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Fleece and Felt as Substrates for Patch Antenna at 2.4GHz

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Abstract

This study explores the development of textile-based patch antennas operating at 2.4 GHz using fleece and felt substrates, aiming to support wearable electronics for applications such as health monitoring and military operations. The antennas were fabricated using copper conductive paint and evaluated through simulation and empirical testing. Dielectric constants for fleece ($\varepsilon' = 1.25$, $\varepsilon'' = 0.024j$) and felt ($\varepsilon' = 1.20$, $\varepsilon'' = 0.067j$) were measured, and antennas were designed accordingly. Simulation results demonstrated gains of 7.46 dBi for fleece and 7.69 dBi for felt, while measured gains were 8.05 dBi and 3.58 dBi respectively. The measured S_{11} values were below -10 dB in both cases, indicating good impedance matching. The fleece antenna outperformed the felt counterpart in real-world measurements, showing better gain stability and fabrication reliability. These findings highlight the potential of fleece-based antennas for reliable wearable communication systems in medical and military contexts.

1. Introduction

A patch antenna with a textile substrate integrates technology with fabric, enabling garments that embody personal style while including sophisticated functionality. This antenna functions as both a transmitter and receiver, allowing it to be incorporated into patient clothing for medical applications such as heart rate monitoring, or integrated into military uniforms for personnel tracking during operations. In recent years, textile materials like felt and fleece have garnered interest in wearable antenna research due to their flexibility, lightweight nature, and comfort. Prior studies have evaluated the electromagnetic performance and durability of these materials in antenna design, showing promising results in terms of return loss and bandwidth. Felt offers high compressibility and thermal insulation, while fleece provides breathability and softness that are advantageous for wearable technologies. These properties, alongside their availability and ease of handling, formed the basis for selecting felt and fleece in this study over other textile substrates such as denim or polyester blends. The study investigates the performance of textile patch antennas utilizing textile fleece and textile felt, with copper paint as the conducting medium. It further explores the manufacturing procedures and analyzes the experimental results to draw practical conclusions.

(a) **(b)**

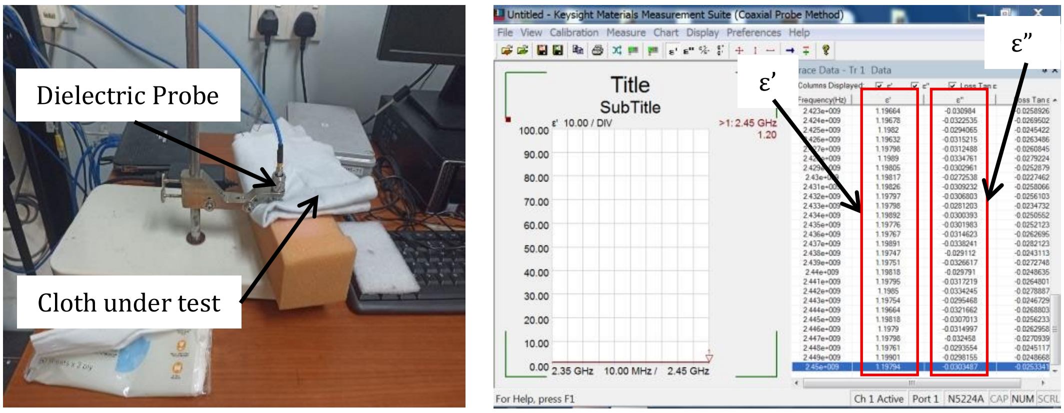
Fig. 1 *(a)Textile antenna incorporated in (a) patient cloths for medical monitoring; (b) military uniforms for tracking and communication*

Although various textile substrates have been explored for wearable antenna applications, including cotton, denim, and leather, fleece and felt offer a distinctive combination of electrical and physical properties. Fleece, known for its soft texture, breathability, and insulation properties, offers consistent dielectric behavior under bending stress which is an important factor for wearable use. Felt, on the other hand, is a dense non-woven fabric made by compressing fibers, known for its structural stability and moderate flexibility. Recent studies, such as Mahfuz et al. [1], emphasize the need for substrates that balance electromagnetic performance with user comfort and material durability. Prior works have often used cotton or polyester substrates, but these materials can be less stable under mechanical deformation. Fleece and felt were therefore selected for this study due to their widespread availability, ease of processing, and suitability for integration into garments, particularly in scenarios where comfort, flexibility, and environmental resistance are critical.

2. Fleece and Felt Substrates of Dielectric Constant

2.1 Method of Measurement and Data

The measurement procedure utilised a dielectric probe to obtain readings at eight distinct locations on the fleece and felt textile, thereby ensuring an averaged outcome. The cable was connected to a Vector Network Analyzer (VNA) to perform the measurements.



(a) **(b)**

Fig. 2 *(a) Measuring the dielectric constant of fleece, followed by repeating the process for felt textile; (b) Gathering results of measurement*

Following the collection of the measured values, the data were analysed, as illustrated in Fig. 3.

