Design and Performance Analysis of WiFi Microstrip Patch Antenna under Different Bending Conditions using Flexible Substrates

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ABSTRACT

Textile-based antennas are of great importance for wearable devices due to their flexible and compact design, which allows the creation of efficient wearable technologies. However, the use of flexible substrates in wearable antennas presents a number of challenges, including frequency shifts that occur during bending. A comprehensive analysis of the bending characteristics of flexible substrates is absent from the existing literature. The objective of this study is to analyze the performance of a Wi-Fi Microstrip Patch Antenna (MPA) designed to operate at 2.4 GHz using flexible substrates, such as leather, fleece, and felt, with a detailed examination of their bending characteristics. A bending analysis was conducted to measure the impact on performance metrics, such as return loss, bandwidth, gain, and Voltage Standing Wave Ratio (VSWR) under bending angles from 0° to 17°. The leather substrate exhibited minimal degradation in performance. The antenna demonstrated a return loss below -15 dB, a bandwidth exceeding 4%, a gain exceeding 5 dB, and a VSWR lower than 2.5 across all tested conditions. The leather substrate has emerged as a promising candidate for wearable Wi-Fi applications due to its ability to maintain stable performance metrics under bending conditions.

Keywords-microstrip patch antenna; textile material; leather; felt; fleece; Wi-Fi applications; ANSYS High-Frequency Structure Simulator (HFSS); Voltage Standing Wave Ratio (VSWR); vector network analyzer; wearable technology

I. INTRODUCTION

The development of textile-based MPAs for Wi-Fi applications at 2.4 GHz has attracted considerable interest in recent years. Authors in [1] devised a stretchable MPA that demonstrated intrinsic strain-sensing capabilities for electronic textiles. Authors in [2] developed a breathable textile rectangular-ring MPA by introducing small holes in the conductive layers to enhance water vapor permeability, rendering it suitable for Wi-Fi applications at 2.45 GHz. This research highlights the significance of dielectric substrates, such as leather, felt, and wool, given their distinctive properties. Multiple studies have concentrated on improving the bandwidth and efficiency of microstrip patch antennas for diverse applications [3]. Authors in [4] made significant contributions to this field with the development of a broadband CPW-fed MPA on a fabric substrate, which demonstrated the capacity to radiate across a frequency range of 1.4 to 3 GHz. This is consistent with the overarching objective of examining MPA on flexible substrates. In their discussion of wearable antennas designed for wireless body area networks, authors in [5] placed particular emphasis on the importance of flexibility, comfort, and durability. They ensured that the antennas could conform to body shapes without any loss of performance.

Authors in [6] conducted a comparative analysis of various textiles for millimeter wave miniaturized antennas for body-centric communications, thereby providing relevant insights into substrate selection. Authors in [7] examined the potential of graphene-based materials for microstrip patch antennas, offering insights into the use of advanced substrate materials.

Further research [8], provides a survey of textile materials deployed in wearable antennas, highlighting the potential of different fabrics for antenna applications. Authors in [9] concentrated their efforts on the development of wearable antennas on textile substrates, exploring the potential of various fabric substrates for unlicensed ultra-wideband applications. Authors in [10] carried out a comprehensive analysis of the dielectric properties of insulating fabrics, thereby contributing to a deeper understanding of the material properties that are critical for optimal antenna performance. The investigation of flexible and wearable antennas remains a prominent area of research, with current studies concentrating on the optimization of design and material selection to enhance performance under diverse conditions. A bending analysis on flexible substrates is a crucial step in advancing the field of wearable and flexible electronics. This ensures practical application and stable performance, while also driving innovation in materials and design. In light of the growing importance of flexible technologies across a range of domains, it is imperative that ongoing research in this area be conducted in order to develop reliable, high-performance antennas that meet the demands of modern applications. This study demonstrates the significance of substrate materials, design principles, and innovative techniques in the advancement of microstrip patch antennas using textile substrates, including leather, felt, and fleece, for Wi-Fi applications at 2.4 GHz.

