

A Radiating Metasurface Circular Patch Antenna with Null Steering for Wireless Body Area Network and Medical Applications

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Abstract: The flexible printed metasurface circular patch antenna is presented for wireless body area network (WBAN) and healthcare monitoring applications. The proposed design is based on combining an ordinary circular patch with concentric-ring metasurfaces to realize wideband operation and passive radiation null steering without the aid of phased arrays or complex feeding networks. By controlling the current distribution, deep radiation nulls are achieved by the antenna at 90° and 270°, reducing radiation in the direction of the human body and mitigating the electromagnetic interference. The antenna is designed for sub-6 GHz applications in the 2.45 GHz ISM band, having an operating frequency range of 2.32–3.82 GHz. The measured and simulated results show good agreement, with reflection coefficients of (−10.86/−15.96) dB and (−8.70/−12.98) dB at 2.45 GHz and 3.6 GHz, respectively; the peak gain of approximately 8 dBi, and the null depth is more than 30 dB, which mainly validates the feasibility of this work for wearable and biomedical communications systems. The antenna is also tested under close to body operating conditions, where the specific absorption rate (SAR) values are calculated for different antenna to body separation distances. The 1 g and 10 g averaged SAR values are found to be well within the limits, with the highest values being 0.834 W/kg and 0.629 W/kg, respectively, which show good electromagnetic exposure performance.

Keywords: Flexible antenna; Metasurface; Null steering; Radiation; Wireless body area network.

1. INTRODUCTION

The rapid growth of wearable electronics, body-centric wireless communication systems, and medical monitoring system technologies has placed a high demand on the development of small size, high efficiency, and smart antenna systems with the feature of stable operation in close distance to human body [1]. In these applications, such as in wireless body area networks (WBANs), implantable and on-body medical sensors, telemedicine platforms, and smart healthcare devices, antennas play crucial roles in providing reliable wireless connectivity while ensuring safe electromagnetic exposure, low interference levels and high radiation efficiency [2]. Nonetheless, human body is a highly lossy, dispersive, and inhomogeneous medium for electromagnetic waves, which leads to significant performance degradation of the antenna and results in antenna impedance mismatch, radiation pattern distortion, absorption losses, and high specific absorption rate level (SAR) [3].

Although conventional microstrip patch antennas are low-profile, easy to fabricate, and mechanically robust, they are fundamentally limited in bandwidth, radiation control and treating of on body environments [4]. Part of this energy is coupled back to antenna, leading to undesired electromagnetic coupling, energy being absorbed, reduction of link efficiency, and potentially safety issues [5]. Further, the narrow impedance bandwidth and fixed radiation pattern of these antennas limit their use in the emerging multi-band wireless systems, in which operation in multiple frequency bands is desired simultaneously [6]. These limitations have motivated the development of new antenna paradigms which will eventually lead to intelligent antennas capable of performing both broadband and smart radiation control without an increase in system complexity [7].

In the past decade, metasurfaces have been recognized as an advanced electromagnetic engineering platform to manipulate wave propagation, radiation and scatterings via subwavelength patterning on 2D planar interfaces [8]. By modifying the surface impedance, local phase response, and current distribution, metasurfaces provide enhanced control over electromagnetic fields with planar, compact and flexible structures [9]. In the field of antennas, the metasurface has been utilized for gain

enhancement, bandwidth enhancement, radiation pattern control, surface wave suppression, beam shaping and beam steering [10]. In contrast to their volumetric metamaterial counterparts, metasurfaces possess the advantages of being ultrathin, lightweight, and easy to fabricate, which is of great significance for practical applications, such as wearable and biomedical devices [11]. Nevertheless, most of the proposed metasurface antenna designs are aimed at improving performance parameters such as gain enhancement, bandwidth extension, and efficiency optimization, with very few of them being concerned with the issues of radiation safety and interference-aware radiation control for body-centric applications [12].

Active beamforming techniques and multi-feed phased arrays can provide a directional control and null steering but at the expense of a complex feeding network with phase shifters, power dividers and control circuits, which lead to increase in the system cost and power consumption and structure complexity [13]. Such approaches are often inappropriate for miniature wearable and medical devices due to the need for simplicity, reliability, and minimal power consumption [14]. To tackle the above issues, in this article, a flexible radiating metasurface-based circular patch antenna is proposed to achieve simultaneous wideband operation and passive radiation null steering by purely geometric surface manipulation [15].

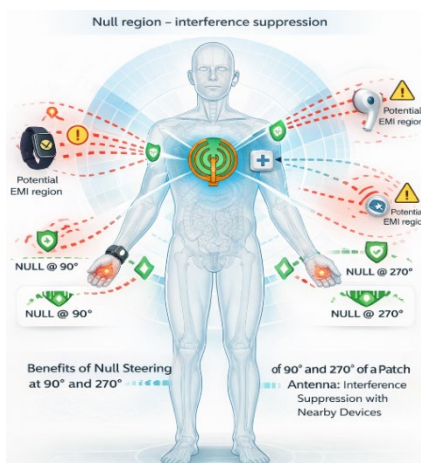
The proposed design is based on classical circular patch antenna theory combined with designed concentric ring metasurface structures to form a single radiating surface with manipulation of surface currents and electromagnetic (EM) phase distribution without the use of active devices or complex feeding schemes [16]. The concentric rings etched on the circular patch behave as engineered impedance discontinuities that generate multiple resonant paths, local phase shifts and a controlled current redistribution, they can produce multi-resonant behavior, wideband impedance matching and beam shaping within a small size [17]. One of the main features of this work is the realization of deep radiation nulls oriented at 90° and 270° , which correspond to the directions toward the human body in typical on-body and wearable configurations as shown in Figure 1. These nulls are generated through destructive electromagnetic interference caused by engineered phase discontinuities and asymmetric current distributions induced by the metasurface geometry [18]. Therefore, electromagnetic coupling is reduced, energy absorption is minimized as well as the body radiation toward the body is suppressed, and the safety operation is improved. Different to traditional phased arrays or adaptive feeding network based null-steering technique, the presented method realizes null steering in a passive way by the structural design, making the design simple, compact and energy efficient [19].