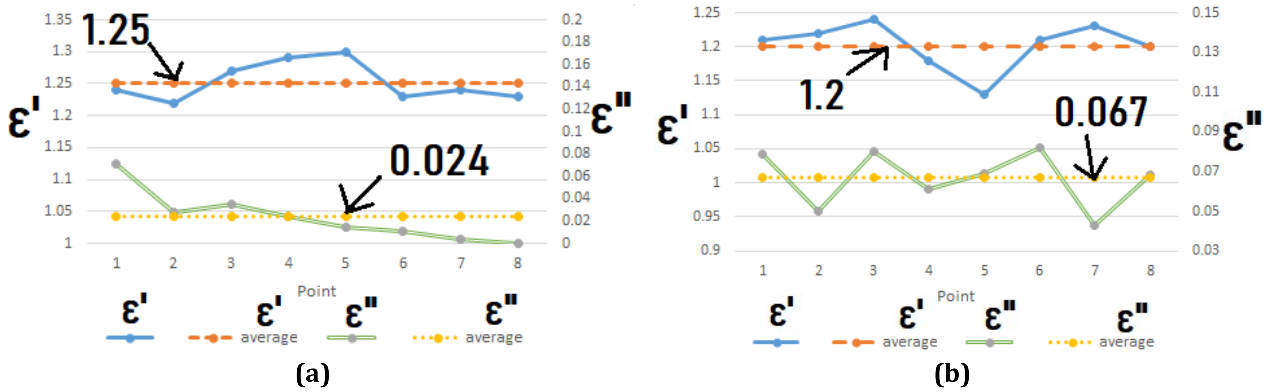


Fig. 3 *(a) Dielectric constant results for fleece textile; (b) Dielectric constant results for felt textile*

$$\varepsilon_m = \varepsilon' + j\varepsilon" \quad (1)$$

$$\sigma = \varepsilon"\varepsilon_0\omega = \varepsilon"/60\lambda_0 \quad (2)$$

For fleece textile, the average value of ε' is 1.25 F/m while ε" is 0.024j. The average value for felt are of ε' is 1.2 F/m while ε" is 0.067j. ε" were imaginary value. λ value from 2.4GHz is 0.125m.

Fleeces,

$$\sigma = \frac{0.024}{60(0.125)} = 0.003\ S/m \quad (3)$$

Felt substrates,

$$\sigma = \frac{0.067}{60(0.125)} = 0.009\ S/m \quad (4)$$

3. Results of Textile Patch Antenna Simulations

3.1 Equation Parameters

Antenna designed based on theoretical calculations and optimized to meet theoretical requirements. Equation for light speed is:

$$c = \frac{1}{\sqrt{\varepsilon_0\mu_0}} \quad (5)$$

The permittivity in free space environment, $\varepsilon_0 = 8.854 \times 10^{-12}$ F/m and the permeability of free space, $\mu_0 = 4\pi \times 10^{-7}$ H/m. Wavelength equation is.

$$\lambda_0 = \frac{c}{f_r} \quad (6)$$

The equation for the wavelength in the dielectric substrate is.

$$\lambda_s = \frac{\lambda_0}{\sqrt{\varepsilon_r}} \quad (7)$$

Patch equation, width is [6].

$$W_p = \frac{c\sqrt{\frac{2}{\varepsilon_r + 1}}}{2f_r} \tag{8}$$

Effective dielectric constant equation.

$$\varepsilon_{reff} = \frac{\varepsilon_r - 1}{2} + \frac{\varepsilon_r - 1}{2\sqrt{1 + \frac{12t}{W_p}}} \tag{9}$$

Patch equation, length [6].

$$L_p = \frac{c}{2f_r\sqrt{\varepsilon_{reff}}} - \frac{0.824t(\varepsilon_{reff} + 0.3)(\frac{W_p}{t} + 0.264}{(\varepsilon_{reff} - 0.258)(\frac{W_p}{t} + 0.8)} \tag{10}$$

Feeding point equation.

$$x_f = \frac{L_p}{\sqrt{\varepsilon_{reff}}} \tag{11}$$

$$y_f = \frac{W_p}{2} \tag{12}$$

Feedline length equation.

$$f = \frac{L_s}{2} - \frac{L_p}{2} \tag{13}$$

Feedline width equation, Z_0=50Ω.

$$Z_0 = \frac{60\ln(\frac{8h}{d} + \frac{d}{4t})}{\sqrt{\varepsilon_{reff}}} \tag{14}$$

The antenna was designed using the FEKO simulator, with S_{11}, impedance, and radiation pattern results obtained from POSTFEKO. Following fabrication, the S_{11} measurement was carried out using a Vector Network Analyser (VNA) in conjunction with Keysight software. The two-dimensional radiation pattern was evaluated in the chamber, and the data were observed and analysed using IAMS Comrel.