II. MPA DESIGN

MPA was designed and optimized utilizing a leather substrate for applications requiring Wi-Fi connectivity within the 2.4 GHz frequency range. The dimensions of the MPA were optimized to achieve optimal performance employing established formulas and simulation tools, including ANSYS HFSS. Comparative studies with fleece and felt substrates have demonstrated that leather exhibits superior performance under bending conditions, therefore underscoring its potential for reliable integration in wearable technology.

A. Antenna Design

The design process for the MPA includes the calculation of the dimensions of the patch and ground plane. The width of the MPA (*W*) is determined, which is used to specify the size of the antenna:

$$W = \frac{c}{2f_c}\sqrt{\frac{2}{\varepsilon_r+1}} \quad (1)$$

where *c* is the speed of light in a vacuum, equivalent to 3×10^8 m/s, ε_r is the dielectric constant of the substrate and the effective dielectric constant, denoted by ε_e, and is calculated as:

$$\varepsilon_e = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[\frac{1}{\sqrt{1+\frac{12h}{W}}}\right] \quad (2)$$

The length extension ΔL is determined by:

$$\Delta L = 0.412h\,\frac{(\varepsilon_e+0.3)+\left(\frac{W}{h}+0.264\right)}{(\varepsilon_e-0.258)\left(\frac{W}{h}+0.8\right)} \quad (3)$$

and the length of the MPA (*L*) is calculated as:

$$L = \frac{1}{2f_c\sqrt{\varepsilon_e}\sqrt{\mu_0\varepsilon_0}} - 2\Delta L \quad (4)$$

To determine the size of the ground plane, the length L_g and width W_g are calculated using (5) and (6), respectively:

$$L_g = 6h + L \quad (5)$$

$$W_g = 6h + W \quad (6)$$

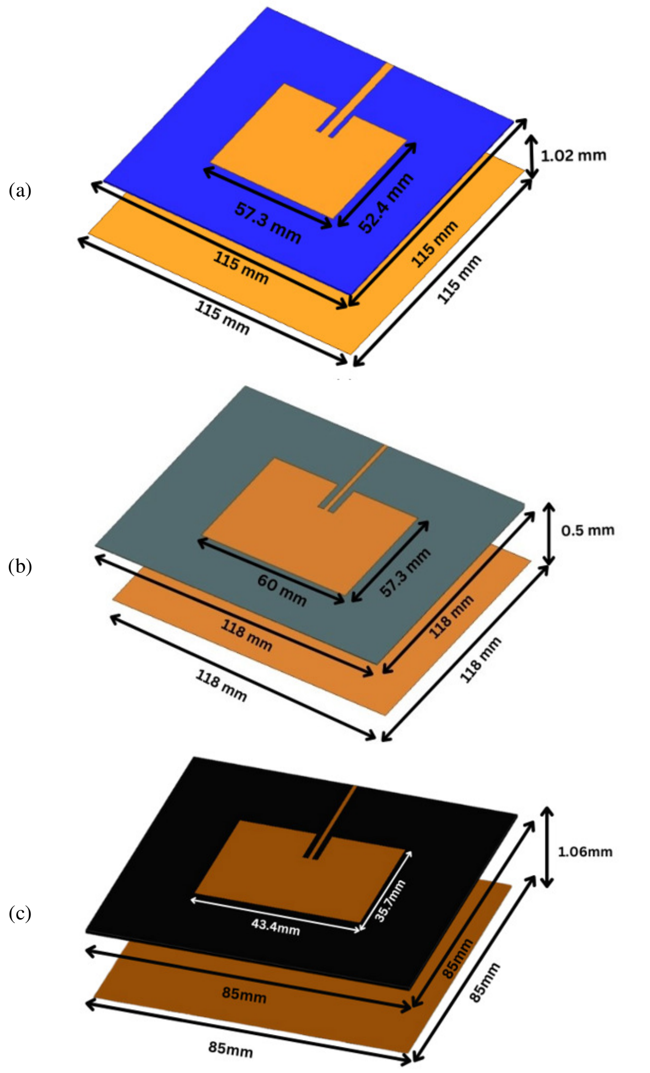

Fig. 1. MPA design with (a) felt, (b) fleece, and (c) leather as substrates.

