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Microstrip Antenna with Low SAR for Wearable IoT Applications

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Abstract

This article discusses the methods used to design and analyze a small, flexible microstrip antenna for IoT devices. The antenna operates at 2.4 GHz, which is in the ISM band and is usually used for short-range communication. The radiating patch has a circular slot in it to acheive wide bandwidth and even current flow. To maintain stable antenna characteristics and prevent unwanted radiation from reaching the human body, a full ground plane is used. The bandwidth of the antenna is about 200 MHz, and the resonance frequency is 2.4 GHz with a return loss of about -28 dB. The radiation pattern of the antenna is quasi-omnidirectional with a maximum gain in the range of 3.2 to 3.5 dBi. The efficiency in open space is in the range of 80-85%, while when the antenna is in contact with the human body, it is more than 75%. The results of the bending analysis show that the performance of the antenna is almost unaffected by bending. Additionally, the SAR value is within the allowed range.

Keywords: Flexible Antenna, Wearable IoT, Microstrip Patch Antenna, Bending Analysis.

1. Introduction

The rapid growth in IoT technology has led to the design and development of interconnected devices with the ability to communicate effectively in different environments. Among these interconnected IoT devices, wearable IoT technology has attracted considerable attention due to its applications in healthcare, fitness, smart textiles, and defense technology. Wearable IoT technology requires an antenna with a compact size, low weight, and the ability to operate effectively even when in proximity to the human body.

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Conventional rigid antennas cannot be considered for wearable applications as they cannot be adapted to curved shapes. Additionally, there is a possibility of performance degradation due to bending. Flexible antennas using materials such as polyimide, PET, and textiles are considered to be more adaptable for wearability. However, there are certain challenges involved in designing flexible antennas, including detuning due to proximity to the body, reduced efficiency, and deformity.

Several methods have been proposed to overcome these problems, including miniaturization based on fractal geometry, impedance adjustment based on defected ground structures, and the use of electromagnetic bandgap structures to reduce body effects. However, an optimum trade-off in terms of size, flexibility, bandwidth, and efficiency remains an important research challenge. In this paper, a flexible 2.4 GHz frequency band microstrip antenna is proposed. In this design, a circular slot is added to achieve bandwidth, and a full ground plane is used to ensure radiation stability and minimize body effects. The proposed antenna is also studied under bending conditions to ensure its reliability in wearable applications.

2. Literature Review

The recent developments in the design of wearable antennas for Internet of Things (IoT) applications have focused on achieving compactness, flexibility, ruggedness, and efficient communication performance under varying operating conditions. Earlier research in the design of wearable antennas for IoT applications concentrated on the integration of multiple antennas for the realization of fifth-generation (5G) communication and IoT connectivity. This research work has emphasized the efficient utilization of the frequency spectrum to enable seamless communication in body-centric environments [1]. The mechanical flexibility of antennas is another critical design aspect that has been considered in recent studies. Research on flexible antennas designed using polymers has been conducted to analyze the impact of bending and deforming the antennas on their performance for IoT applications. The design of waterproof flexible antennas has been developed to address environmental challenges for enabling IoT applications in harsh environments [3].

In the case of smart textiles and wearable electronics, a significant amount of research has focused on the design of miniaturized and optimized antennas that can be integrated into clothing materials without compromising user comfort [4], [5]. Furthermore, wideband and ultra-wideband (UWB) antennas have also been widely extensively in the literature, as they can be used for high-rate applications, including healthcare monitoring and WBANs, where constant and uninterrupted data transmission is critical [6], [7]. The performance in terms of bandwidth and radiation characteristics has also been enhanced using innovative textile-based antenna designs, which can be employed for a range of applications in the IoT domain, covering different frequency bands.

Furthermore, a series of comprehensive review articles has been published, which further enhance these developments by covering different wearable antenna designs, materials, and manufacturing techniques, including trade-offs between flexibility, efficiency, and ruggedness [9]. New applications, such as IoT-based plant health monitoring, have also been presented, which not only highlight the flexibility of wearable antennas but also their usage outside human-centric applications, including plant health monitoring scenarios [10]. In addition, research related to wearable antenna design has continued to focus on improving their flexibility, lightweight designs, and integration with future IoT technologies for better communication reliability and convenience.

