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Antena MIMO Double Curved Dengan Decoupling Ring Structure dan DGS Pada Aplikasi IoT Wearable Berbasis Wi-Fi

Doubled Curved MIMO Antenna with Decoupling Ring Structure and DGS For Wi-Fi Based Wearable IoT Application

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Abstrak

Perkembangan pesat teknologi komunikasi nirkabel dan Internet of Things (IoT) telah meningkatkan kebutuhan akan perangkat wearable yang mampu menyediakan konektivitas berkecepatan tinggi dan andal. Sistem wearable, termasuk tekstil pintar dan platform komunikasi berpusat pada tubuh, memerlukan antena yang kompak dan berprofil rendah serta mampu mempertahankan kinerja yang stabil terhadap pengaruh pergerakan tubuh dan kedekatannya dengan tubuh manusia. Penelitian ini mengusulkan sebuah antena mikrostrip MIMO double-curved yang beroperasi pada frekuensi 5,3 GHz dan dirancang khusus untuk aplikasi IoT wearable. Arsitektur antena merupakan kombinasi konfigurasi geometris double-curved dengan mengintegrasikan struktur cincin dekopling dan Defected Ground Structure (DGS) untuk secara efektif menekan kopling mutual dan meningkatkan kinerja elektromagnetik secara keseluruhan. Antena direalisasikan menggunakan substrat tekstil berbahan jeans dengan dimensi 48 × 32 mm, yang memberikan fleksibilitas sekaligus mempertahankan kekuatan mekanik. Hasil pengukuran menunjukkan pencocokan impedansi yang sangat baik dengan nilai S_{11} sebesar −30,62 dB, isolasi yang tinggi dengan nilai S_{21} sebesar −45,67 dB, nilai ECC sangat rendah sebesar 0.0003, Diversity Gain sebesar 10, serta gain puncak sebesar 3,69 dB. Implementasi gabungan DGS dan struktur cincin dekopling secara signifikan meningkatkan bandwidth antena dan efisiensi radiasi tanpa mengorbankan bentuk yang kompak. Hasil ini mengonfirmasi bahwa antena yang diusulkan sangat sesuai untuk aplikasi IoT wearable dan Wi-Fi yang memerlukan operasi stabil dan efisien pada pita frekuensi sekitar 5,3 GHz. Selain itu, pendekatan desain yang disajikan memberikan kerangka kerja yang menjanjikan untuk pengembangan sistem antena fleksibel dan berkinerja tinggi pada teknologi komunikasi nirkabel generasi mendatang.

Kata kunci: Antena MIMO, Decoupling Ring Structure, DGS, Double Curved, Wearable IoT

Abstract

The swift evolution of wireless communication technologies and the Internet of Things (IoT) has intensified the demand for wearable devices that can deliver high-speed and dependable connectivity. Wearable systems, including smart textiles and body-centric communication platforms, demand compact and low-profile antennas that can sustain stable performance under body motion and in close proximity to the human body. This work proposes a double-curved MIMO microstrip antenna operating at 5.3 GHz, specifically designed for wearable IoT applications. The antenna architecture combines a double-curved geometric configuration with the integration of a decoupling ring structure and a Defected Ground Structure (DGS) to effectively suppress mutual coupling and improve overall electromagnetic performance. A jeans-based textile substrate with dimensions of 48 × 32 mm is utilized in the antenna fabrication, offering flexibility while maintaining mechanical robustness. Measurement

results demonstrate excellent impedance matching with an S11 of −30.62 dB, high isolation characterized by an S21 of −45.67 dB, ECC value of 0.0003, Diversity Gain of 10, and a peak gain of 3.69 dB. The combined implementation of the DGS and decoupling ring structure significantly enhances the antenna bandwidth and radiation efficiency without compromising its compact form factor. These results confirm the suitability of the proposed antenna for wearable IoT and Wi-Fi applications requiring stable and efficient operation around the 5.3 GHz frequency band. Moreover, the presented design approach provides a viable framework for the development of future flexible and high-performance antenna systems for next-generation wireless communication technologies.