The simulated structures of felt, fleece, and leather after the design calculations are portrayed in Figure 1. Table I shows all the dimensions of the substrates and patches obtained using (1)-(6). The leather substrate, being the smallest in dimension, has the smallest patch and the narrowest feedline. This compact size could be beneficial for applications requiring smaller antenna sizes.

TABLE I. COMPARISON OF DESIGNED MICROSTRIP PATCH ANTENNA ON LEATHER, FELT, AND FLEECE SUBSTRATE

Substrate	Leather	Felt	Fleece
Substrate Dimension (mm)	85×85×0.92	115×115×0.88	118×118×0.36
Patch Dimension (mm)	35.7×43. 4	52.4×57.3	57.37×60
Feedline Width (mm)	1	3.5	1.61

B. Simulation Results

The proposed MPA was evaluated using the Ansys HFSS simulator to assess its performance on a range of substrates, including leather, felt, and fleece. The performance metrics evaluated comprise return loss, VSWR, gain, and bandwidth, both in flat and bent conditions ranging from 0° to 17°. Figure 2 depicts the structure under bent conditions for the felt, fleece, and leather substrates, respectively, at the maximum bend of 17°.

(a)
(b)
(c)

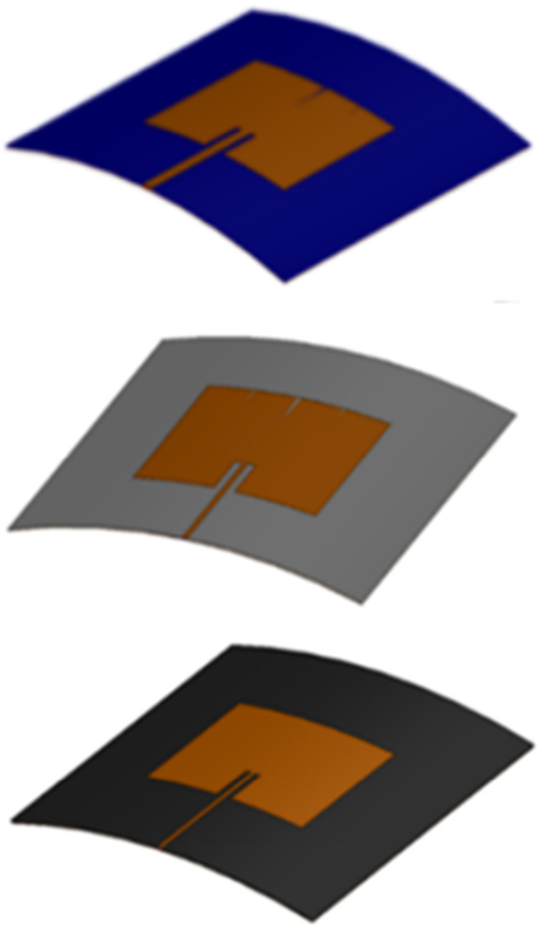

Fig. 2. Microstrip patch antenna design on (a) felt, (b) fleece, and (c) leather substrates at 17° bend.

The return loss, which quantifies the reflected power due to impedance mismatch, should be negative. Figure 3 depicts the simulated return loss for the angles of 0°, 6°, 10°, 14°, and 17°. The VSWR results for leather, as presented in Figure 4, demonstrate values below 2 for all angles, hence confirming an effective impedance match between the antenna and the transmission line.

(a)
(b)
(c)