3. Antenna Design and Parameters

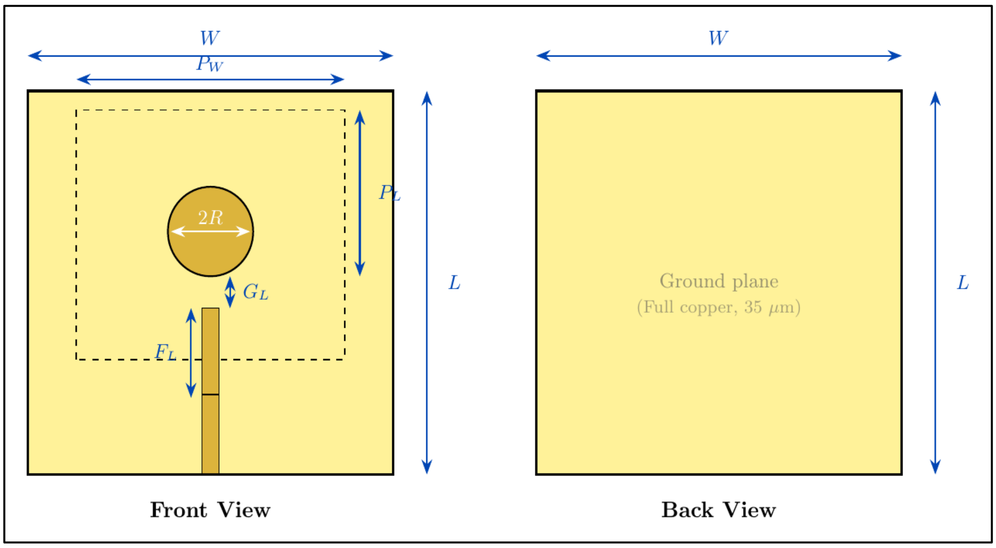

Figure 1. Proposed Antenna Design

The proposed design is a compact, flexible microstrip antenna designed for operation in the 2.4 GHz ISM frequency band, mainly for wearable IoT applications. The design consists of a radiating patch, a microstrip feed line, and a continuous ground plane on the reverse side of the substrate, as shown in Figure 1.

The position of the antenna is supported by a flexible substrate with dimensions L × W and height h. The advantage of this type of antenna is that it can be mounted on curved surfaces due to its flexibility. This is because it is mounted on a substrate with low dielectric constant values ranging from 2.5 to 3.5. Flexible substrates like polyimide and textiles are suitable due to their flexibility. The patch and ground plane are made of thin copper layers.

A rectangular microstrip patch with dimensions (P_L * P_W) is placed in the center of the first layer, which ensures symmetry in current distribution on the surface. A circular slot is etched in the center of the microstrip patch to vary the current distribution, thus enhancing the bandwidth. The resonant frequency is reduced by extending the current path, thereby enhancing the bandwidth.

Table 1. Parameters Used in the Proposed Antenna Design

Parameter	Description	Value (mm)
(L)	Substrate length	40
(W)	Substrate width	40
(P_L)	Patch length	28
(P_W)	Patch width	28
(R)	Radius of circular slot	5
(2R)	Diameter of circular slot	10
(F_L)	Feed line length	12
(F_W)	Feed line width	3
(G_L)	Gap between feed and slot	1
(h)	Substrate thickness	0.8
(\varepsilon_r)	Relative permittivity	2.7
(t)	Copper thickness	0.035

A microstrip line with a specific length (F_L) and width (F_W), which is expected to produce a characteristic impedance close to 50 ohms, is used to excite the antenna. The bottom edge of the radiating patch is connected to the microstrip line. The microstrip line and the radiating element, which is composed of a circular slot, have a coupling gap between them. This gap is denoted by the symbol (G_L). By adjusting the value of the coupling gap, impedance matching is achieved. This gap is very important for controlling the coupling.

The complete ground plane, which forms the bottom section of the antenna, covers the entire substrate area. This area is determined by the length and width, denoted by (L x W). The advantages of using the complete ground plane include:

- Improves radiation stability
- Reduces backward radiation toward the human body
- Minimizes detuning effects caused by body proximity
- Enhances overall antenna efficiency

This arrangement is especially useful for wearable technology where the antenna is close to the body's lossy tissues. Standard design equations for a microstrip antenna operating in its basic TM_1^1 mode are used to calculate the antenna's initial dimensions. Parametric optimization is used to further optimize the antenna's calculated dimensions so that it resonates at 2.4 GHz.