Keywords: Decoupling Ring Structure, DGS, Double Curved, MIMO Antenna, Wearable IoT

I. INTRODUCTION

The accelerated progress of wireless communication and Internet of Things (IoT) technologies has played a crucial role in advancing wearable devices with enhanced high-speed connectivity and reliable data transmission capabilities [1]. Applications in wearable systems such as smart textiles, body-centric communication (BCC) devices, and healthcare monitoring platforms necessitate compact, low-profile, and conformal antenna designs that ensure consistent performance despite body effects and user motion [2]. The growing need for seamless wireless connectivity in the 5.3 GHz Wi-Fi band has significantly driven research into efficient wearable antenna designs, particularly for systems requiring high-throughput transmission and reliable multiport antenna (MIMO) performance. By way of example, Wi-Fi 5 (IEEE 802.11ac) is designed to operate in the 5.15–5.85 GHz band, whereas Wi-Fi 6 (IEEE 802.11ax) extends its operation to include both the 2.4–2.485 GHz and 5.15–5.85 GHz frequency bands [3][4].

Notwithstanding substantial advances in antenna miniaturization and performance optimization, the integration of high-isolation flexible MIMO antennas into wearable platforms remains challenging. Compact antenna arrangements inherently suffer from strong mutual coupling due to element proximity, resulting in degraded isolation (S_{21}) and diminished radiation efficiency [5]. In addition, the flexibility of the substrate and manufacturing tolerances may alter the antenna's impedance characteristics, resulting in fluctuations in the reflection coefficient (S_{11}), voltage standing wave ratio (VSWR), and realized gain [6]. These challenges emphasize the need for antenna design approaches that can concurrently enhance isolation, impedance matching, and gain while maintaining compact size and mechanical flexibility.

Several isolation and impedance enhancement techniques for MIMO antennas have been reported in the literature, with electromagnetic bandgap (EBG) structures being one of the most commonly adopted solutions, L-shaped stubs [7], defected ground structures (DGS) [8], and decoupling structures. Among these techniques, defected ground structures (DGS) and circular decoupling structures have been identified as effective solutions for compact wearable antenna designs. In particular, circular or ring-based decoupling structures are capable of mitigating surface current propagation and enhancing isolation between closely spaced elements without enlarging the antenna footprint [7]. Nevertheless, the majority of reported designs are either planar or based on single-curvature configurations, thereby constraining their conformability to realistic surfaces and reducing their suitability for flexible substrate integration [9]. In addition, numerous reported prototypes are fabricated using traditional rigid materials, including Rogers RT5880 and FR-4, which, although electrically efficient, lack the mechanical flexibility demanded by wearable systems [9][10]. In addition, previous studies generally focus on either isolation enhancement or gain improvement individually, while limited research has investigated the simultaneous integration of DGS and decoupling ring structures in a double-curved wearable MIMO configuration operating at 5.3 GHz. Therefore, a clear research gap still exists in developing a compact, flexible, and doubly curved textile-based MIMO antenna capable of simultaneously achieving high isolation, enhanced gain, stable impedance matching, and mechanical conformability for wearable applications.

Recently, textile-based materials including felt, denim, and cotton have been increasingly explored as substrates for flexible antenna fabrication. [2][6][11]. Among textile substrates, denim (jeans) stands out due to its low permittivity, robust mechanical properties, and straightforward integration with apparel materials [12][13]. As a result, jeans fabric represents a viable substitute for traditional substrate materials, allowing antenna designs to maintain favorable electrical performance while offering low weight and mechanical flexibility [14] [15]. Collectively, these developments emphasize the need to synergistically integrate advanced materials with electromagnetic design optimization to achieve efficient wearable antenna systems.

In response to the identified design requirements, this study introduces a double-curved MIMO antenna that combines a decoupling ring configuration with a defected ground structure (DGS) and is optimized to operate at 5.3 GHz. The antenna reported in [18] was fabricated on a jeans-based textile substrate with εr = 1.7 and a thickness of 1 mm, providing both mechanical flexibility and low dielectric loss. The integration of a decoupling ring achieves strong isolation ($S_{21} < –20$ dB), while the redesigned DGS improves radiation gain, low ECC and impedance matching ($S_{11} < –10$ dB, VSWR $\approx$ 1). The antenna performance was evaluated using parametric simulations and experimentally validated through fabrication and measurement, with a focus on S-parameter behavior and gain consistency.