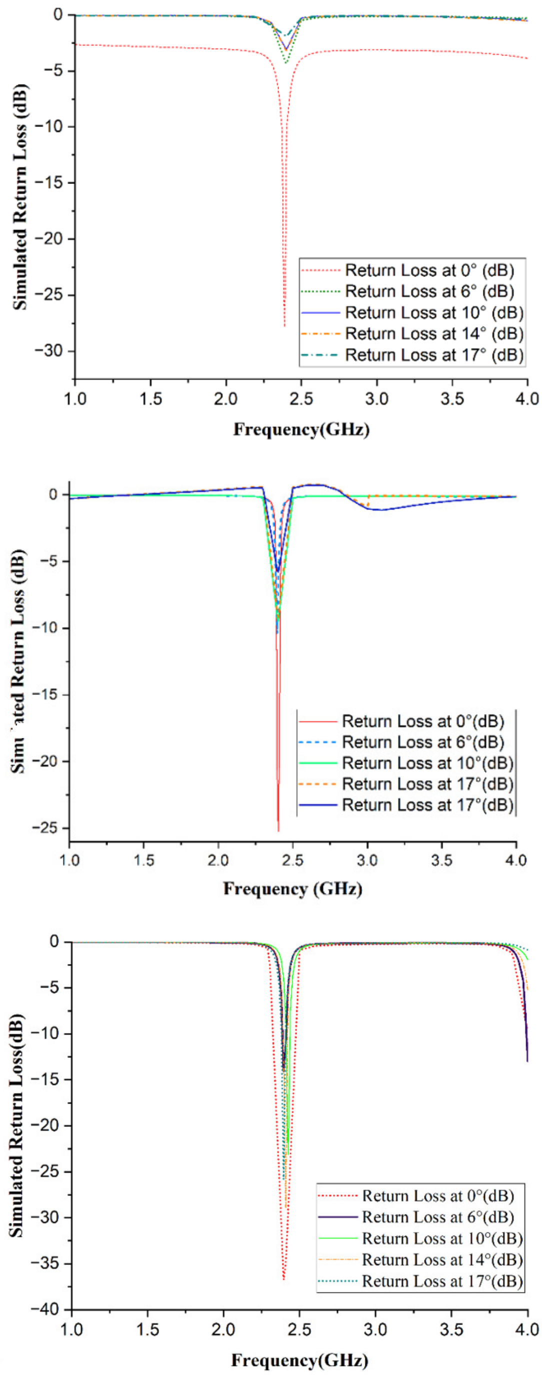

Fig. 3. Simulated return loss of MPA at 0°, 6°, 10°, 14° and 17° bend on (a) felt, (b) fleece, (c) leather substrates.

Table II displays the performance metrics of an MPA on different substrates (leather, felt, and fleece) under various bending angles (0°, 6°, 10°, 14°, and 17°). The parameters measured include the resonant frequency, bandwidth, return loss, VSWR, and gain. Leather consistently demonstrates the optimal performance, exhibiting a high bandwidth, excellent return loss, low VSWR, and high gain across all angles. The performance of felt is moderate at 0°. However, it deteriorates markedly at higher angles, exhibiting a considerable decline in return loss, an elevated VSWR, and a reduction in gain. The performance of fleece is the poorest overall, with negative gain and high VSWR at all angles, indicating that it is the least effective substrate for this antenna.

TABLE II. SIMULATED RESULTS OF MICROSTRIP PATCH ANTENNA ON LEATHER, FELT, AND FLEECE SUBSTRATES AT 0°, 6°, 10°, 14°, AND 17° BEND

Angle	Substrate	Resonant Frequency (GHz)	Bandwidth (MHz)	Return Loss (dB)	VSWR	Gain (dB)
0°	Leather	2.395	150.8	-36.74	1.02	5.60
	Felt	2.4	74.8	-27.09	2.45	3.96
	Fleece	2.4	91.9	-25.83	2.08	-10.65
6°	Leather	2.395	24.6	-14.03	1.32	7.23
	Felt	2.4025	N/A	-4.3	4.85	1.13
	Fleece	2.395	N/A	-10.39	7.95	-10.17
10°	Leather	2.425	26	-23.14	1.14	7.41
	Felt	2.4025	N/A	-3.02	2.13	0.95
	Fleece	2.4025	N/A	-9.48	5.93	-9.84
14°	Leather	2.41	31.9	-28.98	1.07	7.26
	Felt	2.4025	N/A	-3.15	2.58	0.72
	Fleece	2.4025	N/A	-9.17	2.25	-9.26
17°	Leather	2.395	28	-25.79	1.10	7.24
	Felt	2.4025	N/A	-1.88	7.15	0.23
	Fleece	2.4025	N/A	-5.80	4.97	-8.71

