Investigation of the Effects of Different Bending Degrees on the Performance of Microstrip Patch Textile-Based Antennas

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Article History: Received 6 July 2025; Revised 21 November 2025;
Accepted 21 November 2025; Published 30 November 2025

Abstract
Textile-based antennas serve crucial functions in on-body antenna applications. However, their soft form makes them susceptible to bending from body movements and posture changes. This paper aims to investigate the effect of different bending simulation degrees with cylinder diameters of 200 mm, 150 mm, 100 mm and 50 mm using Computer Simulation Technology (CST) Microwave Studio software on the performance of microstrip patch textile-based antennas. Flannel serves as the substrate material, with copper as the conducting part. Results obtained indicate a slight increase in the operating frequency for all bending conditions compared to the initial 2.45 GHz frequency. Additionally, return loss values significantly decrease under bending conditions. Thus, the findings demonstrate that bending significantly affects the characteristics of microstrip patch textile-based antennas, leading to varied performance outcomes.

Keywords: Bending Conditions, Flannel, ISM Band, On-body Antenna, Textile-based Antenna

1.0 Introduction

Textile-based antennas have garnered significant attention due to their flexibility and conformability, making them suitable for various applications, especially in body-centric wireless communication systems. These antennas are designed to be bendable to conform to the human body structure, ensuring consumer comfort and optimal efficiency even under bending circumstances [1]. The use of conductive fabrics in textile antennas allows for flexibility and conformability, enabling them to be bent at different angles without compromising their performance [2].

Studies have shown that textile antennas can be integrated into smart garments, such as safety vests or uniforms, making them ideal for body-centric communication and sensor systems [3]. The impact of textile materials on antenna performance has been investigated, emphasising the importance of understanding how the properties of textiles influence antenna characteristics [4]. Additionally, textile antennas have been designed for specific applications, such as GPS systems, biomedical communication, and glucose level monitoring, showcasing the versatility and adaptability of textile-based antenna technology [5], [6], [7].

A critical consideration in the evaluation of textile antennas for various applications is their bending analysis. Numerous studies have focused on assessing the impact of bending on textile antennas to ensure their flexibility and stability under deformation conditions. For instance, [8] integrated a flexible frequency-selective surface into a limber antenna for Wireless Body Area Network (WBAN) applications and conducted the bending analysis to determine its performance under deformation conditions. Similarly, [1] methodically examined a textile antenna for body-centric wireless communication applications by subjecting it to bending at different angles to assess its behaviour.

Moreover, [9] tested the bending performance of a wearable textile antenna along different planes and achieved a bandwidth of 12 GHz within the Ultra-Wideband (UWB) application frequency range. The study by [10] involved the bending analysis of a miniaturised textile antenna for 5G and Wireless Local Area Network (WLAN) applications using a phantom wrist model to validate its on-body effects. Additionally, [11] highlighted that wearable antennas face scenarios like bending, stretching and flexing, emphasising the importance of evaluating antenna performance under such conditions. On the other hand, research by [12] analysed the effects of bending on polymer-based flexible antennas at different operating frequencies, demonstrating the significance of understanding how bending impacts antenna characteristics. Overall, these studies underscore the importance of bending analysis in ensuring the reliability and performance of textile antennas in various applications, especially those related to wearable and body-centric communication systems.

Among textile materials, flannel has emerged as a promising substrate due to its softness, comfort, and suitability for the development of textile-based antennas. Studies have explored the use of flannel as a substrate material for wearable antennas, particularly in healthcare applications [13]. The design of super-wideband washable antennas on flannel fabric has also been demonstrated, showcasing the versatility and practicality of using flannel in antenna development [14]. Additionally, research has highlighted the importance of clothing components, including flannel, in the design and experimental procedures of wearable textile antennas [15]. Flannel, along with other textile materials, has been investigated for its suitability in wireless applications, emphasising its potential to enhance the performance of textile-based antennas [16]. These studies collectively underscore the significance of flannel as a viable material for textile-based antenna design, especially in the context of wearable and healthcare applications.