II. ANTENNA DESIGN

A quantitative experimental framework based on full-wave electromagnetic simulation is employed to design and optimize a double-curved MIMO antenna incorporating both a decoupling ring structure and a Defected Ground Structure (DGS), targeting wearable Wi-Fi IoT applications at 5.3 GHz. The research methodology adopts a numerical modeling and simulation-driven approach, complemented by parametric optimization, to systematically investigate the impact of geometric variations on antenna performance. The analysis is conducted using ANSYS HFSS version 15, which utilizes the Finite Element Method (FEM) for accurate three-dimensional electromagnetic field analysis [16]. This simulation-based approach enables precise evaluation of scattering parameters, impedance characteristics, and gain performance prior to physical prototyping

A. Specification Identification for Antenna Design

The initial stage of the antenna design process involves defining the key performance requirements, including the operating frequency band, impedance characteristics, gain, return loss, and mutual coupling. The design specifications are established in accordance with the intended application. To ensure efficient radiation and adequate coverage for 5.3 GHz Wi-Fi IoT communication, a minimum antenna gain exceeding 3 dBi is specified, consistent with recent studies reported in the literature.

To ensure efficient power transfer and minimize signal reflections, the antenna design targets a return loss of at least −10 dB, thereby achieving adequate impedance matching over the intended operating band. This criterion is consistent with IEEE design recommendations and established practices in wireless communication systems.

In addition, a mutual coupling isolation level of −20 dB or better is specified to suppress inter-element interference, preserve channel independence, and enhance the overall transmission performance of the MIMO antenna. Previous studies have demonstrated that maintaining isolation below this threshold significantly improves the operational efficiency and channel separation of MIMO systems [17]. Guided by relevant standards and prior research, these design targets are selected to ensure optimal performance for wearable IoT applications operating in the mid-frequency band.

Table I summarizes the key parameters specified for the proposed antenna design.

Table I. Antenna Configuration Details

Parameter	Antenna Charateristic
Frequency	5.3 GHz
Return Loss	< -10 dB
Mutual Coupling	< -20 dB
Gain	> 3 dB

The detailed substrate parameters used in this design are listed in Table II:

Table II. Substrate Size Parameters

Specification	Value
Type of Substrate	Jeans Textile
Dielectric Constant	1.7
Thickness (h)	1 mm
Loss Tangent	0.025

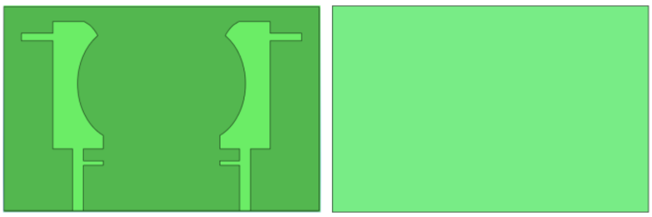
Table III summarizes the theoretical equations employed to determine the optimal physical dimensions of the proposed microstrip patch antenna. The antenna's physical geometry is a critical factor influencing its overall performance, as the electromagnetic field distribution is strongly governed by its dimensional parameters. In particular, the patch length and width control the resonant frequency and radiation characteristics, while the dimensions of the substrate and feedline affect impedance matching, wave propagation, and bandwidth performance [18]. Inaccurate dimensional selection may lead to undesirable effects such as electromagnetic leakage, increased mutual coupling, or impedance mismatch, thereby degrading antenna performance. Therefore, precise coordination between the antenna geometry and the associated material properties is essential to achieve stable field distribution, reduced transmission losses, and consistent radiation behavior, especially in advanced Wi-Fi–enabled IoT applications.

Table III. Theoretical Analysis and Design Computation

Parameter	Size (mm)
Length of Patch	24.4
Width of Patch	21
Length of Ground	30
Width of Ground	27
Width of Feed	1.5
Distance of Antenna	22.1

B. Doubled Curved MIMO Antenna

The double curved MIMO antenna employs a rectangular patch configuration designed to achieve efficient radiation and compact integration on a flexible substrate. In this initial design stage, the antenna is realized without incorporating decoupling ring and Defected Ground Structure (DGS) techniques, and its dimensions are determined using standard microstrip antenna design equations. The dimensional calculations are carried out for a target operating frequency of 5.3 GHz, with a textile substrate selected to provide mechanical flexibility and low dielectric loss. The geometric configuration of the proposed double-curved MIMO antenna is depicted in Figure 1.