This work adheres to a systematic design approach, starting from application-driven requirements definition, then metasurface-antenna conceptualization, concentric ring parametrization, flexible material modeling, and finally full-wave electromagnetics simulation. The physical interpretation of the metasurface is elaborated to investigate the current redistribution, phase control, and radiation shaping [20]. Separately, substrate bandgap structures have been well investigated as they can effectively suppress surface waves and enhance electromagnetic performance [21]. Next, the design is refined to satisfy the electrical and radiation goals, then a flexible prototype is built and measurements are provided. Measured results are compared with simulation data to verify impedance matching, radiation patterns, null steering performance, and operational stability.

The paper is organized as follows. The detailed description of the proposed antenna is first presented in the next section, followed by the workflow of the proposed antenna design, fabrication, and measurement process in Section 3. Section 4 demonstrates the analysis of simulation and experimental results. Finally, Section 5 summarizes this paper.

2. METHODOLOGY OF ANTENNA DESIGN

The configuration of the proposed antenna is designed as a multi-ring flexible patch radiator used for different on-body wireless communications. The development of this antenna follows a progressive design methodology aimed at systematically isolating the individual contributions of the metasurface and the intermediate ring to the overall antenna performance. Three configurations are evaluated and investigated sequentially, starting with a conventional non-metasurface radiator and ending in the proposed structure integrating both the concentric rings and the intermediate ring. The given approach provides a systematic framework for correlating each structural modification with its corresponding impact on operating frequency, impedance bandwidth, impedance matching, and radiation characteristics.



Blue lines: Desired radiation / safe propagation region	The blue fan-shaped lobes extending forward and backward from the chest
	The semi-transparent blue arc field around the torso
	The directions aligned with the body front/back axis
Red dashed lines: Potential interference paths	Toward the smartwatch, earbud, and sensor
	The lateral directions at approximately 90° and 270°
	The areas marked with warning icons

Figure 1. Depiction of null steering at 90° and 270° in an on-body patch antenna, illustrating suppression of side lobes to minimize interference to other surrounding objects.

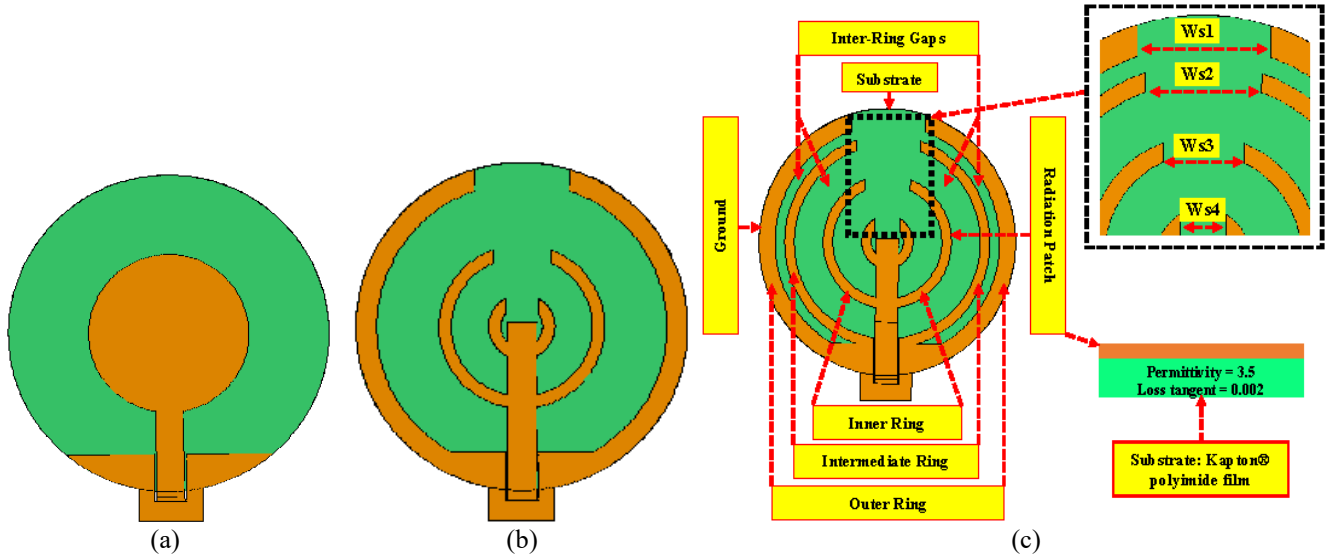


Figure 2. Development stages of the proposed flexible antenna: (a) non-metasurface (conventional), (b) metasurface without intermediate ring, and (c) metasurface with intermediate ring (proposed configuration).

The antenna structure consists of a radiating patch, a flexible dielectric substrate, and a ground plane. Kapton polyimide film is the material chosen for the substrate layer due to its mechanical flexibility, reduced thickness, and stable dielectric behavior across the operating frequency band. The substrate shows a relative permittivity of 3.5 with a loss tangent of 0.002, which together ensure low dielectric losses and well-suited to wearable antenna applications. Furthermore, the flexible characteristic of the substrate enables the antenna to bend to the curvature of the human body while preserving its electromagnetic performance. Figure 2 presents the three analyzed configurations, corresponding respectively to the reference design, the intermediate design, and the final proposed structure, as follows:

- Non-metasurface (conventional) configuration (Figure 2(a)): This configuration considers as the reference geometry and establishes the baseline electrical performance against which the effects of subsequent structural modifications are evaluated.
- Metasurface without intermediate ring (Figure 2(b)): Concentric ring structures are introduced around the radiating patch, altering the surface-current distribution relative to the reference design. This modification provides additional control over the resonance behavior and radiation characteristics, enabling an isolated assessment of the metasurface contribution to antenna performance.
- Metasurface with intermediate ring (Figure 2(c)): An intermediate ring is incorporated within the metasurface structure, further regulating the surface-current distribution, particularly in the vicinity of the feed region. This additional degree of control contributes to improved impedance matching and yields the radiation performance characteristic of the proposed antenna.