The leather substrate demonstrates superior stability and efficiency for the microstrip patch antenna when compared to felt and fleece across a range of bending angles. The material exhibits excellent impedance matching, high bandwidth, minimal power reflection, and consistent positive gain, rendering it an optimal choice for flexible antenna applications. At higher bending angles, felt and fleece exhibit a notable decline in performance, rendering them less suitable for practical applications. Given its flexibility, durability, and favorable dielectric property ($\mathcal{E}_r = 2.95$), leather is an excellent choice for wearable antenna applications. The return losses remain below -10 dB for all selected angles, thereby ensuring effective signal transmission and reception. Accordingly, leather was selected for additional examination and fabrication.

Figure 5 shows the high concentration of current in the central region and along the feed line, which indicates that the antenna exhibits optimal radiation efficiency. The energy is transferred from the feed to the radiating patch in an efficient manner. The symmetrical current distribution and concentration along the feed line suggest that the impedance matching is effective, thereby reducing losses and ensuring maximum power transfer. Furthermore, the proposed antenna demonstrates a consistent and predictable radiation pattern, which is essential for reliable communication.

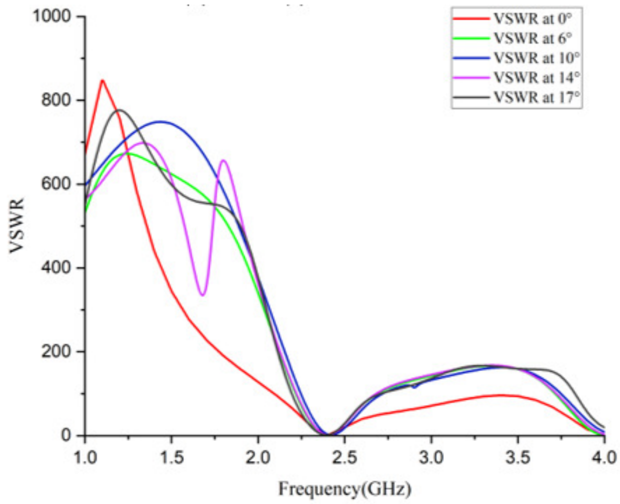

Fig. 4. Simulated VSWR of MPA on leather substrate at 0°, 6°, 10°, 14°, and 17° bend.

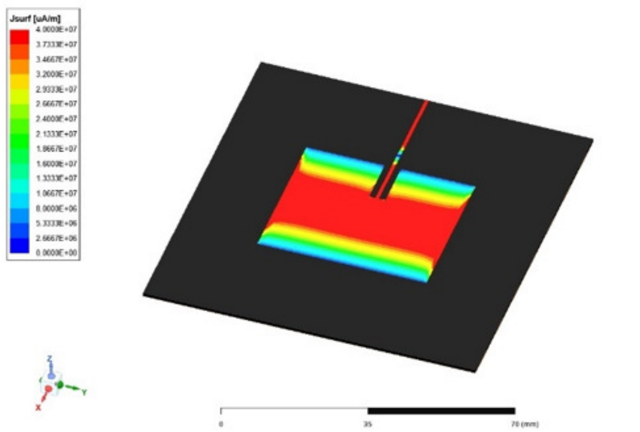

Fig. 5. Current distribution on microstrip patch antenna with leather substrate.

Figure 6 shows that the strong electric field is observed above the patch, indicating high radiation efficiency. This implies that the antenna effectively converts input power into radiated electromagnetic waves. The hemispherical radiation pattern indicates that the MPA is suitable for applications where radiation is desired primarily in one hemisphere, rendering it an optimal choice for surface-mounted applications. Furthermore, the MPA provides optimal impedance matching, ensuring maximum power transfer and minimal reflection losses. The capacity to sustain a robust and uniform *E*-field radiation while utilizing a malleable substrate such as leather renders it well-suited for integration into wearable technology, thus ascertaining dependable communication even when the substrate is subjected to bending or flexing. Figure 7 portrays the simulated gain patterns of MPA on leather substrate, which demonstrate that the MPA performs well with minor bending up to 6°, making it suitable for wearable applications. Nevertheless, considerable bending beyond 17° results in a discernible decline in performance, suggesting that while leather represents a viable substrate for flexible antennas, careful design considerations are essential to ensure optimal performance under bending conditions.