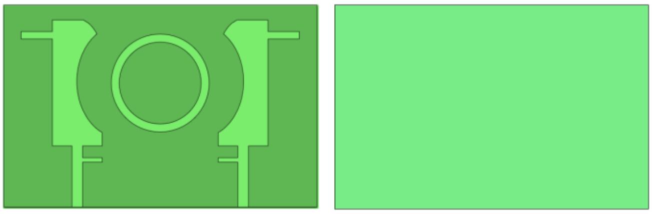


(a) (b)

Figure 1. Double Curve MIMO Antenna (a) Front View (b) Back View

C. Double Curved MIMO Antenna with Decoupling Ring Structure, without DGS

The double curved MIMO antenna is realized using a rectangular patch configuration that incorporates a decoupling ring structure while excluding the Defected Ground Structure (DGS) technique. The antenna dimensions are derived from standard microstrip antenna design formulations and optimized for a target operating frequency of 5.3 GHz. A textile substrate is employed as the supporting material to provide mechanical flexibility and structural robustness. The overall geometry of the proposed double-curved MIMO antenna with a decoupling ring structure, without DGS, is presented in Figure 2.

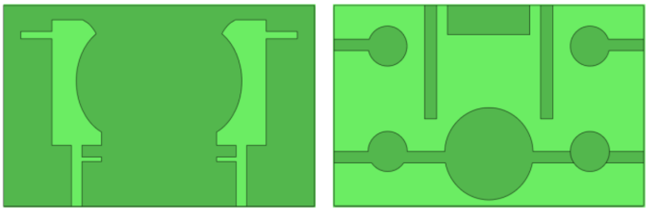


(a) (b)

Figure 2. Double Curve MIMO Antenna with Decoupling Ring Structure, without Defected Ground Structure (a) Front View (b) Back View

D. Double Curved MIMO Antenna with DGS, without Decoupling Ring Structure

The double curved MIMO antenna is implemented using a rectangular patch configuration that incorporates the Defected Ground Structure (DGS) technique while omitting the decoupling ring structure. The antenna dimensions are obtained from standard microstrip antenna design equations and optimized for operation at 5.3 GHz. A textile substrate is employed as the supporting material, providing mechanical flexibility and stable electromagnetic characteristics. The overall geometry of the proposed double-curved MIMO antenna with DGS, without a decoupling ring structure, is illustrated in Figure 3.



(a) (b)

Figure 3. Double Curve MIMO Antenna with DGS, without Decoupling Ring Structure (a) Front View (b) Back View

E. Double Curved MIMO Antenna with Decoupling Ring Structure and DGS Model 1

The double curved MIMO antenna is realized using a rectangular patch configuration that integrates both the decoupling ring structure and the Defected Ground Structure (DGS) techniques. The antenna design parameters are derived from standard microstrip antenna formulation methods and optimized for operation at 5.3 GHz. A textile substrate is utilized as the supporting material, offering mechanical flexibility and stable dielectric characteristics. The structural layout of the proposed double-curved MIMO antenna incorporating both the decoupling ring and DGS techniques (Model 1) is presented in Figure 4.

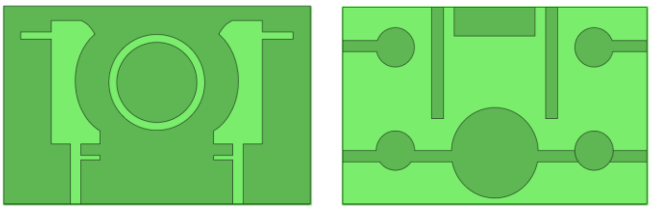


Figure 4. Double Curve MIMO Antenna with Decoupling Ring Structure and Defected Ground Structure Model 1 (a) Front View (b) Back View

F. Double Curved MIMO Antenna with Decoupling Ring Structure and DGS Model 2

The double curved MIMO antenna is implemented using a rectangular patch configuration that integrates both the decoupling ring structure and the Defected Ground Structure (DGS) techniques. The antenna dimensions are derived from standard antenna design equations and optimized for a target operating frequency of 5.3 GHz. A textile substrate is employed as the supporting material, providing mechanical flexibility and stable dielectric performance. The geometric configuration of the proposed double-curved MIMO antenna incorporating both the decoupling ring and DGS techniques (Model 2) is illustrated in Figure 5.