The inter-ring distance (S) plays a significant role in the electromagnetic interaction of two adjacent rings. The compromise between the mutual coupling and the stable resonance characteristics in this distance is crucial. The slope of the sections $Ws1$, $Ws2$, $Ws3$, and $Ws4$ are gradually changed to adjust the effective current path length in order to realize a desired null steering performance. They correspond to some tuning knobs in the design and are shown in Table 1. An antenna element is excited by a compact feed structure integrated with the radiating patch. The feed line is designed to provide the impedance to 50Ω and the flexibility in the material. From an electromagnetic engineering viewpoint, the design strategy represents a parametric optimization, as follows:

- Initial dimensions are derived from classical microstrip patch approximations.
- Ring geometry is introduced to redistribute surface currents and generate controlled radiation nulls.
- Iterative full-wave simulations are used to optimize ring widths, spacing, and feed location.
- Final dimensions are validated under flexible bending scenarios to confirm robustness.

The resulting structure achieves a balance between compact size, mechanical flexibility, and radiation control, making it suitable for wearable and biomedical communication systems.

3. WORKFLOW OF THE ANTENNA DESIGN, FABRICATION AND MEASUREMENT PROCESS

Figure 3 fully describes the proposed architecture for the design, simulation, fabrication, and measurement. The design process consists of three stages: electromagnetic simulation, metasurface realization, and measurement. The application-specific requirements are first imposed, followed by a conceptual design being generated. Next, numerical optimization is performed on the proposed design, and the prototype is constructed. Finally, the measurement results are validated. The antenna design is obtained for a certain application in wearable communications. At this stage, the electrical, mechanical, and safety limitations will be established that will lead the subsequent design stages.

Table 1. Geometrical parameters of the proposed ring antenna.

Parameter	Value (mm)	Parameter	Value (mm)
Distance of the outer resonant ring (S_1) from the center	35	Gap between S_2 and S_3 (G_{23})	9
Distance of the intermediate resonant ring (S_2) from the center	29	Substrate radius (R_{sub})	40
Distance of the inner phase- resonant ring (S_3) from the center	8	Substrate thickness (h)	0.11
Radius of outer ring (Rs_1)	35	W_{s1}	23
Radius of intermediate ring (Rs_2)	29	W_{s2}	20
Radius of inner ring (Rs_3)	17	W_{s3}	14
Gap between S_1 and S_2 (G_{12})	3	W_{s4}	8

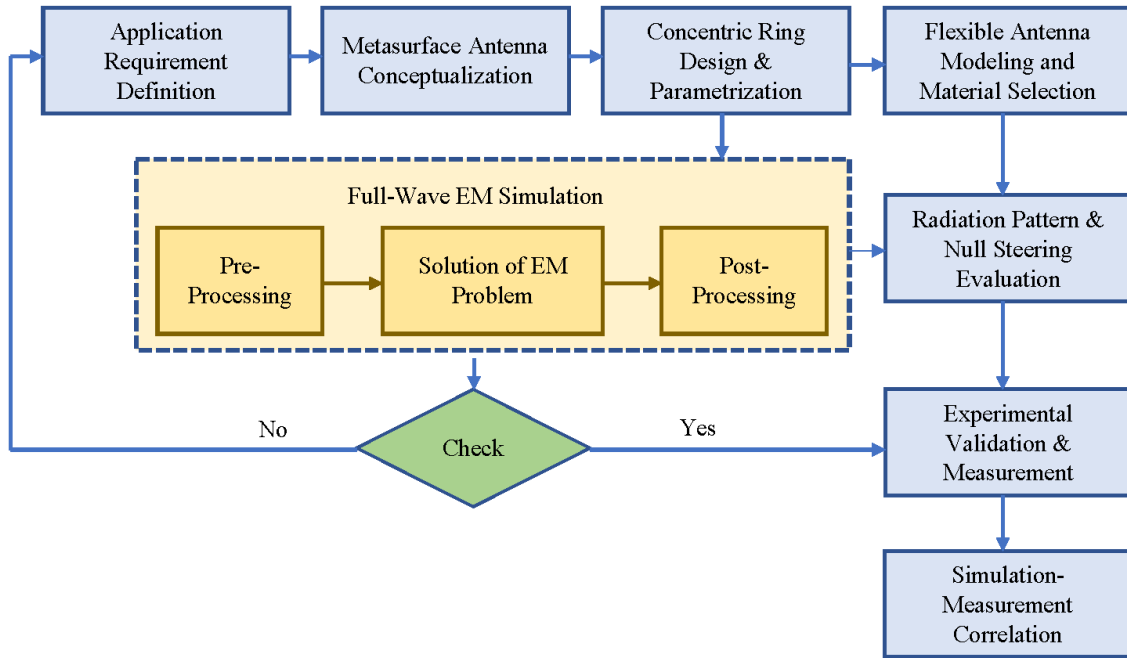


Figure 3. Workflow methodology of the proposed flexible radiating metasurface circular patch antenna.

After the specification of the requirements, a metasurface-antenna design is synthesized to satisfy the system requirements. Then, a concentric ring structure is introduced to manipulate the surface current distribution and directivity of the radiation pattern. The proposed antenna is treated as a flexible material by considering a dielectric substrate and conductive layers in order to achieve mechanical flexibility as well as electromagnetic robustness. The full-wave electromagnetic simulation process consists of three main steps:

- Pre-processing, including the antenna configuration, boundary definition, and then the meshing process is applied,
- Solution of the electromagnetic problem using a full-wave solver,
- Post-processing, where reflection coefficient, current distributions, and radiation characteristics are extracted.

The simulated results are explained by a metasurface-based physical perspective. Then, the obtained optimal configuration is used to analyze the radiation pattern characteristics and investigate the performance of the null steering for effective directional exclusion and desired area of coverage. The design is verified and manufactured for a flexible version, built on a chosen polymer material, by using appropriate metallization processes. Finally, the measured results of the fabricated antenna sample are characterized for its impedance behavior and radiation patterns and the simulated and measured results are then compared for validating the adopted design approach, which consequently confirms the reliability, consistency and feasibility of the proposed design approach for wearable applications.

4. RESULTS AND DISCUSSION

In this section, a comprehensive evaluation of the proposed flexible radiating metasurface-based circular patch antenna is presented. The performance and validation of the design are divided into two main parts: Subsection 4.1 focuses on the full-wave electromagnetic simulation results to study the effect of the ring structures on the antenna performance (reflection coefficient, antenna efficiency, antenna gain, and directivity). Subsequently, Section 4.2 details the experimental results obtained from physical measurements, providing a comparative analysis between the simulated and fabricated prototypes in order to validate the performance of the antenna for wearable applications.

