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Design and Performance Evaluation of a Flexible Microstrip Patch Antenna with Polyimide Protection for Wearable Applications

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ABSTRACT: In this paper, an optimized flexible Microstrip Patch Antenna (MPA) for wearable applications is introduced, particularly characterized by its design concepts of scalable design and comprehensive performance evaluation. The proposed antenna leverages the mechanical flexibility of a leather substrate, complemented by polyimide layers on the upper and lower surfaces of the copper patch, enhancing both structural integrity and electromagnetic performance. The design is optimized for the operation at 2.4 GHz, ensuring durability and stability even under dynamic bending conditions. Various critical performance metrics, such as resonance frequency, bandwidth, return loss, Voltage Standing Wave Ratio (VSWR), Specific Absorption Rate (SAR), and gain, are evaluated experimentally and through simulation across bending angles of 0–90°. Results show that the antenna can reliably operate in an extreme bending scenario while having a resonant frequency near 2.44 GHz with a return loss (S_{11}) less than -20 dB up to 60° bending. At approximately 31 MHz bandwidth stability is preserved, and the VSWR is less than 1.2, thus the impedance matching is effective. Further gain measurements are also made under deformation, which further confirms the stable performance and thus reliability of the wearable application. Additionally, SAR analysis is conducted to ensure the antenna's compliance with electromagnetic exposure safety limits. The maximum SAR value of 0.516 W/kg remains well within FCC (1.6 W/kg) and ICNIRP (2.0 W/kg) standards, confirming safe radiation levels. Polyimide shielding improves durability, reduces interference, and minimizes backward radiation, making the design ideal for Wireless Body Area Networks (WBANs) and biomedical monitoring.

1. INTRODUCTION

The rapid advancement of wearable electronics, the Internet of Things (IoT), and flexible communication systems has necessitated the development of antennas that can operate reliably under mechanical deformation. This demand stems from the growing uses of wearables that require efficient communication in which a large number of wearable devices need to exchange information to reach the desired level of performance, such as those applications in healthcare [1], sports [2], and personal monitoring systems [3]. Recently, these technologies relied largely on the use of microstrip patch antennas which offer compact size, lightweight structure as well as ease of fabrication [4]. However, because flexible substrates are necessary for wearable applications, the materials and processes remain to be optimized to address performance degradation due to mechanical stresses caused by bending or stretching of the material during use [5]. The mechanical deformations also cause frequency shifts of resonant frequency, increase of the return loss, and reduction of bandwidth, resulting in the diminishing efficiency and reliability of the antenna [6].

It is necessary for flexible microstrip patch antennas deployed in dynamic environment to have consistent performance under deformation. Due to their high stiffness, these antennas have been studied in recent studies, which in turn investigate various ways to improve the flexibility and robustness of these antennas, using, for example, Kapton polyimide as a substrate material [7, 8]. The good thermal stability and mechanical flexibility of polyimide based antennas have been demonstrated as promising for biomedical applications. In addition, performance analysis of flexible rectangular microstrip patch antennas is used to demonstrate the importance of substrate selection to optimize antenna performance in the presence of mechanical stress [9, 10]. However, increased mechanical resilience and electrical stability remains an important need for these advancements.

For example, to overcome the challenges of structural resilience and electromagnetic performance under bending conditions, polyimide sheets are incorporated as protective layers for flexible microstrip patch antennas [11, 12]. Polyimide's thermal stability, mechanical flexibility, and favourable dielectric properties are also favoured [13]. The structural integrity of the antenna is reinforced by applying polyimide layers to the upper and lower surfaces of the copper patch and its electromagnetic performance from bending in optimized [14]. Polyimide layers have been extensively investigated and confirmed to maintain performance during both mechanical deformation and dynamic movement [15]. Moreover, leather substrates have been investigated as an alternative for wearable application due to the ad-

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ditional durability and water resistance, as well as robust mechanical properties providing further flexibility and user comfort [16, 17]. User comfort is improved by the natural permeability of leather and supported by its structural strength for further long term usage in wearable applications [18]. Moreover, leather's biocompatibility makes it suitable for biomedical monitoring systems [19]. Studies indicate that leather substrates maintain low dielectric loss and stable performance under bending, validating their potential in flexible antennas [20].

To meet the demand for the rapid advancement of wearable electronics, the Internet of Things (IoT), and flexible communication systems, antennas which can operate under mechanical deformation are under development. There is a growing demand for such features as wearable devices become more popular (e.g., for the use with healthcare, sports, and personal monitoring systems [1–3]. Recent applications of microstrip patch antennas, which are widely recognized for their small size, low weight, and simple fabrication, have evolved to critical components of these technologies [4]. The flexible substrates necessary for such wearable applications impose unique challenges, such as performance degradation as a result of mechanical stresses such as bending, stretching, or twisting during use [5]. These mechanical deformations can generate shifts in resonant frequency, higher return loss, and lower bandwidth, which in turn affects the efficacy and reliability of the antenna [6].

Flexible microstrip patch antennas used in dynamic environments must maintain their consistent performance during deformation. Recent studies have looked at varying substrate materials, such as Kapton polyimide, to provide more flexibility and robustness to these antennas [7, 18]. Polyimide based antennas have shown promise for biomedical applications with their high thermal stability and flexibility [21]. Also, performance analysis of flexible rectangular microstrip patch antennas driven for wireless Body Area Networks (WBANs) stresses the importance of substrate choice to achieve optimum performance in response to mechanical stress [9, 10]. However, despite these benefits there is still a real need to improve this protective layer which enhances its mechanical resilience as well as its electrical stability [22].