Therefore, due to the advantages of flannel, this study focuses on the development of a microstrip patch textile-based antenna operating at the ISM band utilising flannel as the substrate material. Despite being a common textile material, flannel is rarely used as the substrate for microstrip patch antennas. This is why flannel was chosen over more commonly used materials like felt, denim or polyester.

Since the antenna is intended for on-body applications, it is essential to investigate the impact of bending conditions on the antenna's performance. This paper will apply four different bending conditions with cylinder diameters of 200 mm, 150 mm, 100 mm and 50 mm using Computer Simulation Technology (CST) Microwave Studio software to assess their effects on the designed antenna. The findings of this study aim to demonstrate the suitability and reliability of flannel as the material for microstrip patch textile-based antennas and to provide insights into their potential for wearable communication systems. The novelty of this study lies in the application of flannel as a substrate for microstrip patch antennas, which is rarely investigated, combined with a systematic bending analysis across multiple radii. This research contributes to the design guidelines for wearable textile antennas by quantifying the impact of bending on resonant frequency and return loss, thereby informing future developments of flexible, on-body communication devices.

2.0 Methodology

This section is divided into two sub-sections. The first sub-section focuses on the development of the initial design of a microstrip patch textile-based antenna using flannel as the substrate material. The second sub-section addresses the assessment of the antenna's performance under bending conditions. Four bending conditions, represented by cylinder diameters of 200 mm, 150 mm, 100 mm and 50 mm, were selected to simulate typical human body curvatures during movement. The effects of these bending conditions on antenna characteristics were evaluated using CST Microwave Studio software, allowing for a systematic comparison of resonant frequency shifts, return loss, and other relevant performance parameters.

2.1 Initial Design

During the initial design stage, all the material parameters have been identified before the calculation process begins. Equation (1) is utilised to compute the width (W) of the patch antenna [17]:

$$W = \frac{c}{2f_0\sqrt{\frac{(\varepsilon_r + 1)}{2}}} \tag{1}$$

where, W = the width of the patch, f_0 = the resonance frequency, ε_r = the relative permittivity of the dielectric substrate and c = the speed of light: 3 x 10^8 m/s. Meanwhile, to calculate the effective dielectric constant, equation (2) is utilised [17]. This equation is based on the dielectric's height, dielectric constant and the calculated width of the patch antenna.

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{h}{W}\right]^{-\frac{1}{2}} \tag{2}$$

Then, the patch antenna's effective length, length extension ΔL and actual length of the patch antenna were calculated using equations (3), (4) and (5), respectively [17].

$$L_e = \frac{c}{2f_0\sqrt{\varepsilon_e}} \tag{3}$$

$$\Delta L = 0.824h\frac{(\varepsilon_e + 0.3)\left(\frac{W}{h} + 0.264\right)}{(\varepsilon_e - 0.258)\left(\frac{W}{h} + 0.8\right)} \tag{4}$$

$$L = L_e - 2\Delta L \tag{5}$$

The textile antenna design adopts the typical shape of a microstrip patch antenna to ensure compatibility with CST software, a widely used tool among researchers. Employing this typical shape for the preliminary design aims to minimise errors during the simulation process. Figure 1 displays the designed rectangular microstrip patch antenna, utilising flannel as the substrate, with dimensions measuring 46.3 mm in length and 52.7 mm in width.