3.2 Antenna Simulation in FEKO

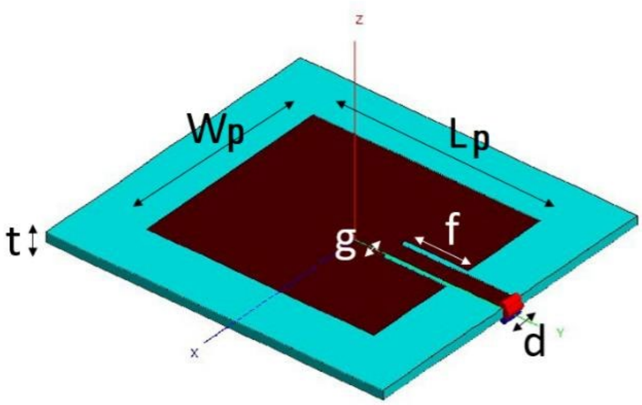


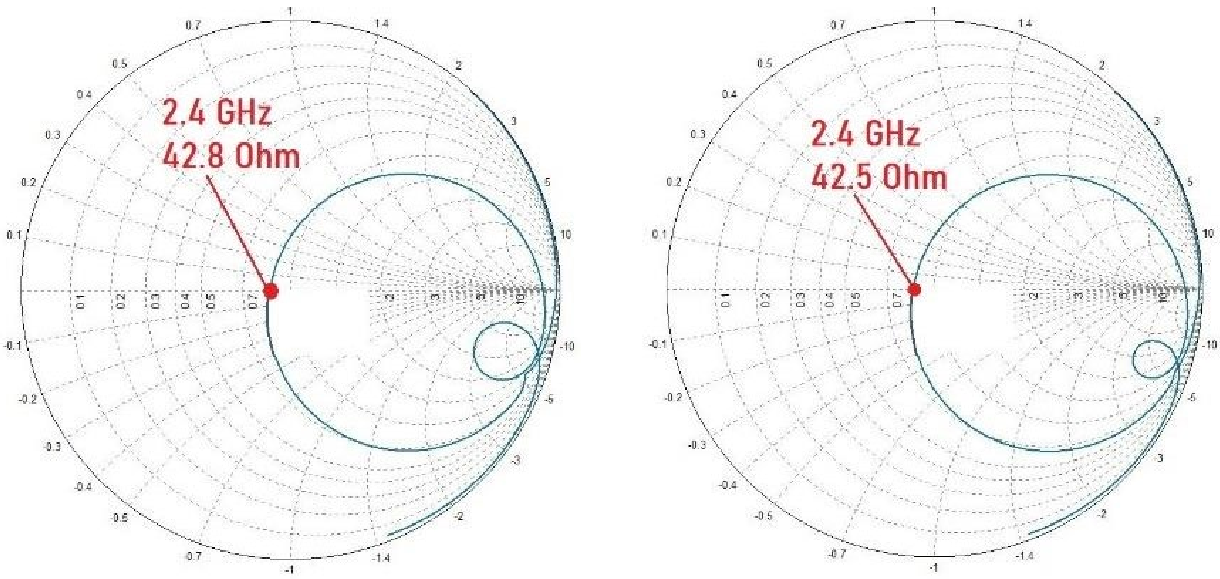
Fig. 4 *Antenna in FEKO simulation*

3.3 Antenna Simulation in FEKO

Table 1 *Parameters of antenna*

Parameter	Fleece	Felt mm
Thickness, t	2 mm	2 mm
Patch length, L_p	52.4 mm	51.69 mm
Patch width, W_p	46 mm	46 mm
Feedline length, f	12 mm	12 mm
Feedline width, d	4 mm	4 mm
Inset gap width, g	1 mm	1 mm

The input impedance of the fleece antenna is 42.8 Ω, while that of the felt antenna is 42.5 Ω, both exhibiting favourable compatibility with a 50 Ω feedline, as illustrated in Fig. 5.



(a) (b)

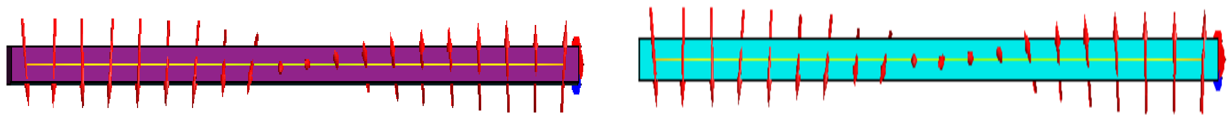
Fig. 5 *Simulated (a) fleece; (b) felt*

The radiation gains of the fleece and felt antennas are 7.46 dBi and 7.69 dBi, respectively. Fig. 6 depicts the two-dimensional radiation patterns and antenna gains.

(a) **(b)**

Fig. 6 *Simulated 2-dimensional radiation of (a) fleece; (b) felt*

Fig. 7 illustrates the electric field of the fleece and felt patch antennas. The electric field distribution corresponds with the data presented in the textbook.