To resolve structural resilience and electromagnetic performance issues under bending conditions, flexible microstrip patch antennas have been protected by polyimide sheets [11, 12]. It is for its thermal stability, mechanical flexibility, and favourable dielectric properties that polyimide is favoured [13]. Structural reinforcement of the antenna is realized by applying polyimide layers on upper and lower surfaces of the copper patch to improve the electromagnetic performance of the antenna under bending conditions [14]. Polyimide layers have also been extensively shown to maintain performance during mechanical deformation and dynamic movements [15]. Leather substrates have also been explored as an avenue of material compatibility with wearable applications for providing durability, water resistance, and robust mechanical properties, which increase overall antenna flexibility and user comfort [16, 17]. Natural permeability of leather serves to support user comfort while structural strength provides support for the ongoing use in wearable applications [18]. Leather is also biocompatible [19], making it well suited for biomedical monitoring systems. Studies showed that leather substrates can give low dielectric loss and stable performance under bending so that they can work as flexible antennas [20].

A design methodology combining a leather substrate with polyimide layers is used to optimize the structural and electromagnetic properties of the antenna. Using this novel approach, the mechanical flexibility and electrical stability necessary for wearable applications are achieved. The enhanced performance of the polyimide protected antenna versus its unprotected counterpart is evaluated in detail in a prior study, with the results published. It is shown that polyimide shielding has an important role to play in preserving dynamic bending performance and is suitable for flexible and wearable electronics.

Performance metrics, such as resonant frequency, return loss, bandwidth, voltage standing wave ratio (VSWR), and gain, were assessed through numerical simulations and experimental validation across bending angles from 0° to 90°. Results show that polyimide protection greatly improves antenna stability and reliability, making this antenna suitable for wearable and flexible communication applications.

2. ANTENNA DESIGN AND SIMULATION

A flexible microstrip patch antenna operating at resonant frequency of 2.4 GHz is proposed to fulfil the requirements of Wi-Fi applications. A rectangular patch with dimensions of 44.2 mm $\times$ 35.8 mm is used in the antenna, fabricated on a leather substrate with a thickness of 0.92 mm and a total thickness of 1.1616 mm, and a dielectric constant of 2.95 for leather and 3.67 for polyimide. As [23] states, leather was chosen because it is both mechanically flexible and well suited for wearable electronics. The intrinsic dielectric constant (ε_r) of leather remains unchanged with polyimide, but the effective dielectric constant (ε_{eff}) of the composite structure is modified. In a multilayer system, ε_{eff} is influenced by the dielectric properties and thickness of each material. With leather ($\varepsilon_r = 2.95$) and polyimide ($\varepsilon_r = 3.67$), ε_{eff} increases slightly, enhancing impedance matching and reducing fringing fields. Polyimide also stabilizes dielectric properties under bending, mitigating variations caused by humidity, temperature, and mechanical stress, ensuring consistent resonance stability.

Polyimide sheets (0.0508 mm thick) were applied to both the top and bottom surfaces of the copper patch, serving as a buffer layer to prevent performance degradation under mechanical deformation. While leather offers flexibility and biocompatibility, its lower dielectric constant ($\varepsilon_r = 2.95$) can lead to increased fringing fields. Polyimide ($\varepsilon_r = 3.67$) compensates for this by improving electromagnetic performance, impedance matching, and durability while also shielding against external interference.

The 0.0508 mm polyimide layer provides an optimal balance between electromagnetic stability and mechanical flexibility. It ensures impedance matching without excessive frequency shifts, maintains stable return loss and VSWR, and reinforces mechanical resilience. This combination of leather and polyimide makes the antenna highly suitable for wearable applications, particularly WBANs and biomedical monitoring.

In addition, polyimide is used as an insulation layer to prevent signal interference on the user's body. Equations (1) to (7) were used to determine the antenna design parameters, and Equation (8) was used to calculate the bending angle to evaluate the effects that mechanical deformation may have on performance. The the design steps are as follows.

Step 1: The width of the patch antenna is calculated using the formula:

$$W = \frac{c}{2f_o}\sqrt{\frac{2}{\varepsilon_r + 1}} \tag{1}$$

where c is the speed of light in vacuum (3×10^8 m/sec), f_o the resonant frequency, and ε_r the dielectric constant of the substrate.

Step 2: The effective dielectric constant is determined by:

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

Step 3: When two substrates are used, the effective dielectric constant is:

$$\varepsilon_e = \frac{\varepsilon_{eff1} t_1 + \varepsilon_{eff2} t_2}{t_1 + t_2} \tag{3}$$

where ε_{eff1} and ε_{eff2} represent the effective dielectric constants of the two substrates, respectively, and t_1 and t_2 are the thicknesses of the substrates.

Step 4: The length extension caused by fringing effects is computed as:

$$\Delta L = 0.412h\frac{(\varepsilon_e + 0.3) + \left(\frac{W}{h} + 0.264\right)}{(\varepsilon_e - 0.258)\left(\frac{W}{h} + 0.8\right)} \tag{4}$$

Step 5: The length of the patch antenna is given by

$$L = \frac{1}{2f_o\sqrt{\varepsilon_e}\sqrt{\mu_0\varepsilon_0}} - 2\Delta L \tag{5}$$

Step 6: The dimensions of the ground plane are calculated as:

$$L_g = 6h + L \tag{6}$$
$$W_g = 6h + W \tag{7}$$

Step 7: The bending angle for the antenna is determined using:

$$\theta = \frac{L \times 360^\circ}{2\pi r} degrees \tag{8}$$

where r is the radius of the cylinder on which the antenna is bent.