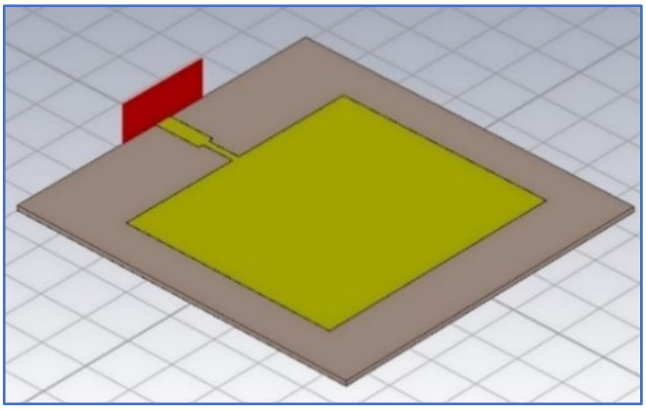


Figure 1: The preliminary design of the microstrip patch antenna

2.2 Bending Conditions

Once the initial design process is completed, the bending analysis is conducted. This analysis involves the addition of a cylinder with a specific radius, positioned along the y-axis as the centre. An example of this bending simulation analysis is depicted in Figure 2, where a 200 mm radius cylinder is added along the y-axis. The cylinder is configured as a vacuum cylinder for the analysis, allowing it to be treated as an imaginary construct. As previously mentioned, four distinct bending conditions are investigated in this research, each utilising cylinders with radii of 200 mm, 150 mm, 100 mm and 50 mm.

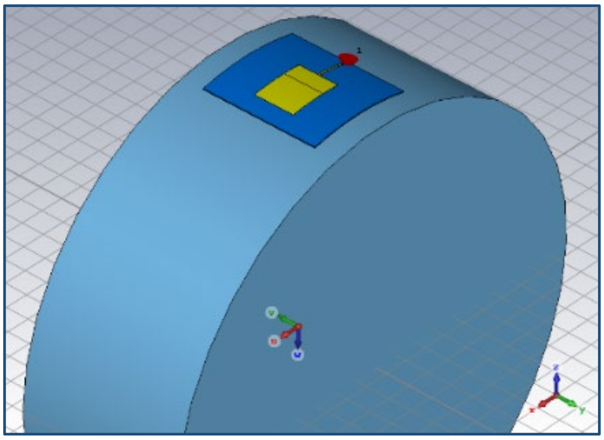


Figure 2: Example of bending simulation at 200 mm radius

3.0 Results and Discussion

This section is divided into two sub-sections: the first section evaluates the performance of the rectangular microstrip textile-based antenna using flannel without any bending, while the second sub-section analyses the effects of different degrees of bending on antenna performance.

3.1 Rectangular Microstrip Textile-Based Antenna using Flannel

The simulation process was conducted to assess the performance of the textile-based microstrip patch antenna design utilising flannel. The farfield of the rectangular microstrip textile-based antenna using flannel is depicted in Figure 3.