4.1 Simulation Results

Figure 4 shows the simulated results of the antenna for three steps of evolution in free space (FS). The conventional antenna is seen to resonate at 3.8 GHz with a reflection coefficient of -14.7 dB and a high impedance bandwidth greater than 1000 MHz, as illustrated in Figure 4(a). The introduction of the metasurface without the intermediate ring shifts the principal resonance frequency to 2.04 GHz with an improved reflection coefficient of -42.6 dB. However, a narrow bandwidth (16 MHz) is associated with it, along with a secondary, weaker resonance at 3.86 GHz. By contrast, the presence of the intermediate ring leads to two well-fitted resonances at 2.03 GHz (-18.3 dB) and 2.62 GHz (-22.7 dB), the latter exhibiting a dramatic enhancement of the bandwidth to 1520 MHz, which means that the intermediate ring is essential to widen the operational bandwidth with good impedance matching. It can be seen from Figure 4(b) that high radiation efficiencies (more than 97%) are achieved for all three designs along the whole band, which confirms low ohmic and dielectric losses regardless of the modification of the metasurface. Remarkably, the efficiency of the design with the intermediate ring still remains constant at about 97 to 98% even over the extended resonance band, indicating that the enhancement of bandwidth is not obtained at the cost of radiation efficiency.

As seen in Figures 4(c) and 4(d), the metasurface-loaded design demonstrates a significant gain and directivity improvement over the conventional one. The gain rises from 2.95 dBi (conventional) to 4.35 dBi and 4.36 dBi for the metasurface setups with and without the intermediate ring, respectively, while the directivity increases to 3.12 dBi, 4.38 dBi and 4.48 dBi, respectively. The higher directivity obtained for the intermediate ring case can be related to that the two rings confine the field more and provide better radiation directionality due to a residual resonant coupling, as the presence of the ring introduces an additional resonant coupling. In summary, the results indicate that the introduction of the intermediate ring within the metasurface structure retains the high radiation efficiency (97%) and gives rise to an excellent compromise among the impedance bandwidth (1520 MHz), the gain (4.36 dBi), and the directivity (4.48 dBi), which is higher than the conventional and the ring-excluded metasurface solutions in overall radiation quality.

The antenna angular radiation at the two frequencies of operation is shown in Figure 5, the polar plots on the left side show a symmetric bidirectional pattern with pronounced null steering (see Figure 5(a)). At 2.45 GHz the deep nulls in the radiation pattern at around $\pm 90^\circ$ illustrate a strong directional suppression. The same behavior can be noticed at 3.6 GHz, but with slightly lower null depth, confirming frequency dependent beam shaping. The patterns illustrate that the antenna maintains the main lobe structure and at the same time the radiation nulls can be steered in a controlled manner, which is beneficial for interference reduction and spatial filtering. To verify this behavior further, the output is evaluated at various Phi angles. The null-steering characteristic is also evident at different steps for these angles, as observed in Figures 5(b) – 5(g).

The strongest null at 2.45 GHz is located close to $\theta = \pm 90^\circ$ and attains about -31.37 dB and -33.34 dB, respectively, and nearby angular position ($\pm 85^\circ$ and $\pm 95^\circ$) also enjoys strong attenuation level larger than -21 dB. The nulls are still very sharp although slightly shallower, about $-19/-23$ dB in the same angular range, at 3.6 GHz. These results verify that the antenna provides uniform directional suppression in both bands. Overall, the results confirm that the proposed design achieves both good impedances matching and a stable null steering performance, which is crucial for adaptive as well as interference aware wireless communication systems.

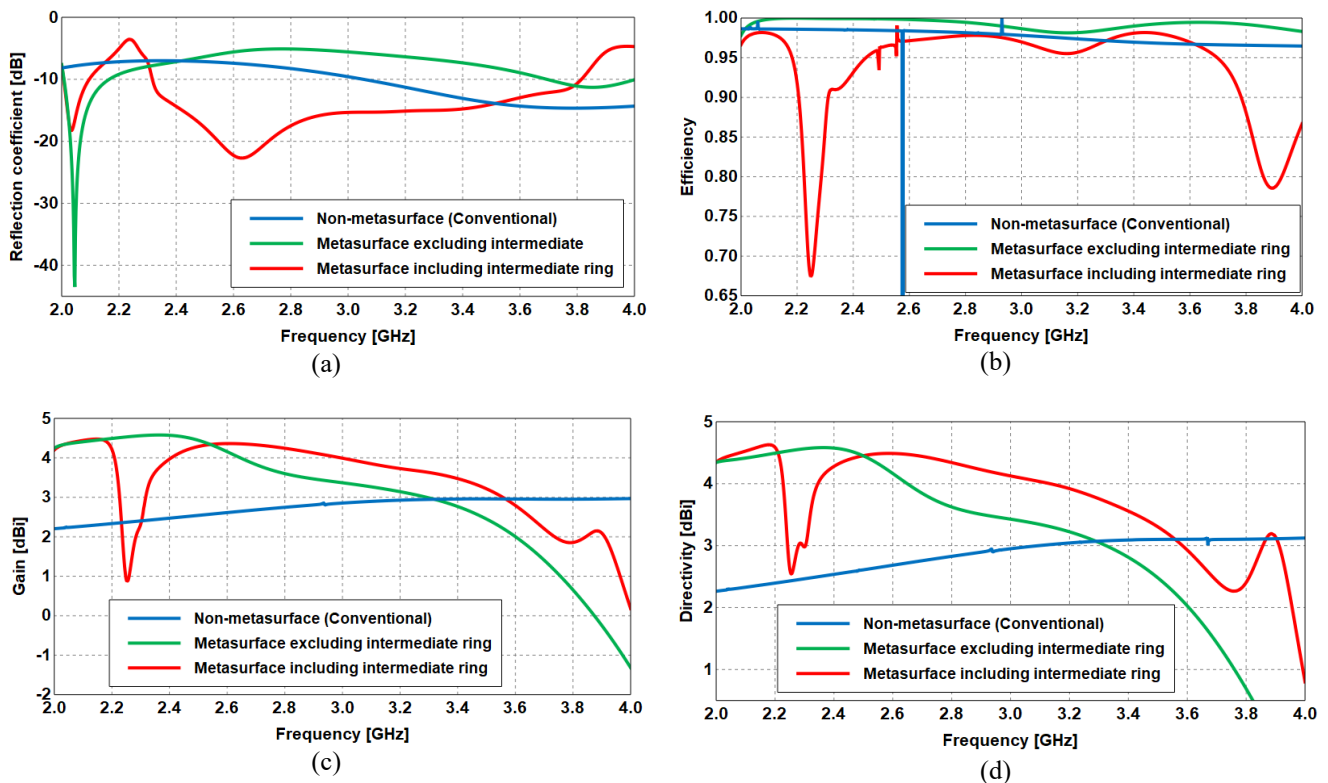


Figure 4. Simulation results of the antenna at different development stages in FS: (a) Reflection coefficient, (b) Efficiency, (c) Gain, (d) Directivity.