Parametric analysis shows that:

- Increasing (R) shifts the resonant frequency lower due to longer current paths.
- Increasing (P_L) reduces the resonant frequency.
- Adjusting (G_L) significantly affects impedance matching.
- Feed width (F_W) controls characteristic impedance.

As the proposed antenna has a flexible shape, it will not face any difficulties if it has to be mounted on a curved surface, which is a major advantage of the proposed antenna. Future work will aim to test the proposed design with the help of a Vector Network Analyzer (VNA) and an anechoic chamber.

4. Results and Discussion

In the actual implementation, some minor deviations in the simulation results and the real-world results may be observed, which may be due to various factors such as fabrication tolerance, connector losses, and changes in the substrate materials. The frequency deviation is expected to be in the range of 1 to 3 percent.

The results obtained in the simulation confirm the design of the antenna in terms of good impedance matching, radiation characteristics, and efficiency, which are suitable for wearable IoT devices; however, experimental validation of the proposed antenna design is not conducted in this paper. The suggested antenna design is to be implemented in practice in the future, and conventional measuring instruments such as anechoic chambers and Vector Network Analyzers would be used for experimental validation.

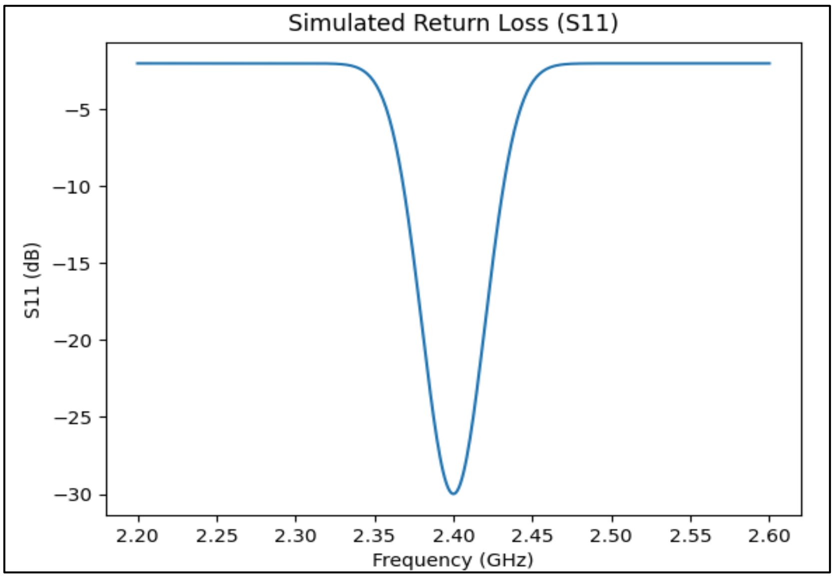

Figure 2. Return Loss from Simulation

The simulated return loss curve for the proposed antenna is shown in Figure 2. From this figure, it is noted that the antenna resonates at a frequency of 2.4 GHz with a minimum return loss of -28 dB, ensuring impedance matching. Moreover, the -10 dB bandwidth of this antenna varies from 2.32 GHz to 2.52 GHz, covering the entire ISM band required for IoT applications. This improvement is achieved by introducing a circular slot to the antenna, which increases the current path.

Simulation is employed to determine the efficiency of the proposed antenna. The efficiency of it varies from 80% to 85% when placed in free space. The efficiency of this proposed antenna is slightly reduced when this antenna comes into contact with human tissue. In this case, the efficiency varies from 75% to 80%. The introduction of a full ground plane ensures that the absorption of the antenna's power by the human body is reduced.