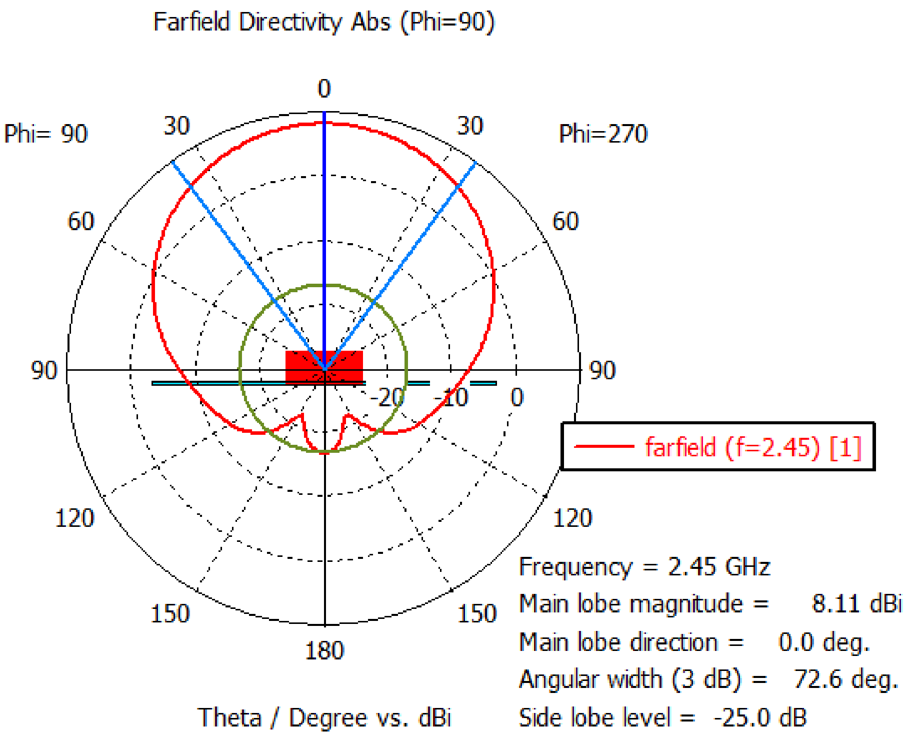


Figure 3: The farfield of the rectangular microstrip textile-based antenna using flannel

The radiation pattern simulation results indicate that the antenna exhibits a forward directivity gain of 8.11 dBi. In simpler terms, the antenna gain surpasses that of an isotropic antenna by more than six times. Similar gain values have been reported for polyester-based antennas designed for WBAN applications, achieving 8.38 dBi at 2.45 GHz [18]. This proves that textile substrates can deliver competitive performance compared to conventional FR4 (Flame Retardant 4)-based antennas.

However, the return loss (S_{11}) result of the rectangular microstrip textile-based antenna using flannel shown in Figure 4 reveals that the antenna resonates below the intended 2.45 GHz ISM band. This observation aligns with findings by Shishir et al. [19], who noted that substrate thickness and patch dimensions significantly influence resonant frequency and gain in fully textile-based antennas. To rectify this discrepancy, adjustments to the patch antenna's dimensions are necessary, which can be accomplished through 'parameter-sweep' analysis in CST software to achieve the desired operating frequency of 2.45 GHz. These adjustments involve modifying the patch antenna's length and width. Specifically, the patch length dictates the antenna's wavelength (λ parameter), which in turn determines the frequency through the formula $\boldsymbol{\lambda} = \frac{c}{f}$. Additionally, the patch width influences the antenna's impedance matching, thereby impacting the return loss.

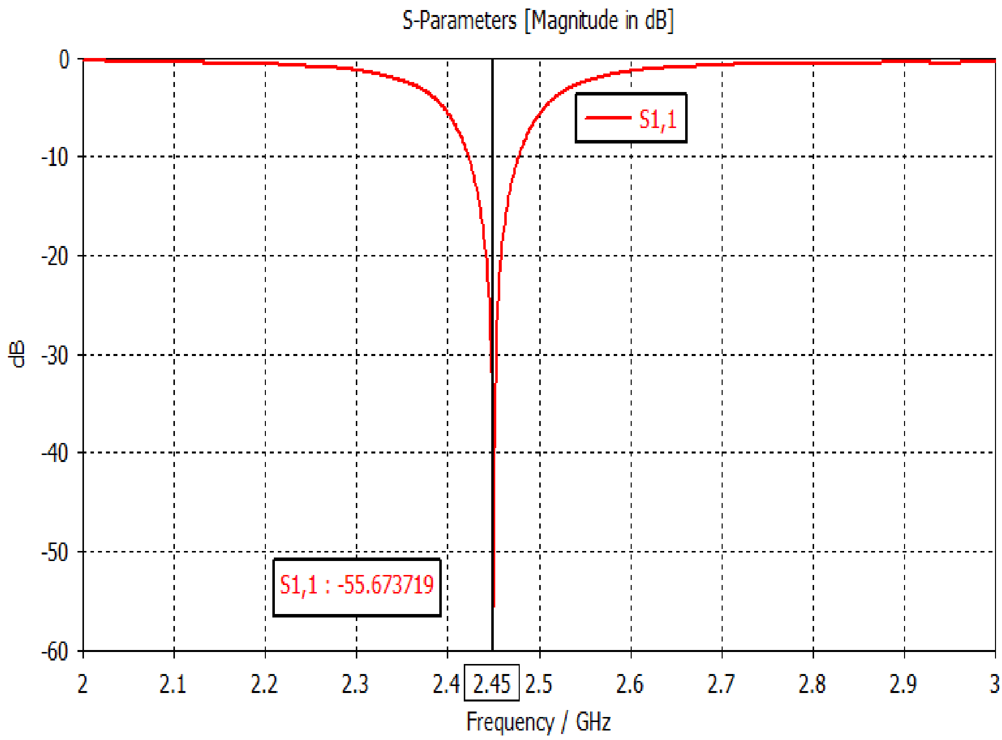


Figure 4: The S_{11} result of the rectangular microstrip textile-based antenna using flannel

