/1.67	Photo Paper/ 3.2	PDMS/ 2.74	Polyester/ 1.9	Polyester/ 1.9
Operating Frequency Range (GHz)	~3.15 to 3.95	3.33–3.75	2.53 to 5.81	3.41 to 3.59	3.11 to 4.27
Reflection coefficient (dB)	-20/-19	~ -30	-45.38	~ -13	-60.73
VSWR	1.19	—	1.01	—	1.001
Bandwidth (GHz)	0.540	—	3.28	0.18	1.17
Gain at center frequency (dB)	—	~1.4	2.58	5.38	2.59
Efficiency (%)	—	70	78.59	—	94.52

Hence this work outperforms previous references in most critical performance parameters. Although [25] has slightly higher gain, its bandwidth and reflection performance are lower. Based on the comparative table, the proposed antenna demonstrates a strong balance between bandwidth, gain, efficiency, compactness, design simplicity, flexibility and wearability. Furthermore, the low profile, small size, cost effective and flexible structure, excellent impedance matching, and omnidirectional radiation pattern making it a suitable candidate for real-world applications in wearable communication and smart clothing technology.

3.3 Experimental Results

The structure of the proposed polyester-based antenna is fabricated, and the reflection coefficient (S11) parameter is measured in free space using LiteVNA 64. Figures 13(a) shows the top view and 13(b) the back view of the fabricated antenna. Figure 14 depicts the experimental arrangement utilized to assess key performance parameters of the fabricated antenna. In Figure 15, the variation in the reflection coefficient (S11) as a function of operating frequency is presented, comparing results obtained through simulation with those measured under laboratory conditions. As seen, the simulated and measured resonant frequencies are 3.52 GHz and 3.54 GHz, which are close to each other and very close to 3.5 GHz of the designed antenna. The measured value of the reflection coefficient at resonant frequency is – 45.42 dB. The measured S-parameters exhibit strong alignment with the simulated data, indicating a high level of consistency between the theoretical model and the fabricated antenna's real-world performance. This agreement reinforces the validity of the simulation approach and confirms the reliability of the design under practical operating conditions. The antenna's operating bandwidth measured at – 10 dB is 1.5 GHz (2.8-4.3 GHz) covering the most popular lower 5G (3.33-4.2 GHz) and WiMAX (3.4-3.6 GHz) band applications, indicating the antenna's performance remains within acceptable limits with the range of these frequencies.

The deviation of experimental results from the simulated ones may results from the real-world factors, such as imperfections in the antenna's construction, the presence of parasitic elements or coupling from nearby structures in the physical setup, lossy materials in the antenna's construction, measurement setup effects, and variations in the measurement environment. Variations or ripples observed in the measured data may arise from multiple sources, including material absorption, electromagnetic dispersion, and scattering effects induced by structural imperfections or inconsistencies in material quality. Additional contributing factors such as connector losses and interface mismatches can further degrade measurement accuracy and antenna performance.