A widely used electromagnetic simulation tool ANSYS HFSS was used to model and simulate the antenna. The frequency range selected for simulation was from 2 GHz to 4 GHz, since the antenna was desired to exhibit behaviour at the 2.4 GHz operating frequency. It was simulated in free space using radiation boundary conditions and the antenna excited by a strip line feed. A fine mesh was used to simulate the antenna geometry and all polyimide layers, to ensure accurate modelling of the antenna geometry and of the polyimide layers. Illustrations of the simulated and fabricated microstrip patch antennas are shown in Figures 1 and 2, respectively.

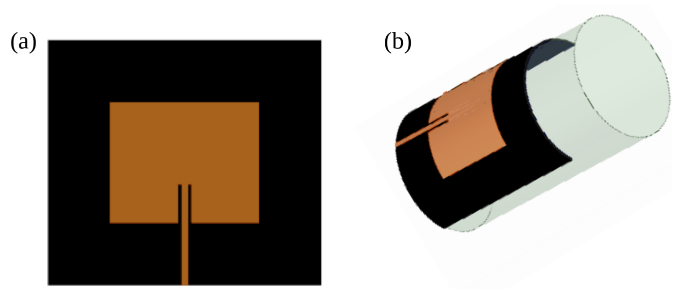

FIGURE 1. The antenna's performance under different bending conditions: (a) Flat Condition and (b) 90° Bend in simulation.

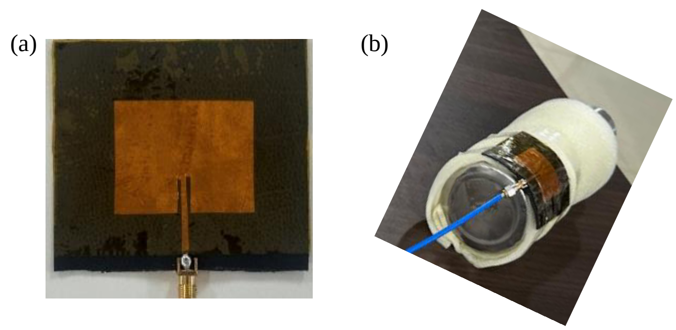

FIGURE 2. The antenna's performance under different bending conditions: (a) Flat Condition, (b) 60° Bend condition in real time.

The antenna's performance under mechanical deformation was modelled in a series of bending simulations. The antenna was simulated at bending angles from 0° to 90°, simulating conditions where the antenna could have been bent during use. Impedance matching was then studied by measuring both return loss (S_{11}) and VSWR at each angle as the antenna is bent along the x axis. The gain and bandwidth were also analysed at this bending angle to observe any performance degradation, and additionally, gain and bandwidth were analysed at each bending angle to see if the system degraded in performance.

The comparison of antenna performances with and without polyimide protection was performed using key performance metrics such as return loss (S_{11}), VSWR, gain, and bandwidth. The VSWR and return loss, necessary for transmitting an efficient signal, were expected to be below 2 and -10 dB, respectively. The antenna efficiency was evaluated across a range of gain and bandwidth under bending conditions with the polyimide layer and focusing on how to minimize degradations in the efficiency due to bending.

While material variations, fabrication tolerances, and measurement errors are valid concerns, careful analysis supports the accuracy of the reported data. The material properties of leather ($\varepsilon_r = 2.95$) and polyimide ($\varepsilon_r = 3.67$) are based on manufacturer specifications, with polyimide exhibiting low moisture

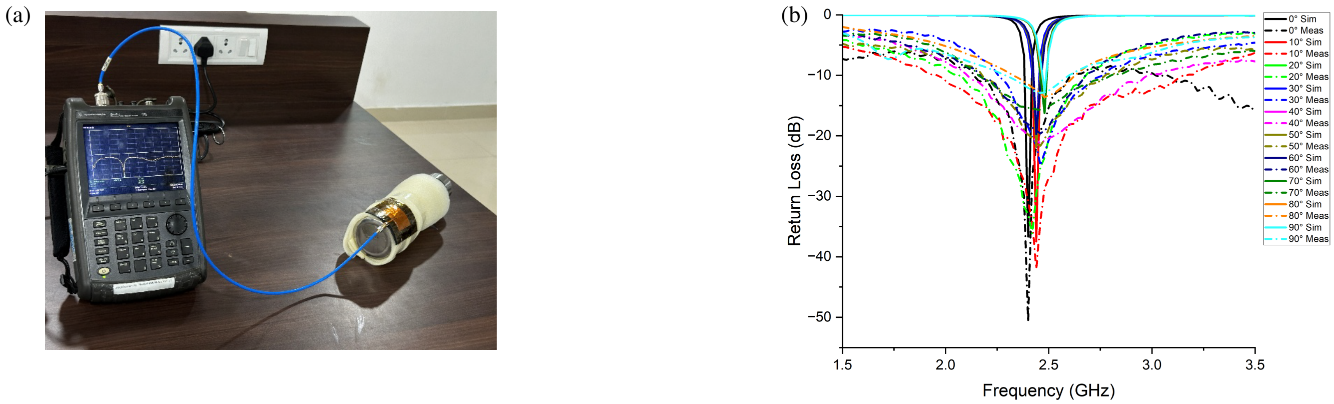

FIGURE 3. (a) Return loss measurement using a Vector Network Analyzer (VNA) and (b) comparison of simulated and measured return loss results across various bending angles.