3.2 Bending Analysis

Figure 5 shows the comparison of the return loss value for each bending degree. The four degrees of bending analysis show a significant deterioration of the return loss value compared to the initial value before the bending. It also means the bending condition can change the impedance matching of the antenna.

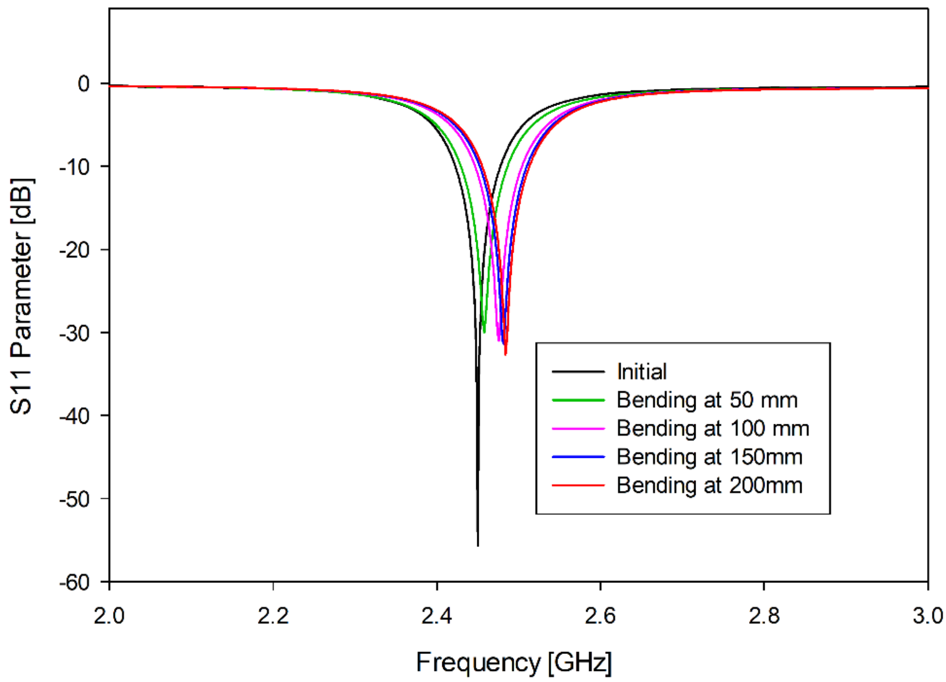
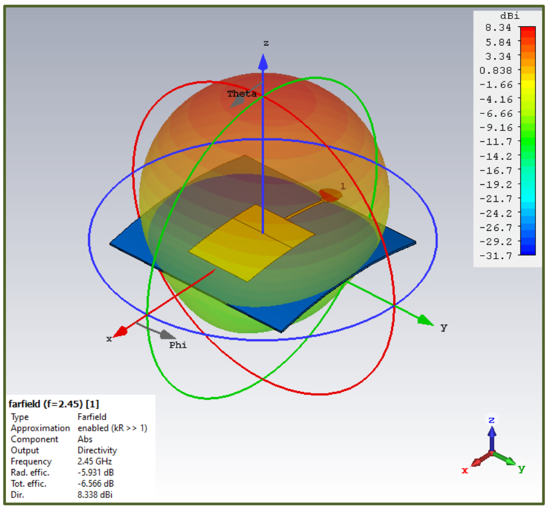