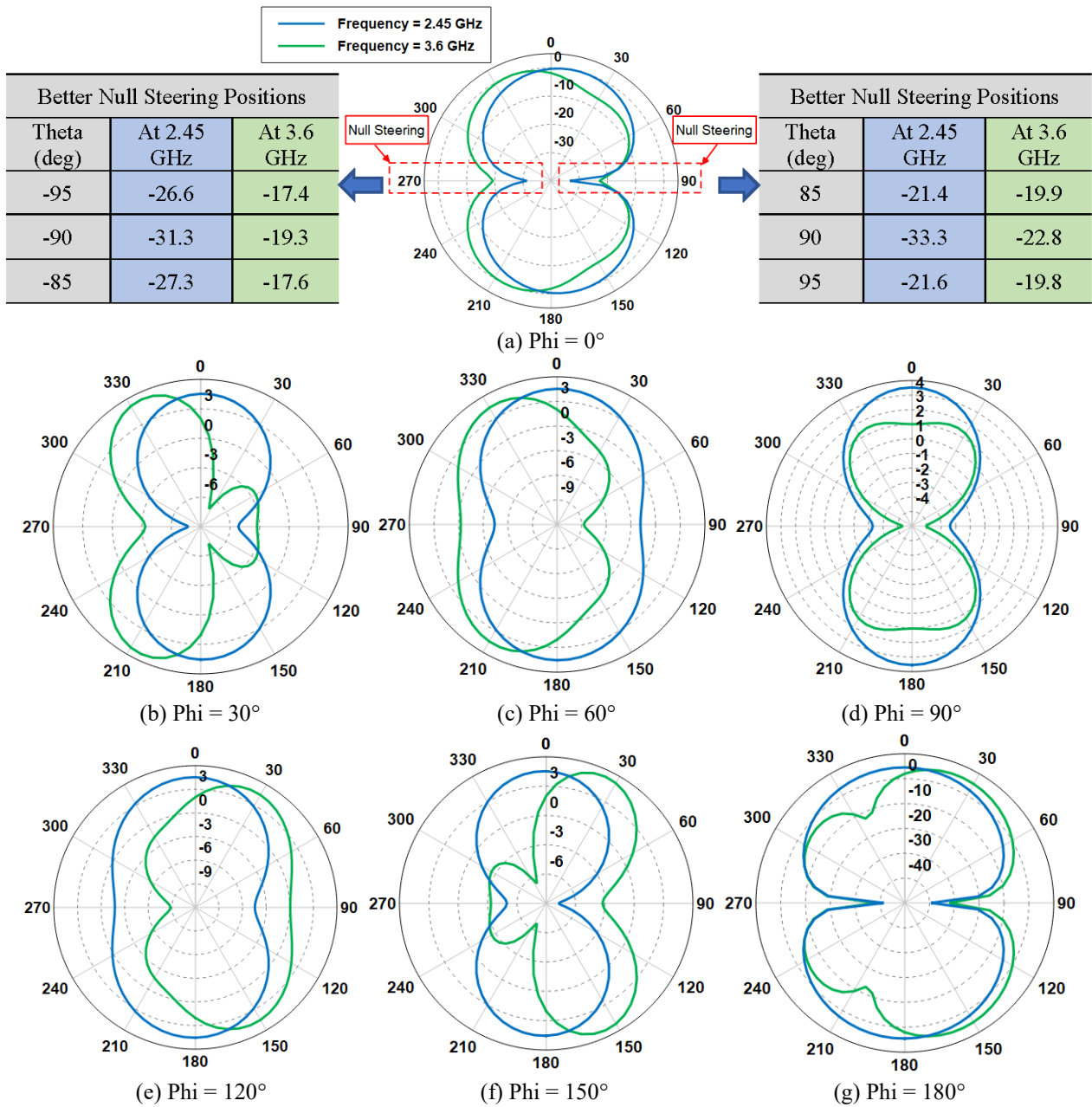


Figure 5. Radiation pattern results at different Phi degrees in FS.

The radiation performance of the proposed flexible antenna is shown in the 3D simulated gain patterns in free space at the two frequencies of 2.45 GHz and 3.6 GHz in Figures 6(a) and 6(b), respectively. At 2.45 GHz radiation patterns of the antenna show a quasi-omni-directional behavior with a smooth and continuous gain distribution around the major radiator. The lack of deep nulls and a somewhat uniform intensity of radiated electromagnetic field implies some degree of stability in the electromagnetic operation, which is very important for flexible and wearable wireless applications where the antenna orientation might easily change during use.

In addition, the gain pattern demonstrates that the bending does not significantly affect the main radiation lobe in the lower operating band. At the higher working frequency of 3.6 GHz, as shown in Figure 6(b), the pattern becomes slightly more directive, a further concentration of radiated power in certain directions is obtained. Such a phenomenon is due to higher-order resonances in the antenna. Although it becomes more directive, the beam pattern remains well-behaved and no excessive back radiation or unexpected side lobes appear. The results indicate that the flexible antenna can achieve good stability of radiation in different frequency bands and is feasible for the multi-band wireless system whose working frequencies cover WLAN and sub-6 GHz 5G.