absorption and high thermal stability, minimizing fluctuations. Simulations in ANSYS HFSS use fixed values, justifying numerical precision. The fabrication techniques enable accurate control of the patch dimensions by minimizing dimensional deviations. Dimensions of the patch were maintained at a width of 44.2 mm and length of 35.8 mm, with thickness of the polyimide as 0.0508 and substrate height as 0.92 mm. The return loss, VSWR, gain, and bandwidth were measured using a Vector Network Analyzer (VNA) (Agilent Technologies, 9 GHz) and an anechoic chamber (7 m $\times$ 3 m $\times$ 3 m) covering a frequency range of 800 MHz to 40 GHz, ensuring high measurement precision. The VNA exhibited an accuracy of ± 0.05 dB for return loss and ± 0.02 for VSWR. Despite minor losses, the strong correlation between simulated and measured results validates the reported precision.

3. RESULTS AND DISCUSSION

Various bending conditions were taken to analyse the performance of the proposed flexible MPA for wearable applications. The analysis was performed based on key performance metrics such as return loss (S_{11}), VSWR, gain, bandwidth, and radiation patterns to evaluate the electromagnetic reliability of the antenna. The design and fabrication process were validated by the comparison of simulated and measured results. They are also discussed based upon performance variations from zero to ninety degrees bending angle where polyimide protection layers protect electrical and mechanical stability. VSWR, return loss, and bandwidth stability show that the antenna maintains consistent performance under mechanical stress, and the radiation patterns prove that the antenna is directional and gain stable. In this section, the performance of the antenna is discussed in detail, making a strong case for the antenna to serve as a building block for IoT, flexible electronics and wearable communication systems.

3.1. Return Loss Analysis

Figure 3 shows the return loss (S_{11}) results for the antenna with simulated and measured data very much aligned, indicating that the antenna performs well under bending (0° to 90°). Simulated and measured return losses of -45.8 dB and -46.2 dB were observed at 2.4 GHz, which correspond to minimal reflection and strong impedance matching at $0°$. At higher bending angles, the return loss is under -20 dB up to 60° and only becomes slightly lower to -14.7 dB at $90°$, which is within the acceptable limits for wireless communication. The frequency shift is negligible (< 40 MHz) across all bending angles, due to the polyimide layers that provide structural stability and maintain uniform electromagnetic field distribution at deformation. This combines the optimized dielectric constant of an effective dielectric constant ($\varepsilon_r = 3.67$) of the polyimide layer and a dielectric constant of the base substrate ($\varepsilon_r = 2.95$), which maintains same impedance matching and performance. Using ANSYS HFSS simulations, these findings, as validated earlier through studies [23], prove the robustness and reliability of the antenna under deformation and prove the suitability of the antenna for wearable applications. Table 1 shows a comparison of return losses with and without polyimide protection.

3.2. Voltage Standing Wave Ratio (VSWR) Analysis

Figure 4 shows the VSWR results which show how the antenna adapts impedance matching across different bending angles. A

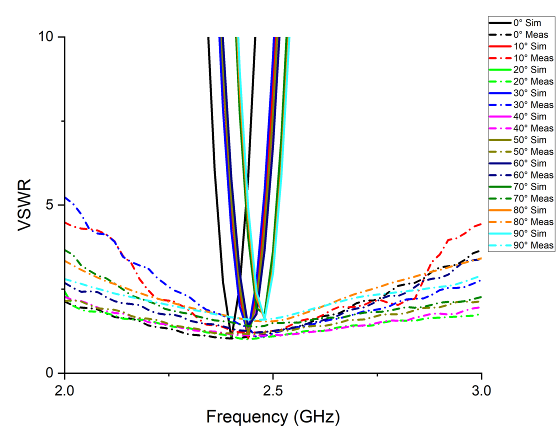

FIGURE 4. Comparison of VSWR for different bending angles between simulated and measured results.

TABLE 1. Comparison of resonant frequency return losses, bandwidths, VSWRs, and gains with and without polyimide protection under different bending angles.

ANGLE	RESONANT FREQUENCY (GHz)		RETURN LOSS(dB)		BANDWIDTH (MHz)		VSWR		GAIN (dBi)	
	Without Polyimide	With Polyimide	Without Polyimide	With Polyimide	Without Polyimide	With Polyimide	Without Polyimide	With Polyimide	Without Polyimide	With Polyimide
0°	2.4	2.4	−24.14	−37.6	25.5	26.6	1.02	1.11	5.6	6.34
10°	2.42	2.44	−23.14	−32.55	26	31.1	1.14	1.04	7.4	6.43
20°	2.38	2.44	−21.57	−22.83	27.9	32.2	1.29	1.15	7.1	6.42
30°	2.39	2.44	−19.38	−22.28	24.6	31.5	1.24	1.2	7.1	6.41
40°	2.38	2.44	−19.9	−21.29	25.2	31.5	1.57	1.18	7	6.38
50°	2.38	2.44	−16.21	−21.69	25.3	31.5	1.17	1.17	6.9	6.44
60°	2.37	2.44	−17.3	−22.31	25.2	30.7	1.22	1.16	6.7	6.36
70°	3.73	2.47	−25.3	−13.84	25	22.5	1.39	1.5	6.6	6.44
80°	3.68	2.47	−28.4	−13.34	23.1	22.2	1.5	1.54	6.4	6.392
90°	3.6	2.47	−22.9	−12.84	22.9	20.4	1.4	1.59	6.3	6.39