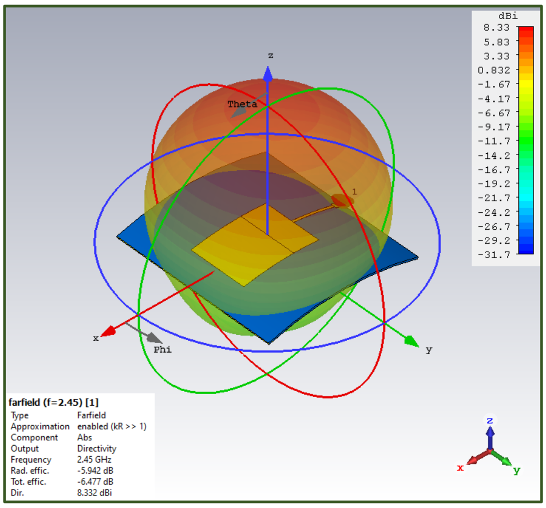
Figure 5: The S_{11} results comparison of different bending degrees

Based on Figure 5, it shows the significant change of the S_{11} parameter from -55.7 dB (in Figure 4) to -32.6 dB, -31.4 dB, -30.96 dB and -30 dB when the bending varies from 200 mm, 150 mm, 100 mm and 50 mm radius, respectively. Referring to all S_{11} parameter bending analysis results, the operating frequency is slightly shifting to the right, making the antenna operate at a higher frequency than 2.45 GHz. As mentioned earlier, the patch length will determine the wavelength of the antenna (lambda parameter), and the lambda parameter will determine the frequency based on the formula of lambda, $\lambda = \frac{c}{f}$. The bending makes the patch length seem slightly shorter. Hence, the shorter patch length will give a higher frequency response to the antenna.

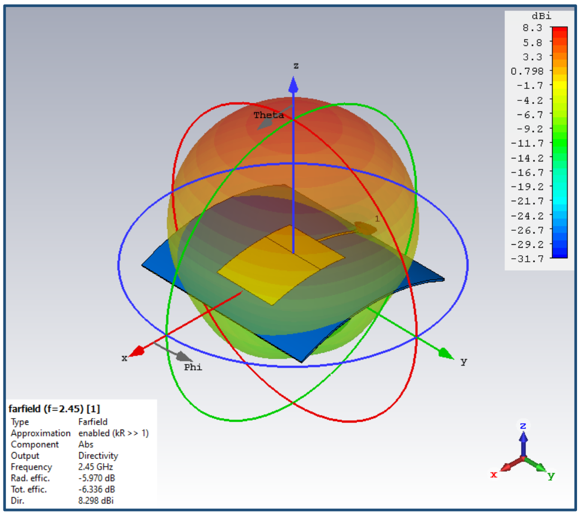
Meanwhile, Figure 6(a)–(d) presents the radiation patterns of the antenna under different bending radius simulations and Figure 7(a)–(d) shows the corresponding polar farfield plots of the antenna. From Figure 6(a), the 200 mm bending antenna has a forward directivity signal radiation with a gain of 8.34 dBi. While in Figure 7(a), the polar farfield shows that the main lobe magnitude is 8.33 dBi gain at 0° direction. Compared to the antenna condition before the bending, there are only slight changes in the radiation pattern parameters. The main lobe is still in the 0° direction. While the side lobe changes from -25 dB to -20.6 dB, which means the side lobe magnitude becomes higher. The angular width changed from 72.6° to 73.3°.



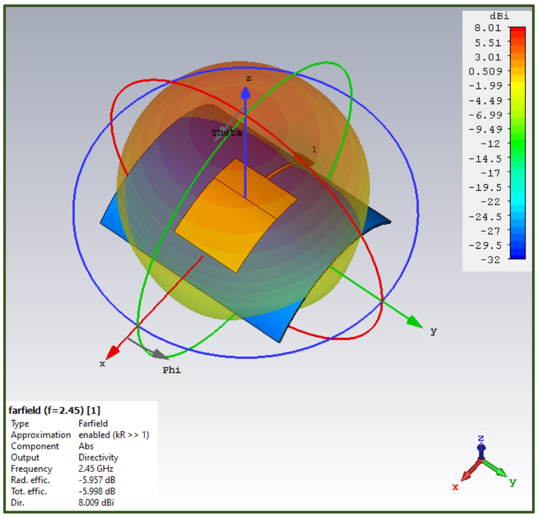
(a)