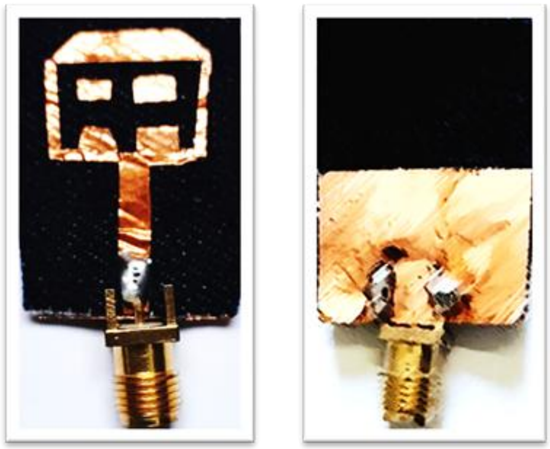


Fig. 13 – (a) Front view, (b) Back view of the proposed antenna

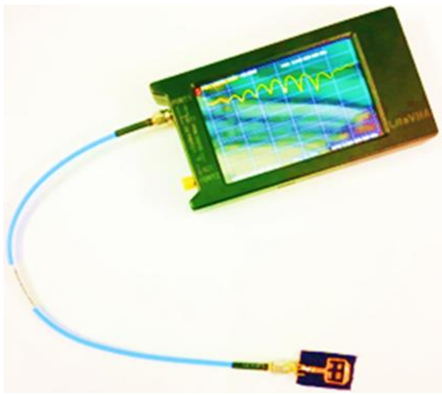


Fig. 14 – Experimental set up for the measurement

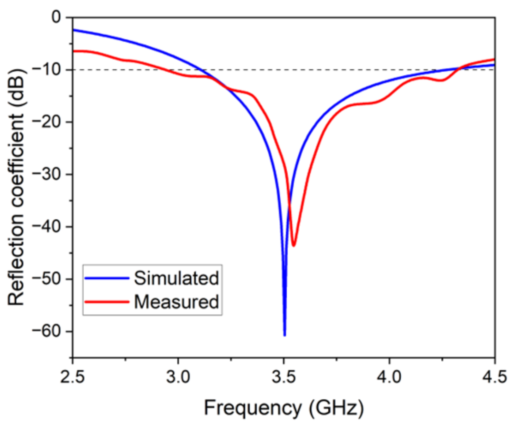


Fig. 15 – Simulate and measured reflection coefficient of the proposed antenna

The simulated results show ideal performance, while the measured results confirm good real-world behavior with slight deviations. The antenna achieves a strong match and wide bandwidth, making it suitable for applications in the 3.5 GHz frequency band (e.g., 5G, WiMAX).

4. CONCLUSION

This paper presents a novel design, development and performance analysis of a low-profile compact flexible antenna at 3.5 GHz using various substrate materials such as FR4, Polyester and Cotton textiles for smart clothing and wearable communication applications. Through simulation, various antenna parameters are evaluated and their comparative analysis shown polyester textile-based antenna perform better at 3.5 GHz band. Hereafter, the well-suited polyester textile is finally chosen as substrate for the proposed antenna design and implementation. The proposed antenna with compact dimensions of 30 × 30 × 0.8 mm^3 operates over a wide frequency range of 3.11-4.27 GHz and satisfy the most popular lower 5G (3.33-4.2 GHz) and WiMAX (3.4-3.6 GHz) bands. Due to its low profile, small size, cost effective and flexible structure, the proposed antenna with excellent impedance matching, satisfactory bandwidth, gain, efficiency, and omnidirectional radiation pattern, can suite on the surface of the human body and potential candidate for smart clothing and wearable communication applications. The experimental results of the proposed antenna provided good agreement with the simulation ones. In future work, the numerical results for antenna radiation pattern, gain, and efficiency will be verified through experimental measurements.

AKNOWLEDGEMENTS

The authors would like to express gratitude to university for providing the resources and support necessary for this research. Authors also grateful for the guidance and encouragement from colleagues who have contributed valuable insights during the development of this work. Their support has been invaluable in completing this study.