VSWR lower than 2 at resonant frequency 2.4 GHz, for both measured and simulated data, shows good impedance matching with low signal reflection under various bending conditions. At higher bending angles (up to 90°), we show consistent VSWR values for the polyimide protected antenna, indicating superior flexibility and mechanical resilience. The measured results are found to have good agreement with the simulated trends and validate the accuracy of this design model and fabrication process. It is noted that the VSWR values increase slightly with increasing bending angle beyond 60°, due to changes in the effective dielectric properties and current distribution resulting from deformation. The values, however, stay within acceptable limits for practical wireless communication uses. Impedance stability is preserved through bending, which is reinforced by these findings and underscores the use of polyimide shielding as being suitable for wearable electronics. Table 1 gives the comparison of resonant frequency, return loss, bandwidth, VSWR, and gain of the antennas with and without polyimide protection under different bending conditions.

The differences between simulated and measured VSWR values arise due to fabrication tolerances, material variations, and environmental factors. Simulations assume ideal, uniform, and lossless dielectric properties, whereas real substrates exhibit permittivity and loss tangent variations, affecting impedance matching. Connector and soldering losses, as well as slight misalignments in the feed structure, further contribute to deviations. Bending and flexibility introduce mechanical stress, altering surface currents. Measurement imperfections such as radiation leakage, cable losses, and fixture misalignments also impact results. Despite these variations, the measured VSWR remains within the acceptable range (< 2), ensuring effective impedance matching [23–27]. The polyimide layers enhance stability, confirming the antenna's suitability for wearable applications.

3.3. Radiation Patterns

To properly validate the performance of the antenna under bending conditions, this work utilized an anechoic chamber to make very accurate measurements of the antenna's radiation patterns. The critical parameters like gain and bandwidth under realistic operating environment can be evaluated with this setup. Through this systematic approach we ensure that the derived antenna's physical and electrical parameters are accurate and its performance under bending conditions optimized. Figure 5 shows radiation patterns of the antenna for 0°, 30°, 60°, and 90° bending angles. We find that the radiation characteristics are omnidirectional throughout the entire bending angle range and are stable. The radiation pattern for antenna is uniform at 0° (flat condition, suitable for the use in Wi-Fi applications). The major lobe direction and radiation efficiency are fairly maintained; however the patterns are slightly distorted for increases in the bending angle.

Flexible antenna designs with the polyimide protection did not suffer from bending induced surface discontinuities. There is a slight change of side lobes and reduced back radiation at 90 degree bending.

The results show that using a leather substrate with polyimide shielding improves the antenna's strength and performance, making it suitable for wearable devices. The mechanical flexibility and electromagnetic reliability of the proposed design make this design suitable for IoT and body worn communication systems.