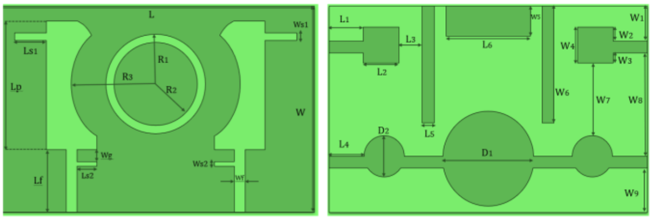


Figure 5. Double Curve MIMO Antenna with Decoupling Ring Structure and Defected Ground Structure Model 2 (a) Front View (b) Back View

Table IV summarizes the optimized antenna parameters along with their corresponding simulation results. Following the optimization process, the antenna exhibits notable enhancements in performance compared to the initial unoptimized configuration.

TABLE IV. Double Curved MIMO Antenna Model 2 Optimization

Parameter	Value (mm)	Parameter	Value (mm)	Parameter	Value (mm)
L	48	R1	8	L6	12
W	32	R2	6.7	W1	5.5
Lf	10	R3	14	W2	2.5
Lp	20	D1	7	W3	2
Ls1	5	D2	5.6	W4	6
Ls2	3.5	L1	5	W5	4
Wg	2	L2	6	W6	18
Wf	1.5	L3	3	W7	13.2
Ws1	1	L4	5.2	W8	17.5
Ws2	0.5	L5	2	W9	6

III. RESULT AND DISCUSSION

ANSYS HFSS version 15 was utilized to simulate the proposed double-curved MIMO antenna in order to assess its electromagnetic performance and to optimize the structural parameters for enhanced gain, return loss, and isolation. Figure 6 illustrates the comparative return loss responses of the double-curved MIMO antenna under different design configurations. The conventional MIMO antenna, which does not incorporate any enhancement structures, exhibits inadequate impedance matching, as its return loss remains above −10 dB over most of the operating frequency range. The introduction of a decoupling ring structure results in improved impedance matching, evidenced by a deeper S11 response near the target frequency. Incorporating the Defected Ground Structure (DGS) also enhances the antenna performance; however, its standalone effect is relatively limited. The optimal performance is achieved when both the decoupling ring and DGS are simultaneously integrated (Model 2), where the antenna attains a minimum return loss of approximately −30.62 dB at 5.3 GHz. This outcome indicates excellent impedance matching and reduced signal reflection, confirming that the combined structure significantly enhances antenna performance for wearable Wi-Fi–based IoT applications operating at 5.3 GHz.

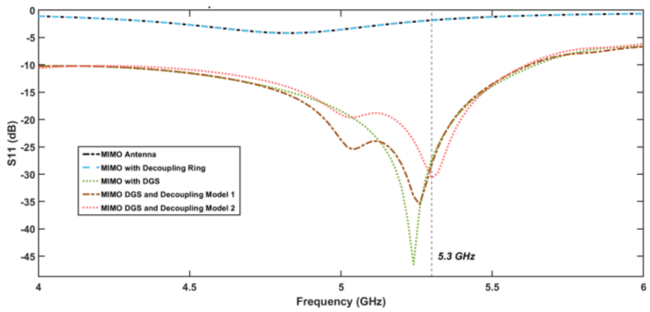


Figure 6. Comparison of Simulated Return Loss Performance in MIMO Antenna Designs

Figure 7 presents a comparative analysis of mutual coupling characteristics for the various configurations of the double-curved MIMO antenna, highlighting their impact on inter-element isolation. The conventional MIMO antenna exhibits relatively poor isolation, with coupling levels of approximately −20 dB, indicating strong electromagnetic interaction between antenna ports. The decoupling ring structure plays an important role in reducing mutual coupling between MIMO antenna elements by interrupting and redirecting coupled surface currents that propagate between adjacent radiators. This mechanism weakens near-field electromagnetic interactions and minimizes undesired energy transfer between antenna ports, resulting in improved isolation, lower correlation, and better diversity performance. The introduction of a decoupling ring structure improves isolation performance, while the incorporation of a Defected Ground Structure (DGS) further suppresses mutual coupling by perturbing surface current distributions. The combined configurations, particularly those integrating both the decoupling ring and DGS techniques (Models 1 and 2), demonstrate the most effective coupling reduction. Among these, Model 2 achieves the highest isolation, attaining a minimum mutual coupling level of −45.67 dB at 5.3 GHz. This result reflects excellent inter-element isolation and minimal signal interference, confirming that the synergistic integration of DGS and a decoupling ring significantly enhances the performance of wearable MIMO antennas operating in the 5.3 GHz IoT band.