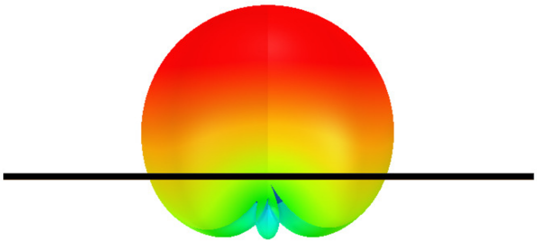

Fig. 6. *E*-field distribution of a microstrip patch antenna on a leather substrate.

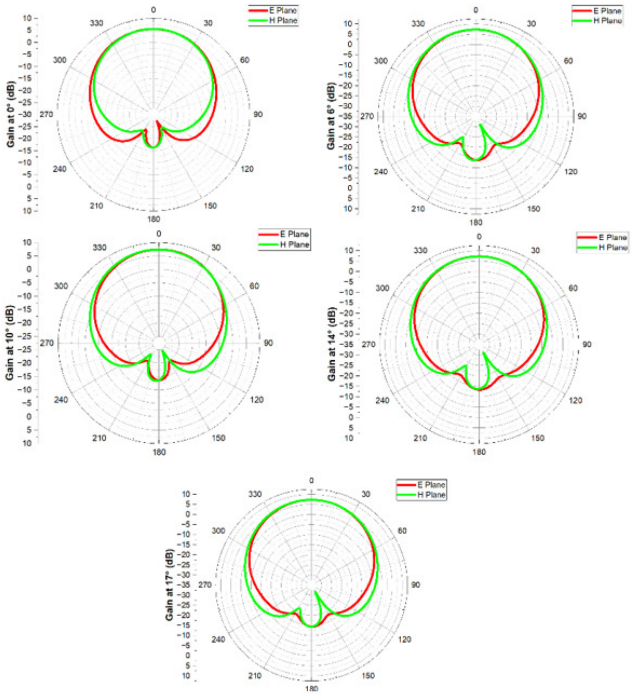

Fig. 7. Simulated gain of microstrip patch antenna on leather substrate at 0°, 6°, 10°, 14°, and 17° bend.

III. ANTENNA FABRICATION

The MPA was fabricated with leather as a substrate, with dimensions as the ones specified in Table I for a Wi-Fi frequency of 2.4 GHz. The design takes into account the leather's $\mathcal{E}_r$ of 2.95 and height (*h*) of 0.92 mm. A 0.07 mm thick conductive adhesive copper was used as the conductive element of the antenna, meticulously fabricated on top of the leather substrate. This choice of material was made due to its high conductivity and its ability to be easily bonded to different surfaces, making it an exceptionally versatile solution for electronic devices. Furthermore, the ground plane was positioned at the bottom of the leather substrate to certify optimal performance. Figure 8 depicts the fabricated microstrip patch antenna on leather substrate.