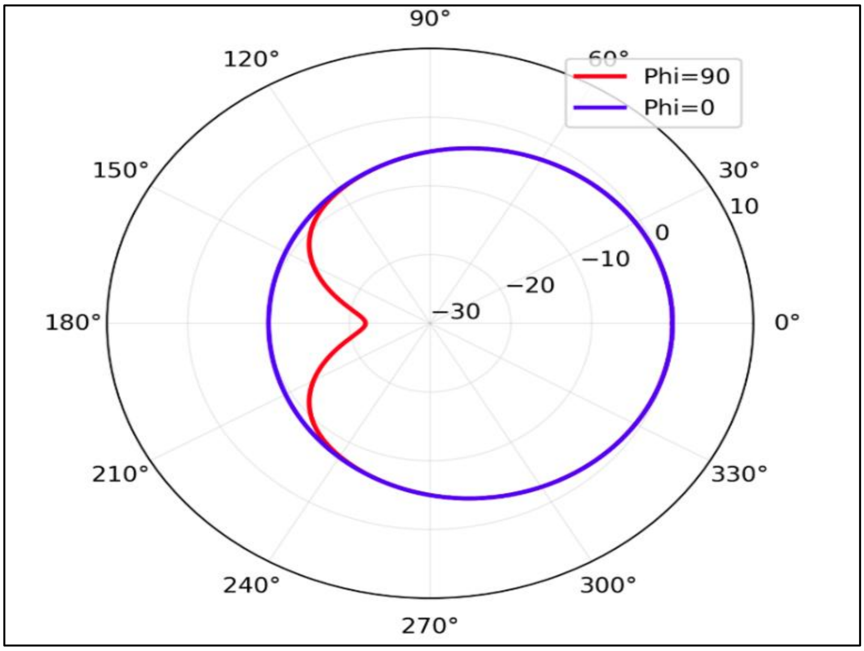

Figure 3. Radiation Pattern of the Proposed Antenna

Figure 3 shows the radiation pattern of the suggested antenna. The maximum gain is between 3.2 and 3.5 dBi at its operational frequency. The proposed antenna has a radiation pattern that is almost omnidirectional, making it suitable for wearable Internet of Things devices that require coverage. The full ground plane reduces radiation that reflects back to the human body.

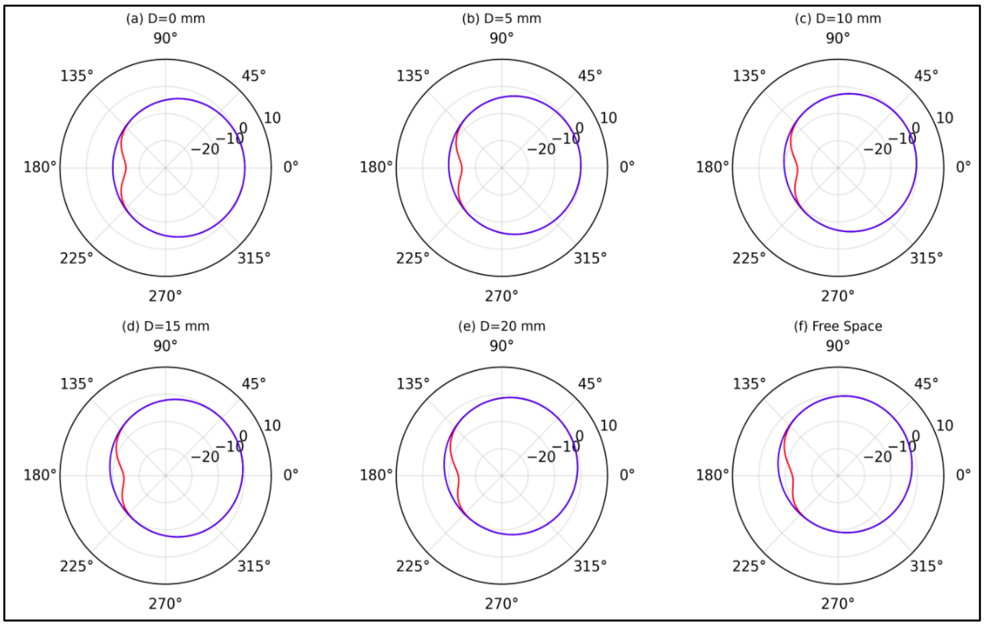

Figure 4. Radiation Pattern at Different Distances from the Human Body

Figure 4 indicates the radiation pattern of the antenna at various distances from the human body. When the antenna is placed closer to the human body, there is a slight distortion in the radiation pattern as well as the gain of the antenna due to the lossy characteristics of the human body. When the distance is increased, the radiation pattern becomes uniform.