(a) **(b)**

Fig. 7 *The e- field distribution of (a) fleece patch antenna; and (b) felt patch antenna*

3.4 Electromagnetic FEKO on Dielectric Medium of Body Equivalent

The textile patch antenna will be integrated into clothing. Therefore, an electromagnetic simulation of the textile patch antenna with a body-equivalent dielectric medium needs to be conducted. The design of the textile antenna with the body-equivalent dielectric medium is shown in Fig. 8.

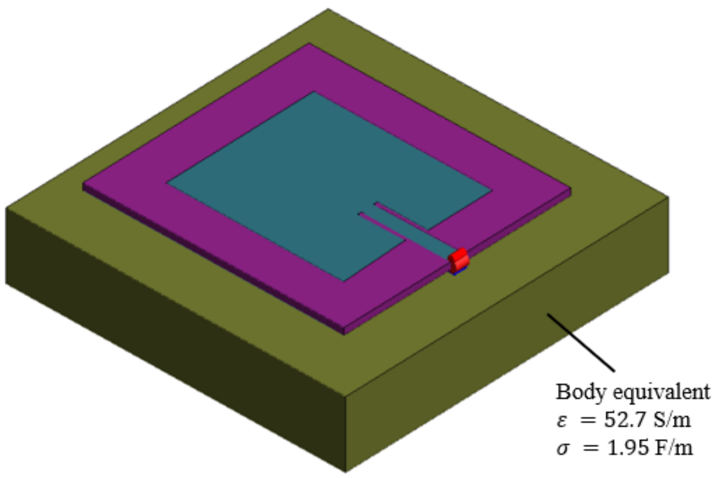


Fig. 8 *The design of textile patch antenna with dielectric medium of body equivalent*

Fig. 9 shows the input impedance of the textile patch antenna on a body-equivalent dielectric medium for both fleece and felt substrates. The impedance values are acceptable, as they are close to 50 Ω. The impedance is 40.93 Ω for fleece and 44.88 Ω for felt.

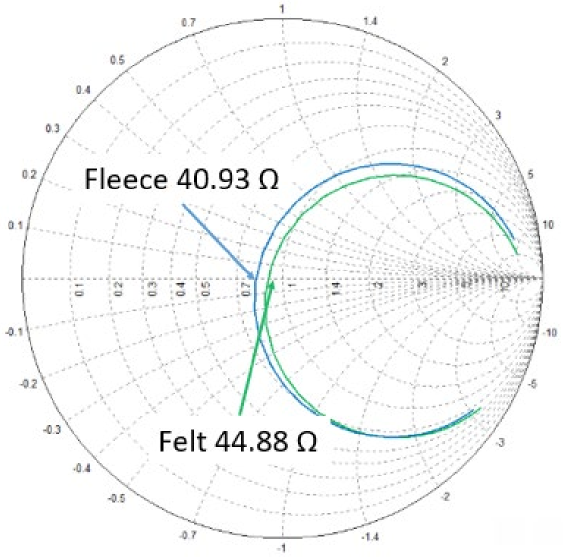


Fig. 9 *The impedance of fleece and felt patch antenna on a dielectric medium of body equivalent*

The S_{11} of the textile patch antenna on the body equivalent are shown in Fig. 10. For fleece patch antenna, the S_{11} is-19.7 dB while felt patch antenna is -23.54 dB. Both of the return loss is below -10 dB hence the results are satisfied. In Fig. 11 shown the 2-dimensional radiation pattern and the gain. The simulated result of the gains is also satisfied.