(b)



(c)



(d)

Figure 6: The antenna's radiation pattern performance of the bending radii simulations at (a) 200 mm, (b) 150 mm, (c) 100 mm, and (d) 50 mm

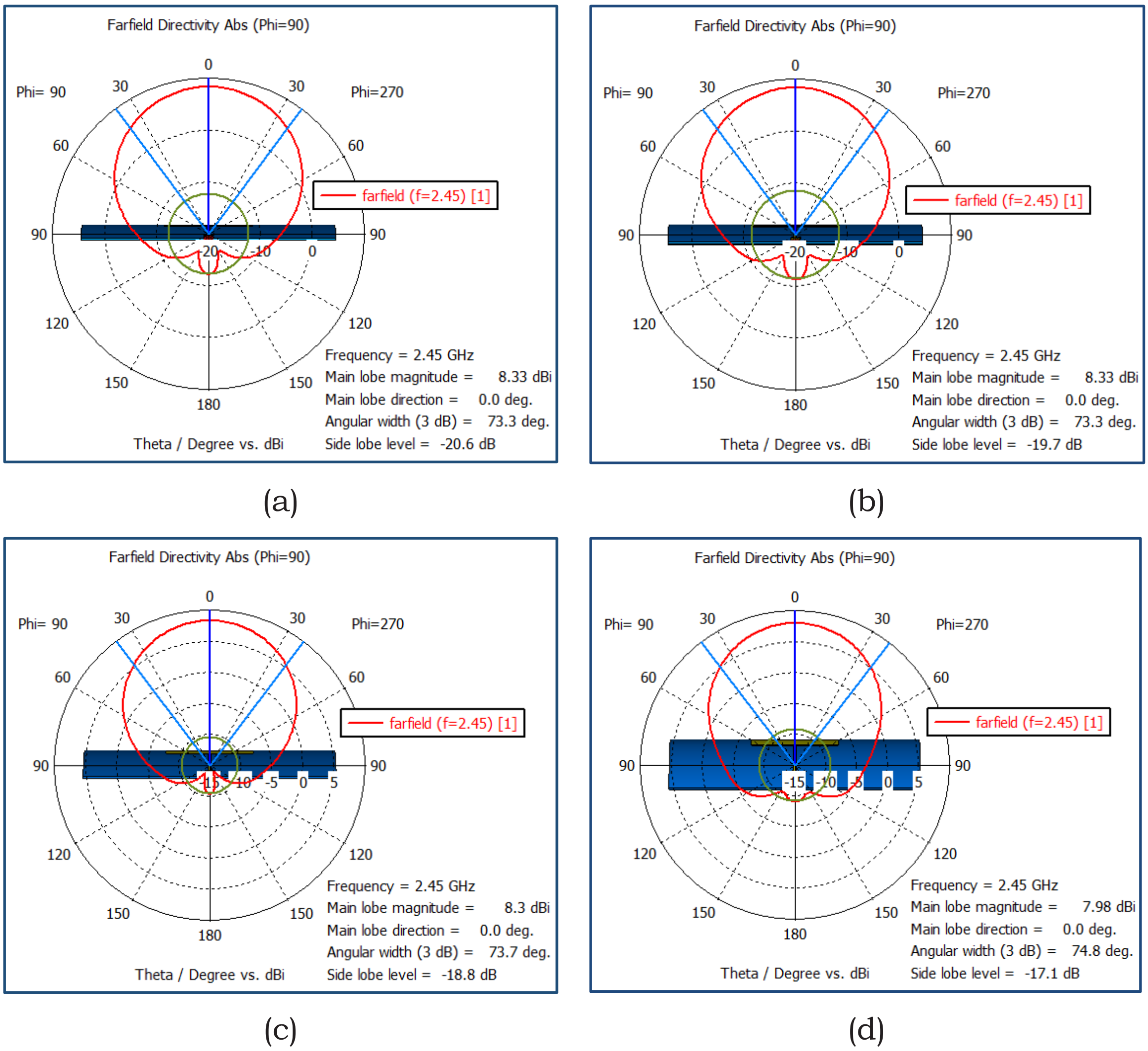


Figure 7: The antenna's polar farfield performance of the bending radii simulations: (a) 200 mm, (b) 150 mm, (c) 100 mm, and (d) 50 mm