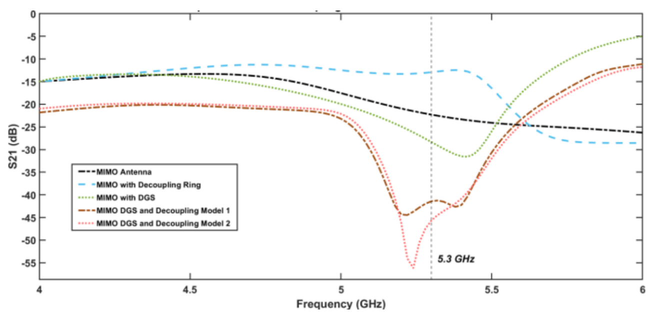


Figure 7. Comparison of Simulated Mutual Coupling Performance in MIMO Antenna Designs

Figure 8 presents the VSWR comparison for different configurations of the double-curved MIMO antenna, illustrating their impedance matching performance. The conventional antenna design exhibits poor impedance matching, with VSWR values exceeding the acceptable limit of 2 across a wide frequency range. The incorporation of the decoupling ring and Defected Ground Structure (DGS) results in a significantly flatter VSWR response that approaches unity, indicating improved impedance matching between the antenna and the feedline. The combined configurations, namely Models 1 and 2 that integrate both DGS and the decoupling ring, demonstrate the most stable and optimized performance around the target operating frequency of 5.3 GHz. Among these, Model 2 achieves the lowest VSWR value of 1.05, indicating near-ideal impedance matching and minimal signal reflection. These findings confirm that the combined implementation of DGS and a decoupling ring substantially enhances the impedance characteristics of the antenna, enabling efficient power transfer for wearable IoT applications operating at 5.3 GHz.

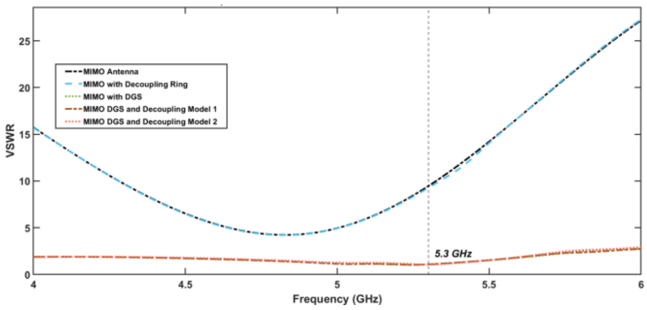


Figure 8. Comparison of VSWR Simulation Results on MIMO

Figure 9 summarizes the simulated total gain performance of several 5.3 GHz MIMO antenna configurations. The conventional antenna structure, which does not incorporate either a decoupling ring or a Defected Ground Structure (DGS), exhibits a negative gain of −6.2 dB, indicating strong mutual coupling and poor radiation efficiency. The inclusion of a decoupling ring alone improves the gain to −4.9 dB, demonstrating its effectiveness in reducing coupling between adjacent radiating elements. In contrast, the implementation of DGS alone results in a gain of 3.53 dB, suggesting that ground-plane modification by itself is insufficient to fully optimize radiation performance. When both the decoupling ring and DGS are simultaneously integrated, the antenna achieves more stable and balanced performance. Specifically, Model 1 attains a gain of 3.34 dB, while Model 2 delivers a slightly higher gain of 3.69 dB. This improvement indicates that the optimized DGS configuration in Model 2 more effectively controls surface current distribution, thereby enhancing the overall performance of the MIMO antenna for wearable IoT applications. The gain enhancement obtained from the implementation of the Defected Ground Structure (DGS) is primarily caused by its capability to alter the surface current distribution and suppress unwanted surface wave propagation on the ground plane, thereby reducing electromagnetic losses and improving radiation efficiency. As a result, more power is effectively radiated in the desired direction, leading to higher antenna gain and improved impedance matching performance.