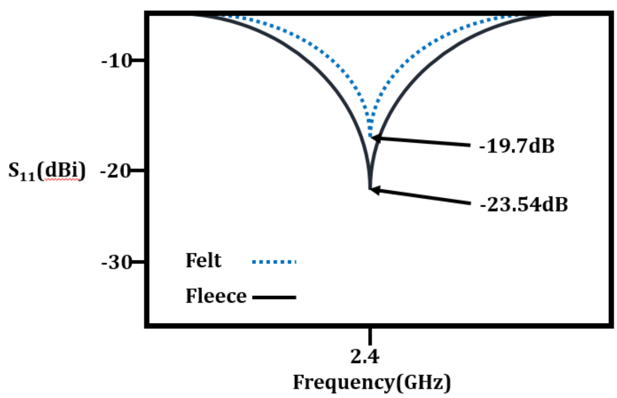


Fig. 10 *S_{11} for both textile antenna on body equivalent medium*

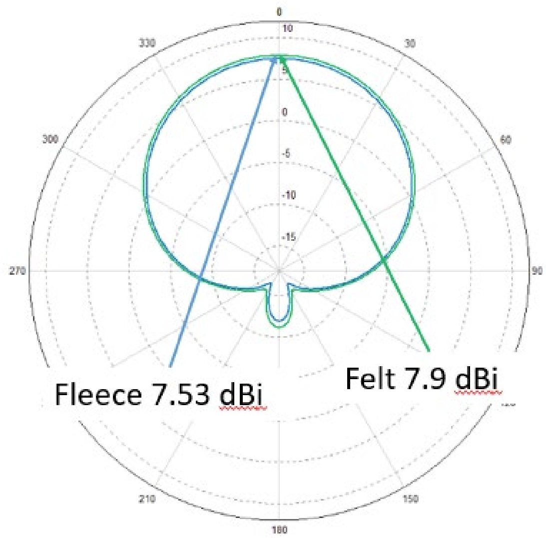


Fig. 11 *The radiation gains for both textile antenna*

4. Fabrication Process of Patch Antennas

Upon completion of the simulation procedure, fabrication will commence. The copper paint, illustrated in Fig. 12, will function as the conducting medium for the patch metallic material. A plastic sheet will be delineated and severed to fabricate a blueprint template, as illustrated in Fig. 13.

Fig. 12 C*opper conductive paint*

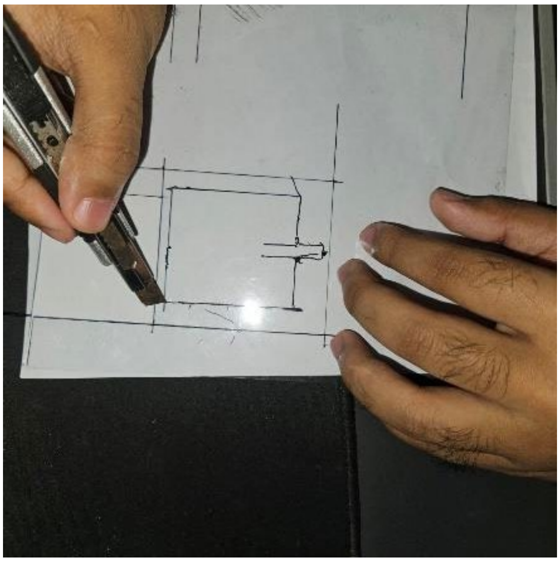


Fig. 13 *Cut based on the patch template*

In Fig. 14, the copper paint is swab to the fleece textile and felt textile utilising the plastic sheet cutout. Fig. 15 illustrates the following result and the drying of the paint. After the paint has completely cured, the patch and ground plane components will be excised and subsequently adhered together.

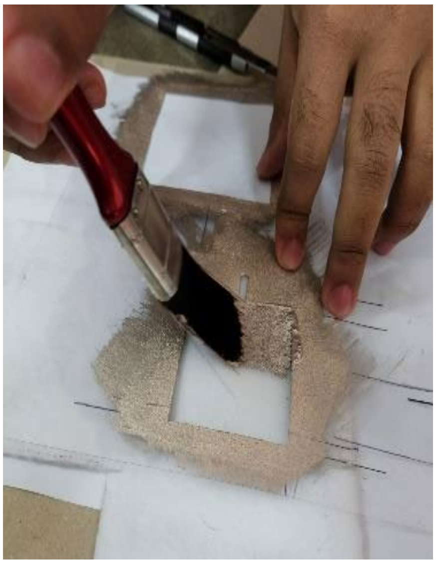


Fig. 14 *Pasting the conductive copper on substrate*

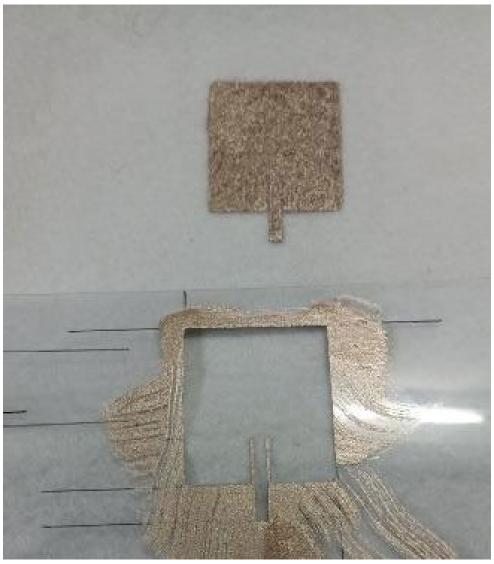


Fig. 15 *Dried the paint*

Subsequently, as illustrated in Fig. 16, the patch textile will be attached to a SMA connector, finalising the manufacture of fleece textile and felt textile antennas. The constructed production will subsequently be measured using the VNA, as illustrated in Fig. 17.