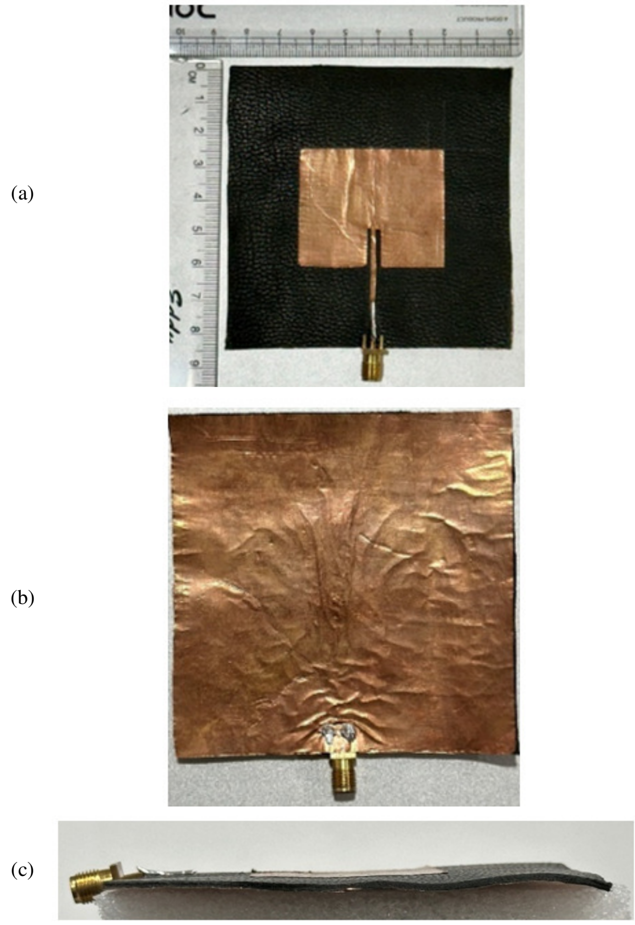

Fig. 8. Fabricated MPA on leather substrate in (a) top view, (b) bottom view, and (c) side view.

IV. MEASUREMENT RESULTS

The antenna was fabricated on a leather substrate, and its parameters, including return loss, bandwidth, and VSWR, were evaluated using an Agilent Technologies Keysight N9925A Vector Network Analyzer (VNA) with a frequency range of 9 GHz. To measure the bending of the antenna in a practical manner, the angle was determined by calculating the central angle using the basic circle geometry as outlined in (7):

$$\theta = \frac{Arc\ Length\ X\ 360^{0}}{2\pi r} \quad (7)$$

The arc length is defined as the length of the ground or substrate. In order to derive the radius for the antenna design in Ansys HFSS, the formula was rearranged. In practice, the angles, which were 0°, 6°, 10°, 14°, and 17°, and their corresponding radii were measured with a protractor and a ruler to define the antenna's bend, as evidenced in Figure 9. To achieve bending in real time, the antenna was affixed to a curved surface of a helmet to simulate realistic bending scenarios. This configuration is designed to assess return loss and other performance metrics in a realistic setting. In consideration of the helmet's curvature, it is probable that the MPA is bent or conformed to fit the helmet's surface.

(a)

(b)

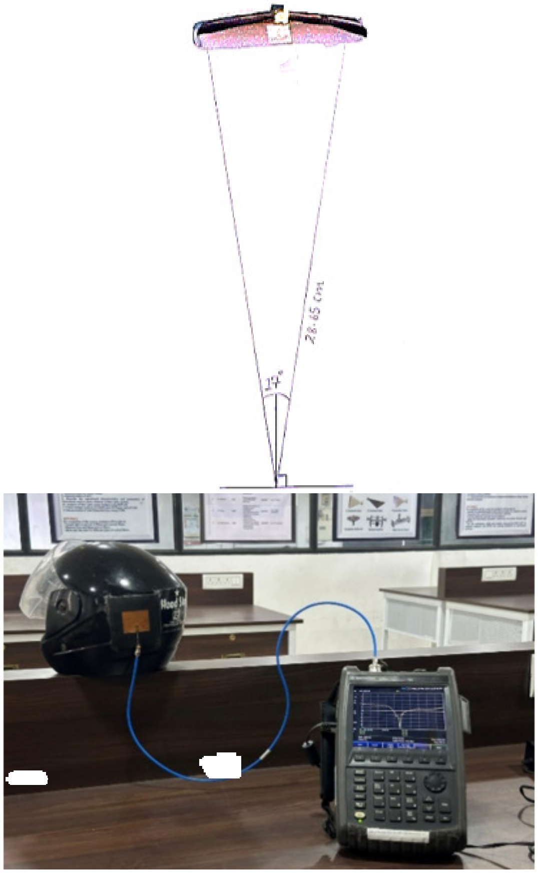

Fig. 9. (a) MPA bend at 17°, (b) measurement of return loss using Agilent Technologies Keysight N9925A Vector Network Analyzer (VNA), connecting it to the MP antenna placed on a helmet.