REFERENCES

1. N. Singh, A.K. Singh, V.K. Singh, *Microw. Opt. Technol. Lett.* **5** No 7, 1553 (2015).
2. M. Agiwal, A. Roy, N. Saxena, *IEEE Commun. Surveys Tuts.* **18**, 1617 (2016).
3. S. Noor, N. Ramli, N.L. Hanapi, *Open J. Sci. Technol.* **3** No 3, 237 (2020).
4. H. Li, J. Du, X.-X. Yang, S.S. C. Gao, *IEEE Antennas Wireless Propag. Lett.* **21** No 4, 779 (2022).
5. M. Wagih, G.S. Hilton, A.S. Weddell, S. Beeby, *IEEE Trans. Antennas Propag.* **69** No 10, 6322 (2021).
6. Y. Yamada, *Electron. Mater.* **3** No 4, 301 (2022).
7. Y. Song, S. Lee, Y. Choi, S. Han, H. Won, T.-H. Sung, J. Bae et al., *Fash. Text.* **8**, 6 (2021).
8. K.N. Paracha, S.K.A. Rahim, P.J. Soh, M. Khalily, *IEEE Access* **7**, 56694 (2019).
9. M. El Gharbi, R. Fernández-García, S. Ahyoud, I. Gil, *Materials* **13** No 17, 3781 (2020).
10. A. Yadav, V.K. Singh, M. Chaudhary, H. Mohan, *J. Telecommun., Switching Syst. Netw.* **2** No 3, 37 (2015).
11. V. Kavitha, K. Malaisamy, T.S. Murugesh, M. Senthil Kumar, *J. Industrial Text.* **53**, 1 (2023).
12. Sedigheh Vaezi, Pejman Rezaei, Ali Akbar Khazaei, *AEU – Int. J. Electron. Commun.* **150**, 154197 (2022).
13. Usman Ali, Sadiq Ullah, Babar Kamal, Ladislau Matekovits, Amir Altaf, *IEEE Access* **11**, 14458 (2023).
14. C.X. Mao, Y. Zhou, Y. Wu, H. Soewardiman, D.H. Werner, J.S. Jur, *IEEE Trans. Antennas Propag.* **68** No 9, 6527 (2020).
15. Abirami Anbalagan, Esther Florence Sundarsingh, Vimal Samsingh Ramalingam, *Microw. Opt. Technol. Lett.* **62** No 2, 789 (2020).
16. Eissa A. Mohammad, Hasliza A. Rahim, Ping Jack Soh, Mohd Faizal Jamlos, Mohamedfareq Abdulmalek, Yeng Seng Lee, *Appl. Phys. A* **124**, 568 (2018).
17. Guzin Tekneci, Alparslan Cinar, Ahmet Gorgun, S. Cumhur Basaran, *Int. J. RF Microwave Comput.-Aid. Eng.* **2024**, 5076232 (2024).
18. Vinod Kumar Singh, Seema Dhupkariya, Naresh Bangari, *Wireless Personal Commun.* **95**, 1075 (2017).
19. R. Dwivedi, D.K. Srivastava, V.K. Singh, *Proceedings of IEEE 16th International Conference on Computational Intelligence and Communication Networks (CICN)*, 59 (Indore, India: 2024).
20. C.G. Bartone, L. Moore, M. Kohli, *Proceedings of the 2016 IEEE International Symposium on Antennas and Propagation (APSURSI)*, 999 (Fajardo, PR, USA: 2016).
21. M.M.H. Mahfuz, Md Rafiqul Islam, Chan-Wang Park et al., *IEEE Access* **10**, 38406 (2022).
22. M. El Gharbi, M. Martinez-Estrada, R. Fernández-García, S. Ahyoud, I. Gil, *J. Text. Inst.* **112** No 3, 437 (2021).
23. Ajit Kumar Singh, Santosh Kumar Mahto, Rashmi Sinha, Mohammad Alibakhshikenari, Ahmed Jamal Abdullah Al-Gburi, Ashfaq Ahmad, Lida Kouhalvandi, Bal S. Virdee, Mariana Dalarsson, *Sensors* **23**, 8996 (2023).
24. Md. Mehedi Hasan, Abu Zafor Md. Touhidul Islam A, *Cureus J. Eng.* **2**, es44388-025-04462-7 (2025).
25. Soukaina Sekkal, Laurent Canale, Mustapha El Halaoui, Othmane Bendaou, Adel Asselman, *Opt. Photon. J.* **11**, 413 (2021).

Проектування та розробка низькопрофільної гнучкої антени на частоті 3,5 ГГц з використанням різних матеріалів підкладки

Md. Samiul Islam, Abu Zafor Md. Touhidul Islam

Antenna Design Lab, Department of Electrical and Electronic Engineering, University of Rajshahi, Rajshahi-6205, Bangladesh

У статті представлено аналіз конструкції та продуктивності низькопрофільної гнучкої антени на частоті 3,5 ГГц з використанням різних матеріалів підкладки, таких як FR4, поліестер та бавовна, для інтелектуального одягу та носимих комунікаційних застосувань. Моделювання було виконано за допомогою програмного забезпечення CST Microwave Studio. Мініатюрні розміри антени становлять 30 × 20 × 0,8 мм3, а покращення її продуктивності було досягнуто завдяки використанню методів пазового кріплення та часткового заземлення. Порівняльний аналіз продуктивності трьох антен із застосуванням різних підкладок показує, що антена на основі поліестеру та текстилю пропонує кращі характеристики. Тому для експериментального тестування реалізації антени та перевірки результатів моделювання було обрано підкладку Rogers RT5880. Отже, для запропонованої реалізації антени на частоті 3,5 ГГц та експериментальної перевірки було обрано добре підходящий текстильний матеріал – поліестер. Антена працює в широкому діапазоні частот 3,11-4,27 ГГц та задовольняє найпопулярніші нижні діапазони 5G (3,33-4,2 ГГц) та WiMAX (3,4-3,6 ГГц). Завдяки своєму низькому профілю, компактним розмірам, економічно ефективній та гнучкій структурі, запропонована текстильна антена на основі поліестеру із задовільною пропускною здатністю, коефіцієнтом посилення, ефективністю та всеспрямованою діаграмою спрямованості може розміщуватися на поверхні людського тіла та добре підходить для використання в розумному одязі та носимих комунікаційних застосунках. Експериментальні результати, отримані на виготовленому прототипі, добре узгоджуються з даними моделювання.

Ключові слова: Поліестерова підкладка, Гнучка, Бездротовий широкосмуговий доступ, Текстильна антена, Розумний одяг.