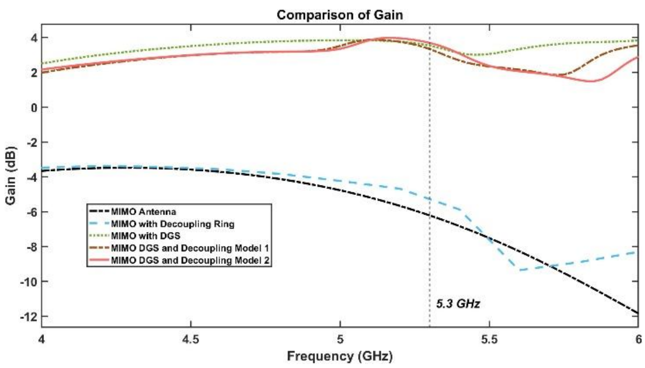


Figure 9. Gain Result of Double Curved MIMO Antenna

Figure 10 illustrates the radiation pattern of the proposed MIMO antenna at 5.3 GHz, highlighting its directional radiation characteristics. The antenna exhibits a predominantly unidirectional radiation pattern, with the main lobe oriented close to 0°, indicating effective concentration of radiated energy in the desired direction. A relatively high front-to-back ratio is observed, signifying substantial suppression of back radiation, which is beneficial for minimizing interference in MIMO systems. Additionally, the smooth and symmetrical radiation profile suggests stable radiation behavior and consistent impedance matching. Overall, the obtained radiation pattern confirms that the antenna achieves adequate directional gain and reduced inter-element coupling, making it well suited for wearable and IoT communication applications that require efficient spatial radiation control.

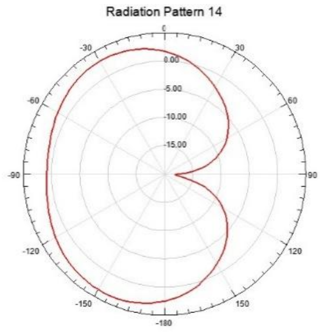


Figure 10. Radiation Pattern on MIMO Antenna

Figure 11 illustrates the performance of the proposed double curved MIMO antenna in terms of Envelope Correlation Coefficient (ECC) and Diversity Gain (DG). The antenna achieves an exceptionally low ECC value of 0.0003, indicating very weak correlation between antenna elements and demonstrating excellent isolation characteristics for MIMO operation. In addition, the obtained Diversity Gain reaches 10 dB, which confirms the antenna's strong capability to improve signal reliability and reduce multipath fading effects. These results demonstrate that the proposed antenna is highly suitable for high-performance wireless communication and wearable IoT applications requiring efficient diversity performance.

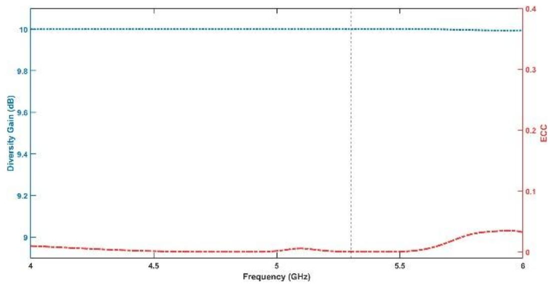


Figure 11. ECC and Diversity Gain on MIMO Antenna

IV. CONCLUSIONS

This study investigates the performance of a double-curved MIMO antenna employing a decoupling ring structure in combination with a Defected Ground Structure (DGS). The optimal reflection coefficient (S_{11}) of −30.62 dB and isolation (S_{21}) of −45.67 dB are achieved in the Model 2 configuration. The combined implementation of the decoupling ring and DGS effectively suppresses mutual coupling between antenna elements, leading to a significant enhancement in overall electromagnetic performance. Furthermore, these techniques contribute to improvements in both antenna gain and bandwidth, with the proposed MIMO antenna attaining a measured gain of 3.57 dB, outperforming conventional designs without coupling-mitigation structures. Such performance enhancements are particularly beneficial for wearable IoT systems operating in the mid-band frequency region around 5.3 GHz, which offers a favorable trade-off between coverage and data capacity. The increased gain enhances signal transmission and reception quality, while the expanded bandwidth supports higher data rates and more reliable communication links. Consequently, the proposed antenna configuration demonstrates strong potential to satisfy the stringent performance requirements of next-generation wearable IoT applications, enabling faster and more reliable wireless connectivity. Future work will emphasize advanced miniaturization approaches, the adaptation of the proposed design for higher-frequency applications including 5G, and comprehensive experimental validation in realistic wearable environments.

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