Figure 6(b) and Figure 7(b) present the antenna's radiation pattern performance and polar farfield of the 150 mm bending radius simulation. Figure 6(b) shows that the 150 mm bending antenna has a forward directivity signal radiation with a gain of 8.33 dBi. While Figure 7(b) shows the same result as 200 mm bending in all parameters except the value of the side lobe. The 200 mm bending radius gives the side lobe value of -20.6 dB, while the 150mm bending radius gives -19.7 dB. Therefore, there are only slight changes in radiation pattern parameters compared to the antenna condition before the bending and compared to the 200 mm bending. The main lobe is still in the 0° direction.

Meanwhile, Figure 6(c) and Figure 7(c) present the antenna's radiation pattern performance and the polar farfield of the 100 mm bending radius simulation. Figure 6(c) and Figure 7(c) show that the 100 mm bending antenna has a forward directivity signal radiation with a gain of 8.3 dBi and the polar farfield shows that the main lobe magnitude is 8.3 dBi gain at 0° direction, respectively. Compared to the antenna condition before the bending, again, there are only slight changes in the radiation pattern parameters. The main lobe is still in the 0° direction. While the side lobe changes from -25 dB to -18.8 dB. The angular width changed from 72.6° to 73.7°.

Lastly, Figure 6(d) and Figure 7(d) present the antenna's radiation pattern performance and polar farfield of the 50 mm bending radius simulation. Both Figure 6(d) and Figure 7(d) show that the 50 mm bending antenna has a forward directivity signal radiation with a gain of 8.01 dBi, and the polar farfield shows that the main lobe magnitude decreased to 7.98 dBi gain but still at 0° direction, respectively. Compared to the antenna condition before the bending, there are only slight changes in the radiation pattern parameters. The main lobe is still in the 0° direction. While the side lobe changes from -25 dB to -17.1 dB. The angular width changed from 72.6° to 74.8°.

4.0 Conclusion

In conclusion, the investigation into the effects of different bending degrees on the performance of microstrip patch textile-based antennas reveals significant insights. The analysis of the S_{11} parameter highlights a notable reduction in return loss as bending increases, leading to a slight shift in the operating frequency to higher values. This frequency shift is attributed to the bending-induced shortening of the patch length, influencing the antenna's resonance. Further examination of the radiation pattern performance demonstrates consistent directional signal radiation across all bending conditions, with marginal changes in main lobe magnitude and angular width. Despite slight variations in the side lobe magnitude, the main lobe remains predominantly in the 0° direction. These findings underscore the impact of bending on the characteristics of microstrip patch textile-based antennas, emphasising the need for careful consideration of bending effects in antenna design for practical applications. Overall, this study contributes valuable insights for the development of robust and adaptable textile-based antennas in on-body antenna applications. For future research, different materials or different shapes of antennas can be proposed.

Acknowledgement

This research was conducted without any financial support or external funding. The authors would like to thank Universiti Malaysia Sarawak (UNIMAS) for providing facilities and technical assistance during this study.

Author Contributions

Nizar Ahmad: Initial Study, Investigation, Methodology, Simulation, Formal Analysis, Writing - Original Draft, Review & Editing; **Dyg Norkhairunnisa Abang Zaidel**: Project Administration, Conceptualisation, Validation, Supervision and Writing - Review & Editing.

Conflicts of Interest

The manuscript has not been published elsewhere and is not under consideration by any other journal. All authors have approved the review, agreed to its submission and declared no conflict of interest regarding the manuscript.

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