A more detailed understanding of the electromagnetic characteristics of the antenna is obtained from the surface current distributions shown in Figures 7(a) and 7(b) at 2.45 GHz and 3.6 GHz, respectively. At 2.45 GHz, the surface currents are mostly along the feed line and the inner radiating paths of the antenna. This proves that the staple mode is mainly determined by the effective electrical length of the main radiator. The symmetric current flow suggests efficient excitation of the radiate element and low current cancellation which contributes to the stable radiation pattern as shown in Figure 6(a).

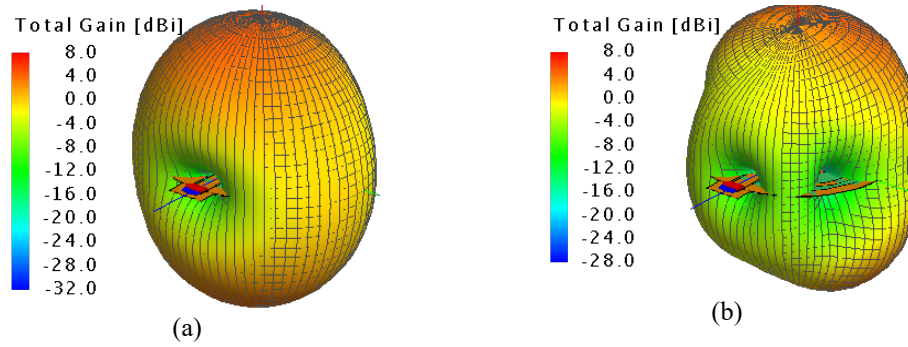


Figure 6. Simulated three-dimensional (3D) total gain radiation patterns of the proposed flexible antenna in FS: (a) at 2.45 GHz, (b) at 3.6 GHz.

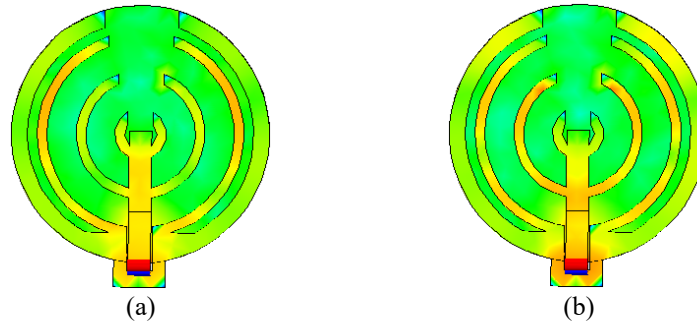


Figure 7. Simulated surface current distribution of the proposed flexible antenna in FS: (a) at 2.45 GHz, (b) at 3.6 GHz.



Figure 8. Antenna placement on the multilayer human-tissue heterogeneous model.

At 3.6 GHz, the surface current distribution is also depicted and one notices a stronger concentration of currents on the inner and outer resonant paths. Such a redistribution of the surface currents is an indication to the excitation of other resonant modes in the upper frequency range. The augmented current density over the longer conductive medium is the reason for the improved radiation directionality in Figure 6(b). Notably, the current distribution appears well localized within the antenna shape, indicating negligible surface wave leakage and high radiation performance in spite of the bending of the antenna. Additionally, the proposed antenna is also evaluated for the human body using a heterogeneous model. The model is composed of four layers of tissue - skin, fat, muscle, and bone, as shown in Figure 8 [22-24].

The results produced in Figure 9 show the simulated reflection coefficient and SAR for different distances from the human body (chest) with clothes for the proposed antenna, and Table 2 lists the results values. It is observed from Figure 9(a) that the antenna achieves good impedance matching within the entire examined frequency band, and the resonant behavior is significantly influenced by the distance from the body. At 2 mm, two resonances appear at 2.07 and 3.34 GHz, with reflection coefficients of -38.31 and -19.34 dB, respectively. The resonances are shifted toward 2.34 and 3.94 GHz (with reflection coefficients of -18.26 dB and -17.10 dB) when the separation is increased to 6 mm, whilst at 10 mm distance, the resonances take place at 2.38 and 3.72 GHz (with reflection coefficient of -18.82 dB and -23.50 dB). The obtained bandwidths are also presented in Table 2 as proof of wide impedance bandwidth, especially at the upper-frequency resonance.

Furthermore, the SAR distributions also show the electromagnetic exposure behavior of the antenna as a function of the distance to the human body, as shown in Figure 9(b). In some of cases, an increase in the separation distance changes the SAR response and reduces the electromagnetic absorption at a required frequency. The results show that the 1-g averaged SAR values are between 0.18 and 0.834 W/kg, while the 10-g averaged values are between 0.184 and 0.629 W/kg. The highest values are 0.834 W/kg (1-g cube) and 0.629 W/kg (10-g cube) at the frequencies investigated. These results show that the proposed antenna provides a good compromise between impedance matching, wideband performance, and electromagnetic

exposure performance for different separation conditions. The results confirm the effectiveness of the proposed design for body-centric wireless applications, where reliable antenna performance and controlled electromagnetic absorption.

The optimal separation distance of 2 mm between the antenna and the human chest model is chosen for the evaluation of the performance of the proposed antenna for wearable applications, since it provided the widest impedance bandwidth. It should be noted that the dominant resonance at the 2 mm separation shifts to 2.07 GHz as a result of the high dielectric loading of skin and fat layers, while the broad -10 dB impedance bandwidth attained at this distance (> 2000 MHz) ensures that the reflection coefficient will be kept below -10 dB over the entire 2.45 GHz ISM band (2.400–2.4835 GHz). This demonstrates that the proposed antenna maintains good impedance matching at the desired design frequency despite the resonance shift caused by proximity to the body, a widely reported and anticipated characteristic of wearable antennas placed close to human tissue. The two-dimensional radiation patterns of the antenna in FS and on-body conditions are shown in Figure 10 (at 2.45 GHz and 3.6 GHz). In FS, the antenna has a nearly quasi-omnidirectional radiation characteristic with uniform gain distribution. On the other hand, the radiation gain is significantly reduced in both forward and backward directions when the antenna is located on the body. The backward radiation towards the body is largely shielded and absorbed as a result of the high dielectric permittivity and conductivity of biological tissues. Moreover, the decrease in forward radiation gain is mainly due to the electromagnetic power absorption in the lossy human tissues, as well as the dielectric loading and destructive interference (due to energy reflections off the body surface).