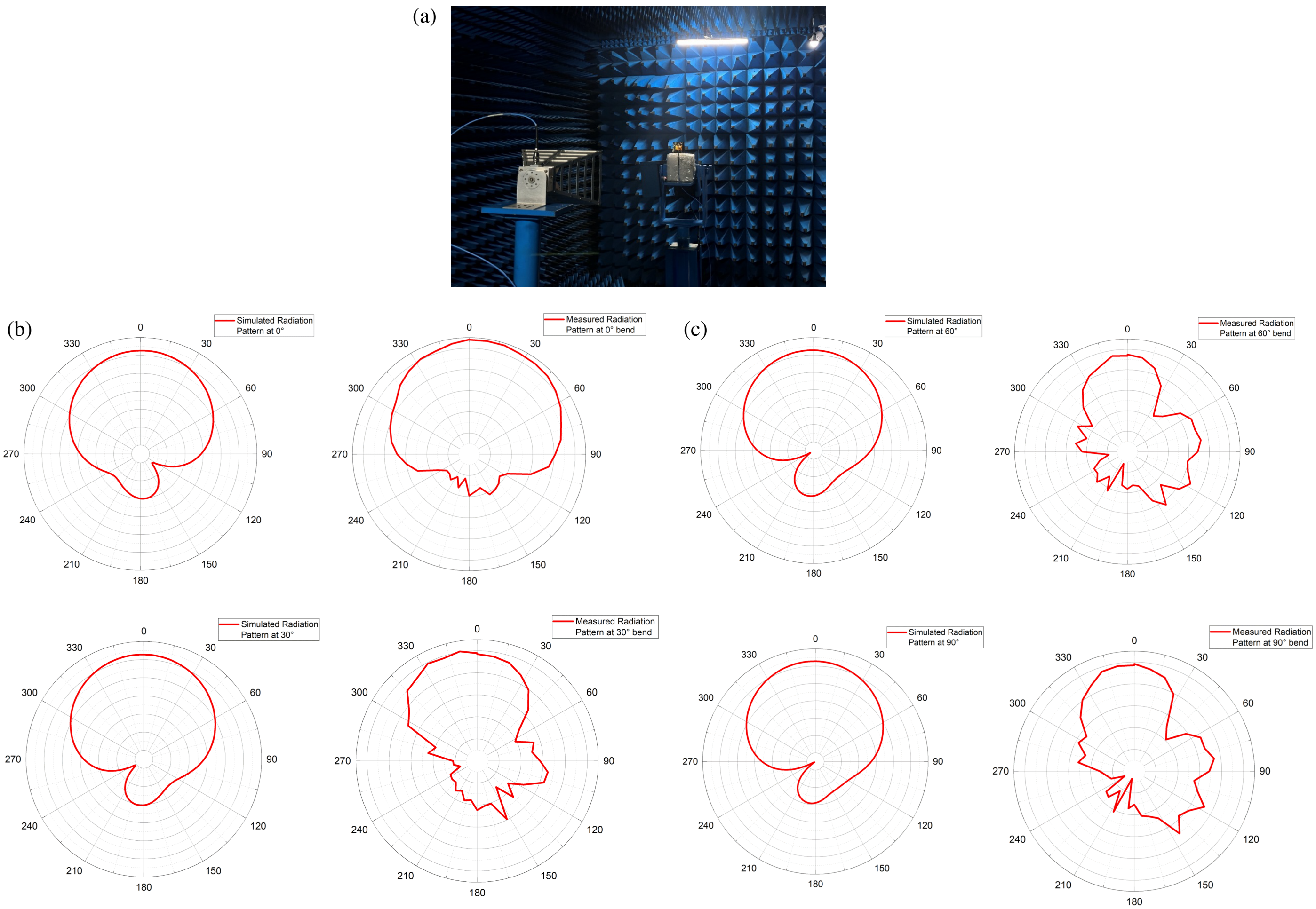

FIGURE 5. (a) Measurement setup for radiation pattern, (b) comparison of simulated and measured radiation patterns at 0° and 30° bending angles, and (c) comparison of simulated and measured radiation patterns at 60° and 90° bending angles.

3.4. Bandwidth Analysis

Analysis of bandwidth performance of flexible MPA with and without polyimide protection was carried out at varying bending angles from 0° to 90° and tabulated in Table 1. Results show wider and more stable bandwidth for the polyimide protected antenna than the unprotected antenna across all of these bending conditions. The bandwidth of the polyimide protected antenna at 0° (flat condition) is 26.6 MHz, slightly higher than that of the unprotected antenna (25.5 MHz), which shows better performance due to the enhanced stability from the polyimide layer. The polyimide protected antenna has 31 $\sim$ 32.2 MHz bandwidth for bending angles of moderate 10 $\sim$ 60°, while that of the unprotected antenna drops to 24.6 $\sim$ 27.9 MHz bandwidth. The polyimide protected antenna retains 20.4 to 22.5 MHz bandwidth at higher bending angles (70°–90°), much higher than the unprotected antenna that takes only 22.9 MHz in the 90° configuration. Mechanically resistant and electrically stable polyimide layers are demonstrated with these results to maintain consistent impedance matching as well as structural integrity under applied deformation. The results support the reliability and flexibility of the antenna for wearable applications and support previous flexible antenna findings [23] on polyimide shielding to maintain electrical performance under mechanical stress.

3.5. Gain Analysis

The gain performances of the flexure MPA with and without polyimide protection were evaluated over the range of bending angles from 0° to 90° (Table 1). The mechanical robustness and electromagnetic reliability of the polyimide protected antenna are demonstrated by maintaining stable gain values over all bending angles. In flat condition (0°), the polyimide protected antenna achieves a gain of 6.34 dBi, exceeding 5.6 dBi in the unprotected antenna, suggesting better impedance matching and radiation efficiency conveyed by the polyimide layer.

The polyimide-protected antenna maintains its gain above 6.3 dBi from 10° to 60° bending, but an antenna without polyimide protection maintains higher gain between 7.4 dBi at 10° and 6.7 dBi at 60°. The gain level of the protected antenna stays between 6.39 dBi and 6.44 dBi from 70° to 90° whereas the unprotected antenna loses 6.3 dBi of its gain when being bent to 90°.

To date, the polyimide protected antenna shows overall consistent gain performance under deformation which makes it

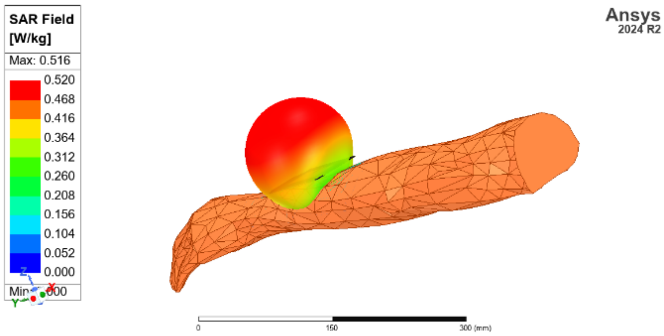

FIGURE 6. SAR Distribution of the Flexible MPA on a Human Arm at 2.4 GHz.

suitable for wearable applications that require radiation stability and mechanical flexibility, which validates the superior performance of this antenna as reported in previous studies [23].

4. SPECIFIC ABSORPTION RATE (SAR)

The SAR analysis shown in Figure 6 confirms that the antenna maintains safe radiation levels while ensuring effective performance. The maximum observed SAR value of 0.516 W/kg is well within regulatory limits, reinforcing the feasibility of this design for wearable applications [28–34]. The SAR distribution reveals that energy absorption is concentrated near the antenna and gradually dissipates, indicating minimal penetration into body tissues. The flexible leather substrate provides a dielectric buffer, further reducing energy absorption and enhancing user safety. The inclusion of polyimide layers aids in stabilizing impedance and minimizing radiation exposure fluctuations. The observed SAR values remain significantly lower than the Federal Communications Commission (FCC) (1.6 W/kg) and International Commission on Non-Ionizing Radiation Protection (ICNIRP) (2.0 W/kg) thresholds, validating that the antenna does not pose a health risk. Future enhancements, such as ground plane shielding and optimized radiation patterns, can further mitigate SAR while maintaining antenna efficiency.