Fig. 16 *Solder process*

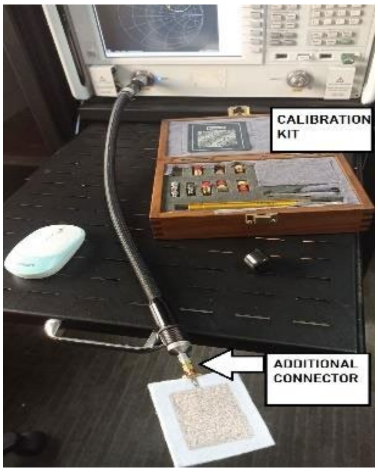
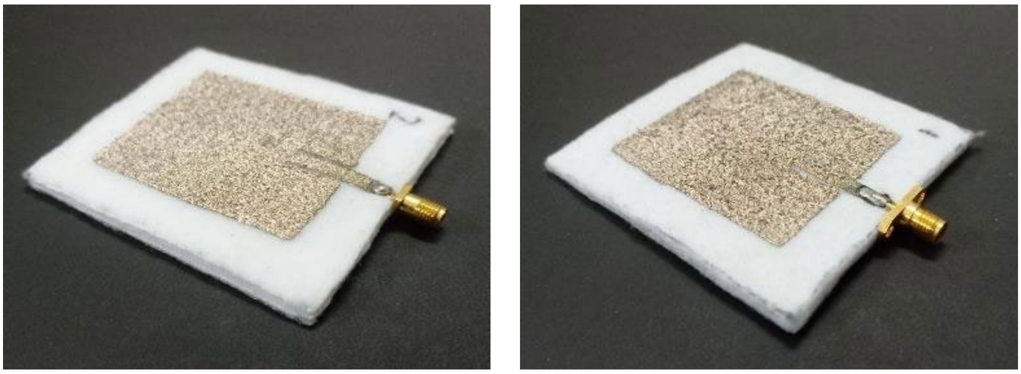


Fig. 17 *Using VNA for measurement process*

Antenna textile with substrate fleece and substrate felt, connect with SMA connectors, are shown in Fig. 18 respectively.



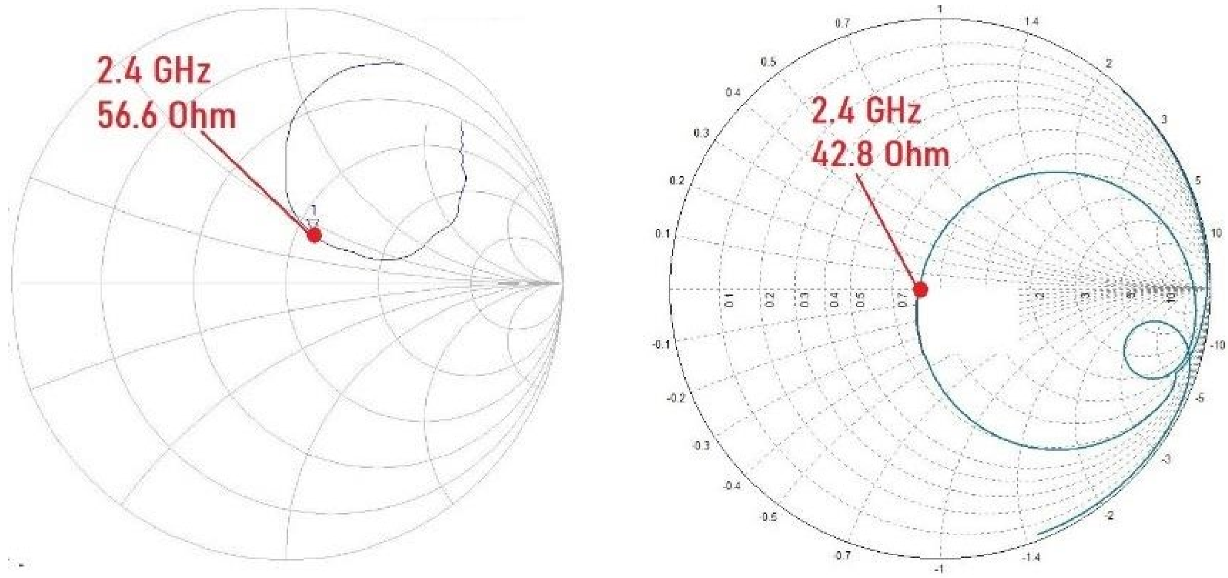
(a) **(b)**

Fig. 18 *(a) Fleece antenna; (b) felt antenna*

5. Measurement Results

5.1 Fleece Textile Antenna

The impedance matching of the fleece antenna, as depicted on the Smith chart, is displaced towards the inductive region, registering 56.6Ω at 2.4GHz, whereas the simulation indicates 42.8Ω at the same frequency, as illustrated in Fig. 19 This alteration implies the assessed impedance possesses a positive imaginary value, signifying inductance. The mismatch may stem from the test configuration, including cables and supplementary connectors, which could introduce inductive reactance if not well adjusted.