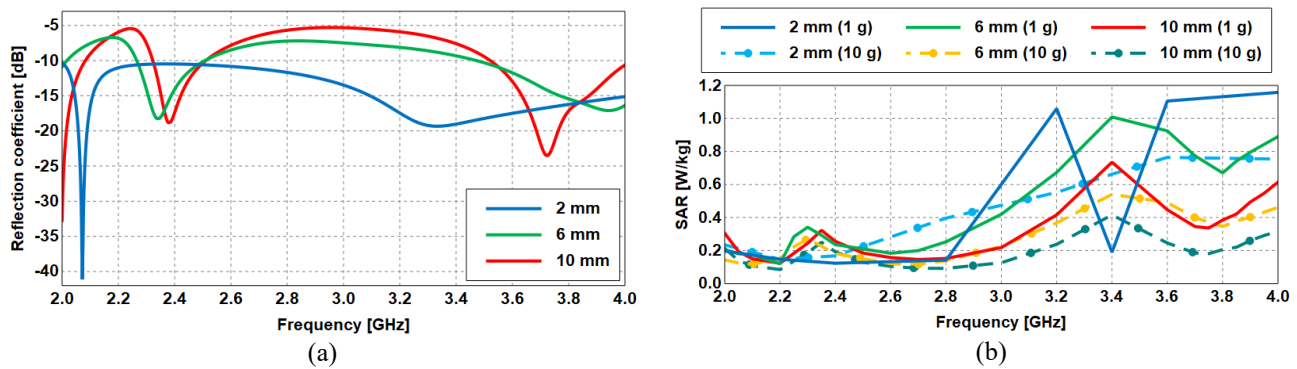


Figure 9. Simulated performance of the proposed antenna at different antenna-to-body separation distances: (a) reflection coefficient, (b) SAR values averaged over 1-g and 10-g tissue masses.

Table 2. Resonant frequencies, reflection coefficients, impedance bandwidths, and SAR values of the proposed antenna at different separation distances.

Distance (mm)	Resonant Frequency (GHz)		Reflection Coefficient (dB)		Bandwidth (MHz)		SAR Values (W/kg)			
							1 g Cube		10 g Cube	
2	2.07	3.34	-38.31	-19.34	Greater than 2000		0.18	0.443	0.204	0.629
6	2.34	3.94	-18.26	-17.1	242	Greater than 513	0.302	0.834	0.235	0.427
10	2.38	3.72	-18.82	-23.5	190	Greater than 476	0.283	0.342	0.216	0.184

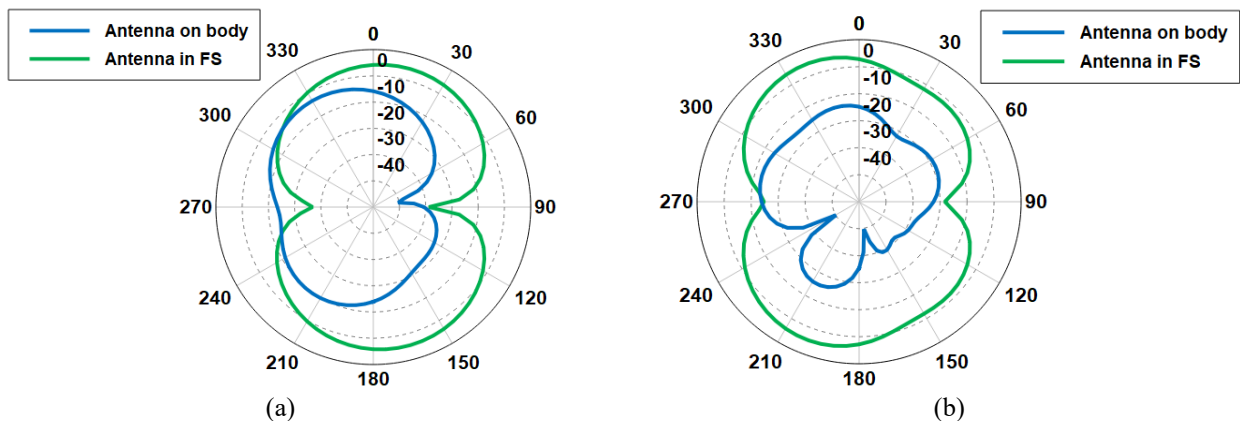


Figure 10. Radiation patterns of the proposed antenna in FS and on-body at: (a) 2.45, (b) 3.6.

4.2 Experimental Results

The antenna fabrication process and its evaluation on the human chest are described as illustrated in Figure 11. Geometry of flexible multi-ring patch with proposed dimensions is first printed on the paper to retain the patch shape and to prevent its deformation during the integration process. Next, the printed template is adhered to a flexible substrate a bit larger the size of the patch. Then, the patch and ground plane are cut along the pattern by means of scissors and a knife. The patch and ground plane were made from self-adhesive aluminum foil tape ($\sigma \approx 3.5 \times 10^7$ S/m, thickness ≈ 0.03 mm, i.e., much greater than the skin depth of ≈ 1.7 μ m at 2.45 GHz), and silver epoxy was used only to secure the SMA connector. Finally, the patch and the ground planes are bonded to the front and back surfaces of a Kapton substrate, respectively, and a Sub Miniature Version A (SMA) connector is soldered to the feed line with silver epoxy.

The differences in the results between the measured and simulated reflection coefficients shown in Figure 12 for both FS and on-body are attributed to practical issues such as feeding position misalignments, fabrication tolerances, uncertainties in the dielectric constant of the substrate, and connector/cable losses. In FS (the blue curves), a slight frequency shift reduces the measured bandwidth to about 779 MHz. In addition, the simulated and measured reflection coefficients at 2.45 GHz are -15.96 dB and -10.86 dB, and at 3.6 GHz are -12.98 dB and -8.70 dB, respectively, which show good agreement between the simulated and fabricated prototypes at both target operating frequencies. On the human chest (red curves), a sharp resonance emerges at around 2.1 GHz due to body loading. In particular, excellent agreement is achieved between simulated and measured results in the on-body case for the whole frequency band.

Numerous body-oriented antennas that use methods like AMCs, EBGs, metamaterials, and multi-layer metasurfaces to increase the power of the antenna, bandwidth, and radiation efficiency have been documented in the literature. Nevertheless, many of these methods result in increased power consumption or structural complexity of the antenna profile. A thorough comparison of the performance of representative contemporary disposable and surface-mount antennas against reference antennas is given in Table 3 to highlight the importance of this work.