5. CONCLUSION

A flexible MPA operating at 2.4 GHz was fabricated using a 1 mm thick leather substrate ($\varepsilon_r = 2.95$) with two polyimide layers ($\varepsilon_r = 3.67$). The antenna was evaluated for return loss, VSWR, gain, bandwidth, and radiation patterns, demonstrating consistent and reliable performance across various bending angles, promoting its application in wearable and flexible communication systems. The polyimide-protected antenna achieved return loss better than -20 dB up to 60° bending and remained functional at 90° bending with a 40 MHz frequency shift. Impedance remained well-matched with VSWR below 1.2 across most bending angles.

The polyimide-protected MPA achieved 20.4–32.2 MHz bandwidth, consistently outperforming the unprotected design. Gain values remained stable between 6.34 dBi and 6.44 dBi, proving mechanical resilience and electromagnetic reliability even under extreme bending conditions. Radiation patterns were omnidirectional across all bending angles, maintaining stable radiation efficiency and usability in flexible applications. The antenna exhibited a maximum SAR of 0.516 W/kg, which is well within FCC (1.6 W/kg) and ICNIRP (2.0 W/kg) safety limits, ensuring safe usage for wearable electronics.

Leather substrate and polyimide layers played a crucial role in reducing backward radiation and stabilizing performance under mechanical stress. The results confirm that mechanical robustness and electromagnetic reliability are enhanced with the combination of leather and polyimide, making the antenna a viable option for wearable electronics, IoT devices, and flexible communication systems. Future work will explore additional flexible materials, advanced shielding techniques, and higher frequency optimizations to further enhance the antenna's performance for next-generation wireless applications.

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REFERENCES

[1] Soni, G. K., D. Yadav, and A. Kumar, "A comprehensive review of wearable antenna design for On-Body and Off-Body communication," *International Journal of Electronics and Telecommunications*, Vol. 70, No. 2, 525–532, 2024.

[2] Thangarasu, D., R. R. Thipparaju, S. K. Palaniswamy, M. Kanagasabai, M. G. N. Alsath, D. Potti, and S. Kumar, "On the design and performance analysis of flexible planar monopole ultra-wideband antennas for wearable wireless applications," *International Journal of Antennas and Propagation*, Vol. 2022, No. 1, 5049173, 2022.

[3] Kumar, A., A. De, and R. K. Jain, "Circular polarized two-element textile antenna with high isolation and polarization diversity for wearable applications," *International Journal of Microwave and Wireless Technologies*, Vol. 15, No. 3, 493–501, 2023.

[4] Soni, G. K., D. Yadav, and A. Kumar, "Design consideration and recent developments in flexible, transparent and wearable antenna technology: A review," *Transactions on Emerging Telecommunications Technologies*, Vol. 35, No. 1, e4894, 2024.

[5] Jilani, S. F., Q. H. Abbasi, and A. Alomainy, "Inkjet-printed millimetre-wave PET-based flexible antenna for 5G wireless applications," in *2018 IEEE MTT-S International Microwave Workshop Series on 5G Hardware and System Technologies (IMWS-5G)*, 1–3, Dublin, Ireland, 2018.

[6] Kirtania, S. G., A. W. Elger, M. R. Hasan, A. Wisniewska, K. Sekhar, T. Karacolak, and P. K. Sekhar, "Flexible antennas: A review," *Micromachines*, Vol. 11, No. 9, 847, 2020.

[7] Prasanna, R., G. T. Selvi, K. Annaram, K. Venkatalakshmi, M. Jenath, and B. P. Prathaban, "Multiband flexible ultra-wideband antenna for wearable electronics and biomedical applications," *International Journal for Multiscale Computational Engineering*, Vol. 21, No. 5, 93–104, 2023.

[8] Venkatachalam, D., V. Jagadeesan, K. B. M. Ismail, M. A. Kumar, S. Mahalingam, and J. Kim, "Compact flexible planar antennas for biomedical applications: Insight into materials and systems design," *Bioengineering*, Vol. 10, No. 10, 1137, 2023.

[9] Geyikoglu, M. D., "A novel UWB flexible antenna with dual notch bands for wearable biomedical devices," *Analog Integrated Circuits and Signal Processing*, Vol. 114, No. 3, 439–450, 2023.

[10] Varma, S., S. Sharma, M. John, R. Bharadwaj, A. Dhawan, and S. K. Koul, "Design and performance analysis of compact wearable textile antennas for IoT and body-centric communication applications," *International Journal of Antennas and Propagation*, Vol. 2021, No. 1, 7698765, 2021.

[11] Wang, M., L. Crocco, and M. Cavagnaro, "Antipodal vivaldi antenna with ceramic cone lens for biomedical microwave imaging systems," in *2021 15th European Conference on Antennas and Propagation (EuCAP)*, 1–5, Dusseldorf, Germany, 2021.

[12] Aldhaibani, J. A., M. Q. Mohammed, A. A. Mahmood, and M. S. Hamza, "Development of wearable textile patch antenna 2.43 GHz for biomedical applications," *International Journal of Advanced Technology and Engineering Exploration*, Vol. 11, No. 111, 177, 2024.

[13] Mahfuz, M. M. H., M. R. Islam, C.-W. Park, E. A. A. Elsheikh, F. M. Suliman, M. H. Habaebi, N. A. Malek, and N. Sakib, "Wearable textile patch antenna: Challenges and future directions," *IEEE Access*, Vol. 10, 38 406–38 427, 2022.