The antenna was connected to the VNA via a cable, and measurements were taken at each specified bending angle. The data obtained from the VNA, offered comprehensive insights into the antenna's performance under diverse bending circumstances. The results, including the resonant frequency, bandwidth, return loss, and VSWR for these angles, are presented in Table III. As shown in Figure 10, the return losses for the specified angles consistently remain below -10 dB within their respective bandwidths, exhibiting a slight frequency shift. The return loss results indicate that the substrate has the potential for fabrication, particularly for applications in the 2.4 GHz frequency range. The antenna exhibits optimal matching at 0° with a return loss of -30 dB and maintains reasonable performance across various angles. This indicates that the dielectric properties of the leather substrate are appropriate for high-frequency applications. The results disclose that the leather substrate is capable of effectively supporting signal transmission and reception within the designated bandwidth, even under conditions of deformation. The results obtained were compared with the results in [1] and it was observed that leather substrate displays superior performance, with a lower return loss of -36.74 dB in simulation and -31.46 dB in measurement under flat conditions.

TABLE III. MEASURED RESULTS OF RESONANT FREQUENCY (FR) RETURN LOSS (RL), BANDWIDTH (BW), AND MPA ON LEATHER SUBSTRATE

Angle (Degree)	Fr (GHz)	BW (MHz)	RL (dB)	VSWR
0°	2.41	481.7	-31.46	1.038
6°	2.41	95.8	-13.69	1.516
10°	2.38	102.7	-18.56	1.367
14°	2.425	373.9	-31.02	1.414
17°	2.395	118	-21.10	1.672

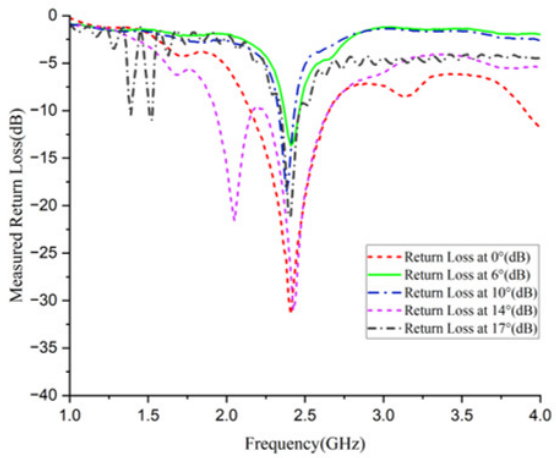

Fig. 10. Return loss of microstrip patch antenna on leather substrate at various bending angles.

V. CONCLUSIONS

This study presents a novel approach to the design and fabrication of a Microstrip Patch Antenna (MPA) on leather textile for 2.4 GHz Wi-Fi applications, thereby demonstrating the potential of leather as a substrate for wearable technologies. Its findings indicate that leather exhibits favorable bending properties and dielectric characteristics, rendering it an optimal material for flexible and wearable antenna applications. Despite slight discrepancies between the measured and simulated results, the MPA met the minimum performance requirements, achieving a Return Loss (RL) of -31.46 dB at the resonant frequency of 2.4 GHz at a 0° bend. It is noteworthy that even at bending angles of up to 17°, the return losses remained below -10 dB, thus confirming the antenna's operational capacity under deformation. The contribution of this work is the use of leather as a substrate. While previous studies have focused on substrates such as flexible polymers and fabrics, the current work highlights the distinctive advantages of leather, including its intrinsic flexibility, durability, and favorable dielectric properties. In comparison to analogous studies on textile-based antennas, this study's MPA exhibits competitive performance, notably in regard to the maintenance of stable return loss under conditions of significant bending. For example, antennas on flexible polymers often demonstrate a significant increase in return loss when bent, whereas the proposed leather-based MPA maintains its performance integrity.

This research provides a foundation for further research into the use of leather and other unconventional substrates in the field of wearable technologies. Further research may concentrate on the optimization of antenna designs with the objective of enhancing performance. This may entail the utilization of pioneering fabrication techniques, the employment of alternative materials, or the implementation of novel design configurations, with the objective of surmounting existing constraints and enhancing functionality. Moreover, the integration of these antennas into practical wearable devices for applications in military, sports, and healthcare contexts can be investigated for their efficacy in real-world scenarios to be ascertained.

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