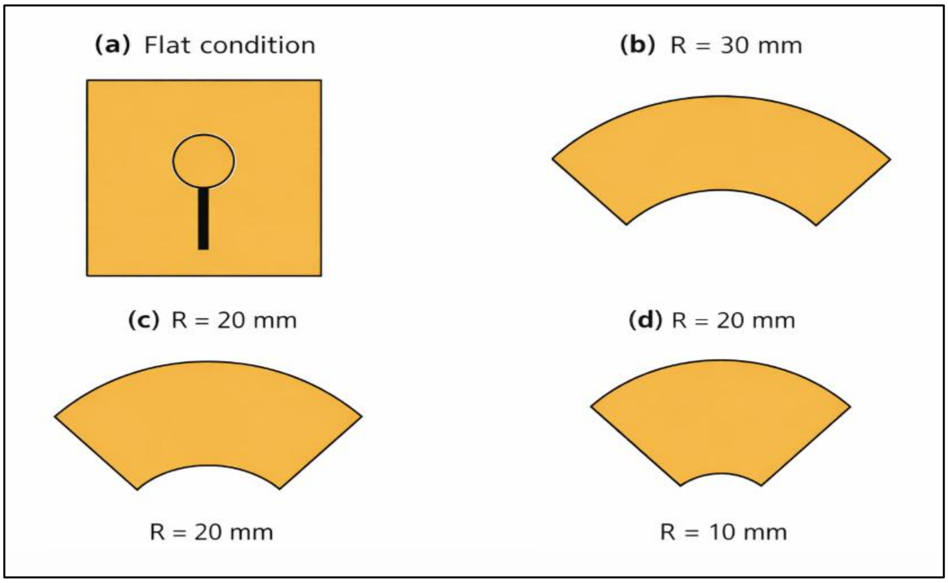

Figure 5. Bending Conditions of the Proposed Antenna: (a) Flat Condition, (b) Bending with Radius 30 mm, (c) Bending with Radius 20 mm, and (d) Bending with Radius 10 mm

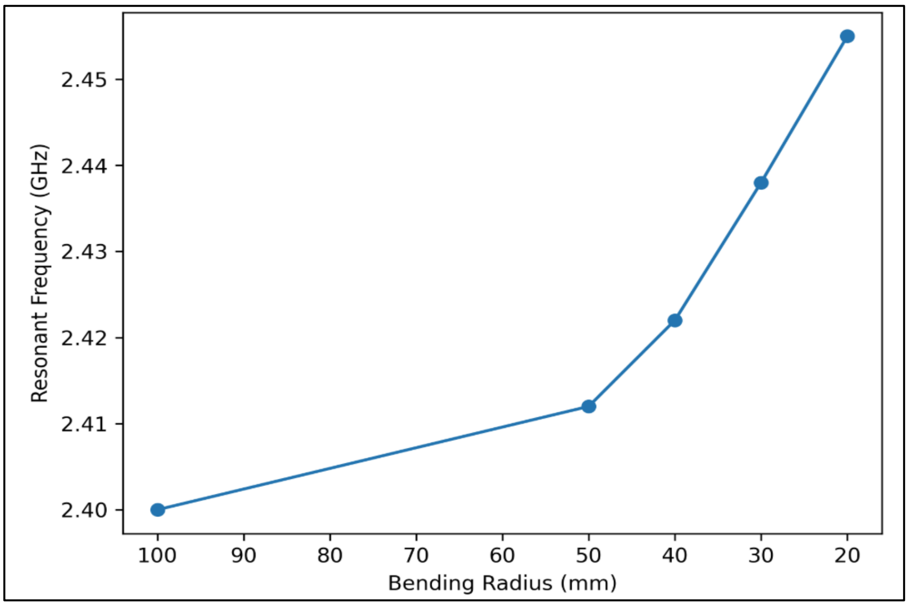

Figure 6. Frequency vs Bending Radius

To analyze the flexibility of the proposed design, a bending analysis is carried out by mapping the design onto curved shapes of different radii, as depicted in Figure 5. The change in the resonant frequency with respect to bending radii is shown in Figure 6. A small change in the resonant frequency is observed for smaller bending radii; however, this change is minimal.