[14] Kumar, S. A., T. Shanmuganantham, and G. Sasikala, "Design and development of implantable CPW fed monopole U slot antenna at 2.45 GHz ISM band for biomedical applications," *Microwave and Optical Technology Letters*, Vol. 57, No. 7, 1604–1608, 2015.

[15] Cheng, S. and Z. Wu, "Microfluidic stretchable RF electronics," *Lab on a Chip*, Vol. 10, No. 23, 3227–3234, 2010.

[16] Mu, G. and P. Ren, "A compact dual-band metasurface-based antenna for wearable medical body-area network devices," *Journal of Electrical and Computer Engineering*, Vol. 2020, No. 1, 4967198, 2020.

[17] Goswami, N. and M. A. Rahman, "A 9.73 GHz wide-band off-body patch antenna for biomedical applications," *Indonesian Journal of Electrical Engineering and Computer Science*, Vol. 33, No. 1, 151–158, 2024.

[18] Raad, H. K., H. M. Al-Rizzo, A. Abbosh, and A. I. Hammoodi, "A compact dual band polyimide based antenna for wearable and flexible telemedicine devices," *Progress In Electromagnetics Research C*, Vol. 63, 153–161, 2016.

[19] Khanna, P., A. Sharma, A. K. Singh, and A. Kumar, "A novel approach for production challenges of flexible microstrip patch antenna," *Brilliant Engineering*, Vol. 1, 7–12, 2019.

[20] Gil, I., R. Seager, and R. Fernández-García, "Embroidered metamaterial antenna for optimized performance on wearable applications," *Physica Status Solidi (A)*, Vol. 215, No. 21, 1800377, 2018.

[21] Naik, K. K., S. C. S. Teja, B. V. Sailaja, and P. A. Sri, "Design of flexible parasitic element patch antenna for biomedical application," *Progress In Electromagnetics Research M*, Vol. 94, 143–153, 2020.

[22] Kumar, S. A. and T. Shanmuganantham, "Implantable CPW-fed rectangular patch antenna for ISM band biomedical applications," *Microwave and Optical Technology Letters*, Vol. 56, No. 5, 1060–1065, 2014.

[23] Prabhu, S. and C. Tharini, "Design and analysis of flexible microstrip antennas using polyimide protection," *Engineering, Technology & Applied Science Research*, Vol. 14, No. 2, 289–297, 2023.

[24] Firdaus, R. A., M. Khoiro, E. Rahmawati, Dzulkiflih, and M. Yantidewi, "Design of folded dipole antenna with stub feed line at 3.5 Ghz operating frequency for 5G cellular network," in *Journal of Physics: Conference Series*, Vol. 2900, No. 1, 012056, 2024.

[25] Nashef, G. Z. E., F. Torrès, S. Mons, T. Reveyrand, E. Ngoya, T. Monédière, M. Thévenot, and R. Quéré, "An accurate modeling technique for antennas and nonlinear RF power amplifier mixed simulation," *International Journal of Microwave and Wireless Technologies*, Vol. 3, No. 6, 647–655, 2011.

[26] Khairanisa, N., S. Aulia, S. Yusnita, and Y. Yulindon, "Analyzing troubleshooting of BTS transmit power and 4G LTE coverage area via VSWR value measurement," *Andalas Journal of Electrical and Electronic Engineering Technology*, Vol. 3, No. 2, 82–88, 2023.

[27] Lee, C.-I., W.-C. Lin, and Y.-T. Lin, "Temperature dependence on RF avalanche breakdown of RF mosfets in the impact ionization region," *Microwave and Optical Technology Letters*, Vol. 57, No. 4, 817–820, 2015.

[28] Shah, S. M., N. F. A. Kadir, Z. Z. Abidin, F. C. Seman, S. A. Hamzah, and N. Katiran, "A 2.45 GHz semi-flexible wearable antenna for industrial, scientific and medical band applications," *Indonesian Journal of Electrical Engineering and Computer Science*, Vol. 15, No. 2, 814–822, 2019.

[29] Ali, U., S. Ullah, J. Khan, M. Shafi, B. Kamal, A. Basir, J. A. Flint, and R. D. Seager, "Design and SAR analysis of wearable antenna on various parts of human body, using conventional and artificial ground planes," *Journal of Electrical Engineering and Technology*, Vol. 12, No. 1, 317–328, 2017.

[30] Abdou, T. S., R. Saad, and S. K. Khamas, "A circularly polarized mmWave dielectric-resonator-antenna array for off-body communications," *Applied Sciences*, Vol. 13, No. 3, 2002, 2023.

[31] Gandhi, O. P., "Microwave emissions from cell phones exceed safety limits in Europe and the US when touching the body," *IEEE Access*, Vol. 7, 47 050–47 052, 2019.

[32] Shamsudin, N. A. and S. M. Shah, "Miniaturized dual-band dual-mode microstrip patch antenna with defected ground structure for wearable applications," *Journal of Electronic Voltage and Application*, Vol. 2, No. 2, 120–128, 2021.

[33] Koyama, S., E. Narita, Y. Suzuki, M. Taki, N. Shinohara, and J. Miyakoshi, "Effect of a 2.45-GHz radiofrequency electromagnetic field on neutrophil chemotaxis and phagocytosis in differentiated human HL-60 cells," *Journal of Radiation Research*, Vol. 56, No. 1, 30–36, 2015.

[34] Benkalfate, C., A. Ouslimani, A.-E. Kasbari, and M. Feham, "A new compact triple-band triangular patch antenna for RF energy harvesting applications in IoT devices," *Sensors*, Vol. 22, No. 20, 8009, 2022.