(a) **(b)**

Fig. 19 *(a) Impedance measurement; and (b) impedance of the simulation*

Both the observed and simulated S_{11} values of the antenna are below −10 dB, indicating efficient power transmission with less than 10% reflection, which is generally considered acceptable, as illustrated in Fig. 20. According to Fig. 21, the measured and simulated gain and two-dimensional radiation patterns are in good agreement, with gains of 8.05 dBi and 7.46 dBi, respectively. The measured gain can be calculated by using equation (15).

$$G_{AUT} = 11 + \left(-58.12 - (-55.17)\right) = 8.05\ dBi \tag{15}$$

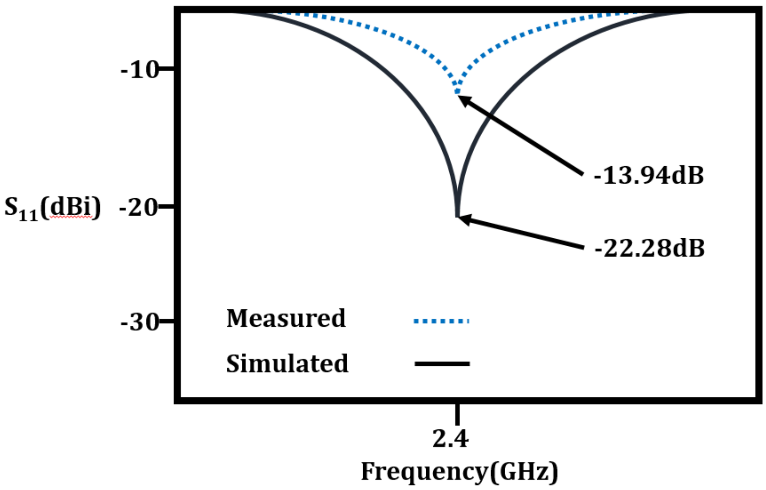


Fig. 20 *S_{11} of fleece*

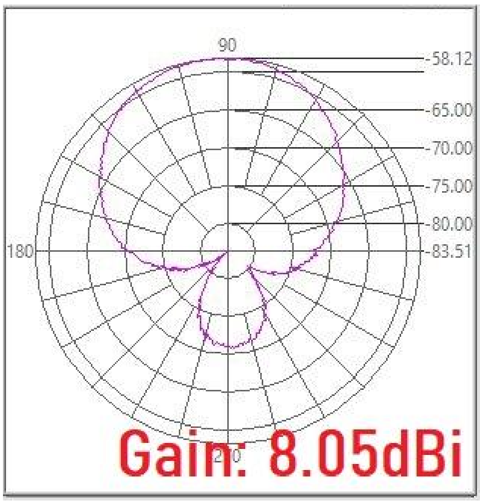
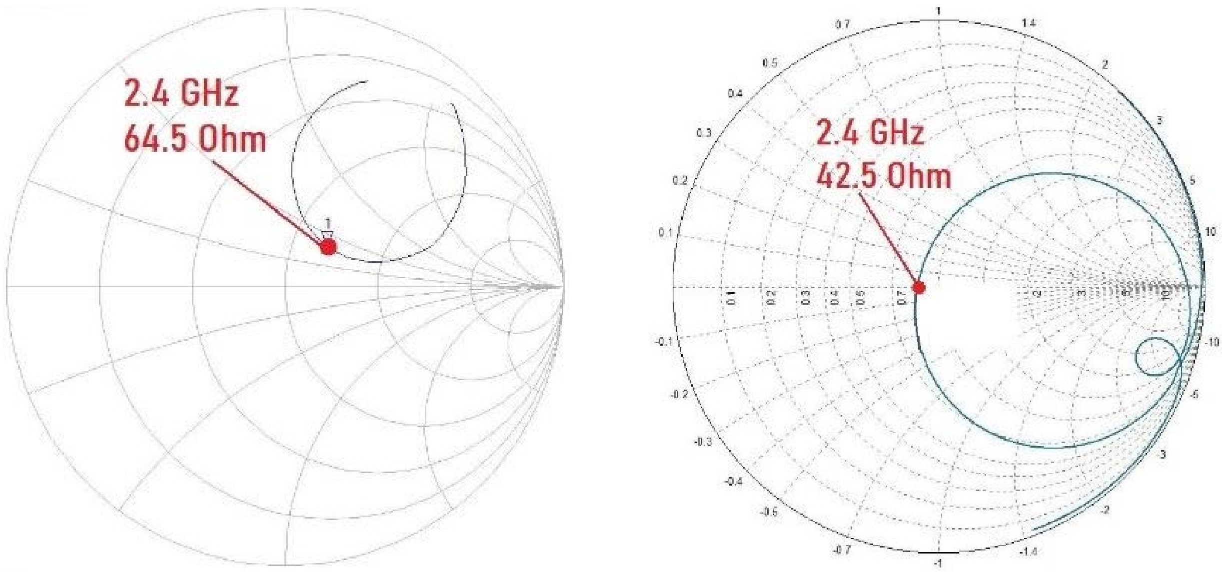


Fig. 21 *2-dimensional radiation and gain*

5.2 Felt Antenna

Input impedance of the felt antenna, as represented on the Smith chart, is displaced towards the inductive region, registering at 64.5Ω at 2.4GHz, whereas the simulation indicates 42.5Ω at the same frequency, as illustrated in Fig. 22. This shift signifies that impedance measurement possesses a positive imaginary value, indicating inductance. The impedance measurement may indicate the impedance characteristic plus any reactance attributable to the line length, resulting in this change. The 64.5Ω impedance indicates around a 28% divergence from the 50Ω standard, which may remain permissible for specific applications, particularly if the performance effect is negligible.