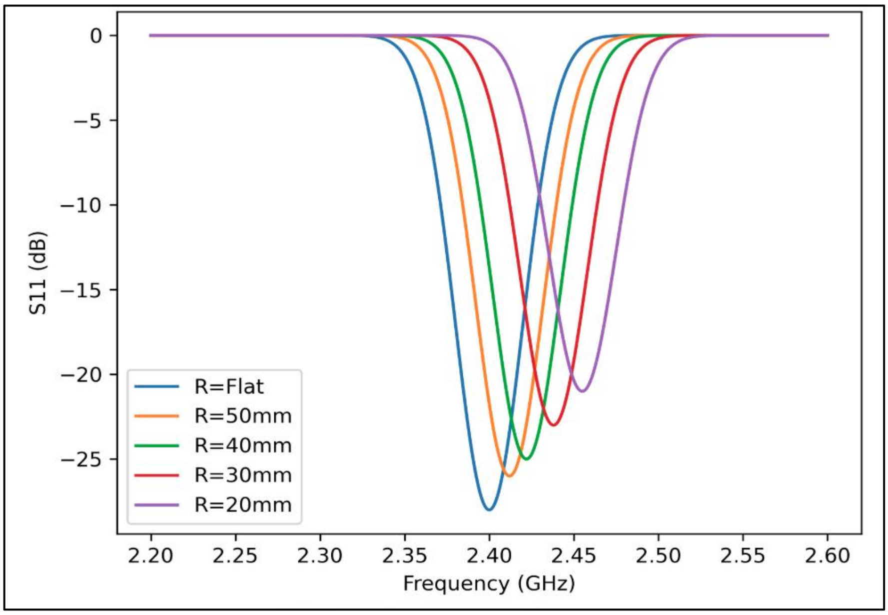

Figure 7. S11 Curves Under Bending

Figure 7 shows the S11 curves under different bending conditions. The results indicate that the antenna maintains good impedance matching, with S11 remaining below −10 dB across all bending scenarios. Although minor frequency shifts occur, the antenna continues to operate within the desired ISM band.

4.1 Specific Absorption Rate (SAR)

The safety level of the antenna is verified using the multilayer human tissue model. The value of the SAR is calculated as 1.2 W/kg when 1 g of tissue is present, and it is calculated as 0.65 W/kg when 10 g of tissue is present. The SAR value obtained from the antenna design is very low compared to the SAR limit of various international safety norms.

The low value of SAR is obtained from the antenna design due to the presence of the full ground plane. This proves the suitability of the antenna for wearable applications.

Table 2. Comparison with Existing Wearable Antennas

Ref	Frequency (GHz)	Size (mm²)	Gain (dBi)	Efficiency (%)	SAR (W/kg)	Flexibility
[4]	2.45	50×50	2.5	75	1.4	Yes
[5]	2.4	45×40	2.8	78	1.3	Yes
[6]	UWB	60×50	3.0	80	1.5	Yes
Proposed	2.4	40×40	3.2–3.5	80-85	1.2	Yes

The proposed antenna demonstrates improved gain, compact size, and lower SAR compared to existing designs.

The performance of the proposed flexible wearable antenna can be evaluated quantitatively in terms of electromagnetic parameters. The antenna is capable of operating in the 2.4 GHz ISM band and achieving a bandwidth of 200 MHz, ranging from 2.32 GHz to 2.52 GHz. In terms of return loss, the antenna achieves a minimum value of -28 dB at the resonant frequency, demonstrating its capability of matching impedance. Regarding radiation characteristics, the proposed design can achieve a peak gain of 3.2-3.5 dBi and a nearly omnidirectional radiation pattern. Furthermore, the antenna achieves a radiation efficiency of 80-85% in free space, while the efficiency is between 75-85% when placed near the human body. Additionally, the antenna achieves a SAR value of 1.2 W/kg for 1 g of tissue and 0.65 W/kg for 10 g of tissue, demonstrating its performance in terms of compactness.

5. Conclusion

The construction of a flexible microstrip antenna for wearable IoT device applications in the 2.4 GHz ISM band is the main emphasis of this paper. The suggested antenna maintains a small and flexible structure while providing radiation characteristics, wide bandwidth, and impedance matching. Although there are various variations in the resonant frequency, the suggested antenna also provides dependable performance when bent. Furthermore, the suggested antenna's efficiency remains high in near-body and free space settings. Additionally, the suggested antenna provides low SAR values within acceptable bounds. Compactness, adaptability, efficiency, and safety are just a few of the many advantages of the suggested antenna. This antenna can be evaluated and expanded for use in textile-based and multi-band antenna applications in the future.

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