In addition to electrical performance metrics like operating frequency bandwidth gain and efficiency, the comparison will consider practical factors like construction complexity and sizing flexibility. In order to achieve competitive power, a wider bandwidth, small size, and intrinsic passive null-sensing characteristics, the proposed antenna is obviously based on a simple one-layer geometry. These features make it especially appropriate for wearables and medical applications.

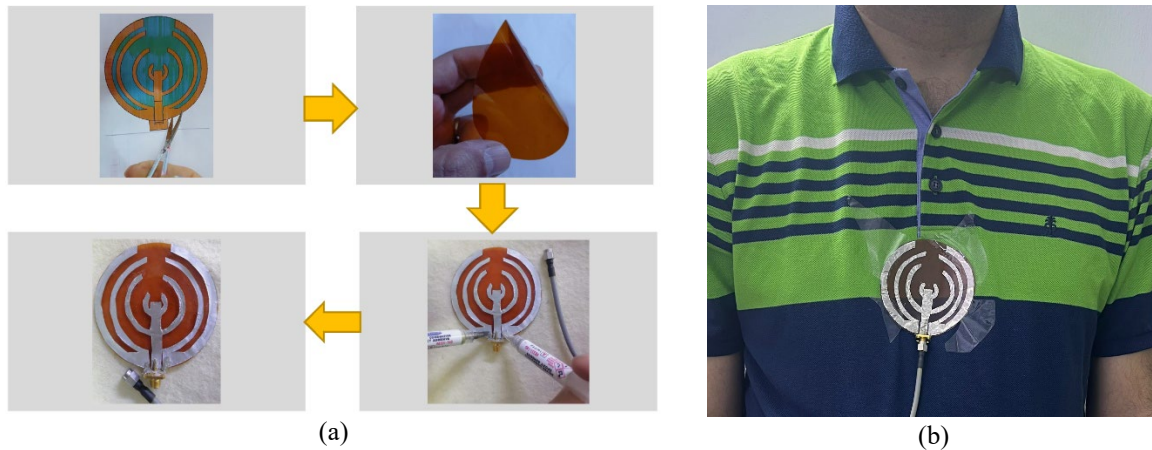


Figure 11. (a) fabrication process of proposed antenna, (b) antenna on body.

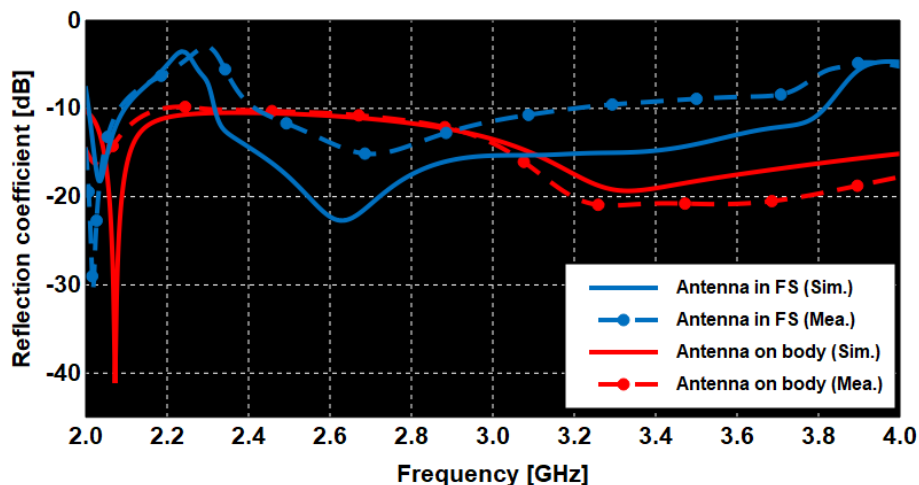


Figure 12. Reflection coefficient from simulation and measurement of proposed flexible antenna.

Table 3. Performance comparison with recently reported wearable and metasurface based antennas.

Ref	Antenna Type	Technique	Size (mm ³)	Bands (GHz)	Bandwidth	Peak Gain (dBi)	Efficiency (%)	Flexible	Null Steering	Complexity
[25]	Textile CP antenna	Metasurface ground	50×45×2	5.8	12%	6.1	low	Yes	No	Medium
[26]	UWB wearable	AMC reflector	60×50×4	5.1–13	UWB	7.5	80	Yes	No	High
[27]	Flexible WBAN	Metasurface sheet	40×40×2	2.45	10%	6.8	75	Yes	No	Medium
[28]	Slot patch	Defected ground	35×35×1.6	2.45	8%	5.5	70	Partial	No	Low
This work	Circular patch	Concentric rings as a metasurface	23×23×0.1	2.45 / 3.6	Wide (≈60%)	8	95% (2.45 GHz), 97% (3.6 GHz)	Yes	Yes (−30 dB)	Low (passive)

5. CONCLUSION

In this paper, a flexible circular patch antenna that works as radiating metasurfaces for medical and body-centric wireless communications is proposed. By applying concentric rings on the metasurfaces, the surface impedance and phase discontinuities were achieved for multi-resonance features, wide impedance bandwidth and controlled pattern at both 2.45 GHz and 3.6 GHz frequencies. The novel feature of the proposed design is that it introduces deep nulls at 90° and 270° in the pattern to minimize radiation towards the direction of the human body and consequently reduces the interference and harmful effects in wearable and medical communication systems. Both simulation and measurement results validate the proposed concept of the radiating metasurfaces. Moreover, the evaluation of the proposed antenna in approximity of the human chest showed acceptable SAR results for the studied distances of separation, averaging to peak 1-g and 10-g SAR values of 0.834 W/kg and 0.629 W/kg, respectively. The results confirm the adequacy of the proposed antenna for the body-centric wireless communication application. The measured results of wideband impedance matching with a stable peak gain of about 8 dBi, and large null depths over −30 dB demonstrate the excellent performance of the proposed antenna for the application of compact and interference-free radiating elements in future wearable and medical devices. The proposed flexible antenna also serves as a clear design paradigm for future flexible antenna systems.

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DECLARATION OF CONFLICTING INTERESTS

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