(a) **(b)**

Fig. 22 *(a) Impedance measurement; and (b) Impedance simulation*

The measured and simulated S_{11} values are both below −10 dB, indicating efficient power transmission with less than 10% reflection. This is regarded as suitable performance, as illustrated in Fig. 23. According to Fig. 24, the comparison of gain and two-dimensional radiation patterns between the measurement and simulation shows gain values of 3.58 dBi and 7.69 dBi, respectively. This discrepancy is likely due to measurement error and a defective antenna. This anomaly arose from the antenna fabrication process, where glue was used to bond the felt material. . The measured gain can be calculated by using equation (16).

$$G_{AUT} = 11 + \left(-64.54 - (-57.12)\right) = 3.58\ dBi \quad (16)$$

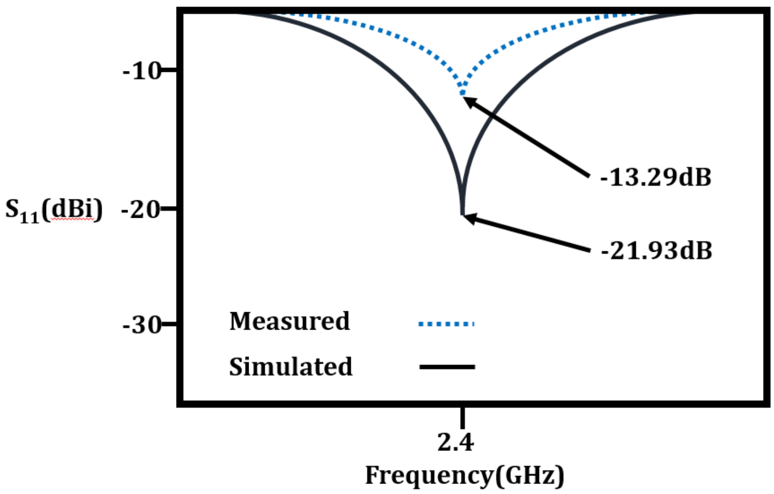


Fig. 23 *S_{11} for measured and simulated result*

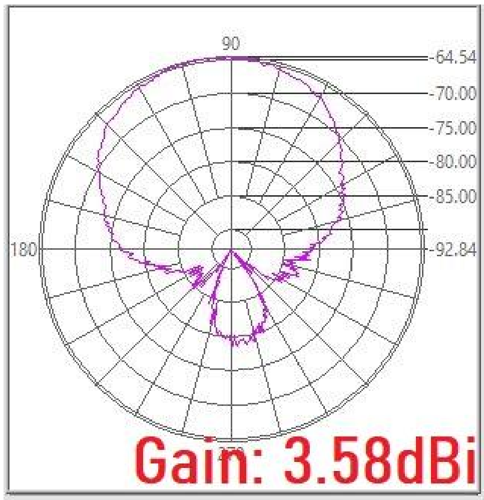


Fig. 24 *Measured radiation pattern and gain*

6. Conclusions

This research investigated the viability of using fleece and felt textiles as dielectric substrates in 2.4 GHz wearable patch antennas. Both simulation and experimental results demonstrated the antennas' functionality, with return loss (S_{11}) values below -10 dB and input impedance values close to the desired 50 Ω standard. The fleece-based antenna showed strong agreement between simulated and measured gain (7.46 dBi simulated vs. 8.05 dBi measured), suggesting a robust design and reliable fabrication process. On the other hand, the felt antenna showed a significant deviation in gain (7.69 dBi simulated vs. 3.58 dBi measured), attributed to fabrication inconsistencies such as glue application, which affected performance. Among the two materials, fleece proved to be the more promising candidate for practical wearable antenna applications. Its superior performance in both radiation characteristics and structural reliability makes it better suited for integration into garments where consistent wireless communication is essential. Future research should aim to optimize fabrication techniques, investigate long-term wearability and durability, and assess performance under dynamic conditions like bending and movement. Additionally, expanding the analysis to higher-frequency bands and multiband configurations could further solidify the role of textile-based antennas in emerging 6G and IoT enabled wearable systems.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Badrul Amin Azahari, Kamilia Kamardin, Muhammad Syamim Fitri Othman, Hazilah Mad Kaidi;* ***data collection:*** *Badrul Amin Azahari, Muhammad Syamim Fitri Othman;* ***analysis and interpretation of results:*** *Badrul Amin Azahari, Kamilia Kamardin, Muhammad Syamim Fitri Othman;* ***draft manuscript preparation:*** *Badrul Amin Azahari, Kamilia Kamardin, Muhammad Syamim Fitri Othman, Hazilah Mad Kaidi. All authors reviewed the results and approved the final version of the manuscript.*

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