Journal of Modeling & Simulation in Electrical & Electronics Engineering Vol 6 (2). 61-70.

Semnan University

Journal of Modeling & Simulation in Electrical & Electronics Engineering (MSEEE)

Journal homepage: **https://mseee.semnan.ac.ir/**

ISSN: 2821-0786

Compact Meandered MIMO Antenna with Parasitic Element for Suppressing Mutual Coupling in ISM Band

Elham Atashpanjeh[1] and Pejman Rezaei[1]*

***Abstract*--This paper proposes the design of an antenna array with two closely spaced elements to achieve desired radiation characteristics in the ISM band. First, a microstrip array consisting of two elements that are in front of each other is considered. By varying the length of the current path, the frequency band is moved to 2-6.3 GHz. Furthermore, a parasitic element is placed between two antennas to prevent surface current leakage and reduce mutual coupling to -55 dB. Ultimately, less coupling occurs in the intended band as a result of the proposed structure, which consists of two adjacent meandering antennas with a parasitic element between them. The simultaneous use of both the current path extension technique and the parasitic element for coupling reduction represents a novel approach to achieving the desired radiation characteristics. According to the HFSS software simulation results, the designed structure exhibits an omnidirectional radiation pattern, a gain of -5.23 dB, and a bandwidth of 6.3 GHz, which falls within the UWB structure classification. To validate the simulation results, the final structure is fabricated on a FR4 substrate with a thickness of 1.6 mm, and dimensions of 50×30×1.6mm3. The measurement results validate the simulation model.**

***Index Terms*- MIMO Systems, Decoupling Network, Dual-Element Arrays, Parasitic Element, ISM/GSM Bands, Meandered Array Antenna.**

I. Introduction

The integration of massive MIMO technology with UWB antenna arrays has demonstrated significant potential to meet the increasing demand for higher data rate transmission-based communication systems [1]. This combination has opened up new possibilities for high-speed wireless communication systems [2]–[4]. Thus, microstrip antennas have become a preferred choice for MIMO configurations due to their distinctive qualities, adaptability, and desirable characteristics. Their performance can be further enhanced when integrated with filters, as discussed in [5].

On the other hand, minimization of component size is a critical objective in antenna design. This is driven by the need for compact systems across various applications and the mitigation of mutual coupling effects [6]. Mutual coupling is a critical consideration in antenna array design. This phenomenon, arising from interactions between closely spaced elements, can degrade antenna performance by distorting the radiation patterns. Mutual coupling effects are especially strong in densely packed antenna arrays [7]. Experimental results demonstrate that when antenna elements are separated by less

Received; 2026-01-25 Revised; 2026-04-24 Accepted; 2026-05-04

1. Electrical and Computer Engineering Faculty, Semnan University, Semnan, Iran.
*Corresponding author: prezaei@semnan.ac.ir

Cite this article as:
Atashpanjeh, E. and Rezaei, P. (2026). Compact Meandered MIMO Antenna with Parasitic Element for Suppressing Mutual Coupling in ISM Band. *Journal of Modeling & Simulation in Electrical & Electronics Engineering (MSEEE)*. Semnan University Press . 6 (2), 61-70.
DOI: https://doi.org/10.22075/MSEEE.2026.40375.1248

than half a wavelength (< $\lambda_0/2$), surface wave and near-field coupling effects between adjacent elements significantly impact radiation characteristics [8], [9]. A solution to reduce mutual coupling in patch array antennas was proposed in [10]. Metallic walls and shorting pins were employed in this work to address the issue. An alternative approach, as detailed in [11], was introduced that uses plane spiral orbital angular momentum electromagnetic waves to mitigate mutual coupling within an antenna array.

To address the challenge of mutual coupling between antennas, a variety of decoupling techniques have been investigated in the literature. These methods can be broadly categorized into structural and network-based approaches. Structural techniques involve manipulating antenna configuration and spatial arrangement, while network-based methods employ analytical techniques applied to network parameters [12]. Several studies have investigated structural approaches to mitigate mutual coupling issues. For instance, [13] presents a novel topology for a differential negative group delay circuit utilizing a reverse nested double U-shaped DGS. This approach demonstrates potential for mitigating mutual coupling effects. Additionally, [14] presents a flexible design methodology for microstrip band-stop, high-pass, and band-pass filters using similar DGS concepts. Comprehensive reviews of techniques for mitigating mutual coupling in MIMO antenna systems, with particular emphasis on DGS and parasitic elements, are provided in [15], [16]. Furthermore, [17] presents a detailed investigation of mutual coupling in collocated dipole antenna arrays, emphasizing its impact and potential countermeasures.

Reference [18] presents a millimeter-wave antenna design for 5G communication systems that incorporates MIMO technology through slot/slit etching techniques. The authors emphasize the critical role of mutual coupling reduction in the performance of next-generation wireless networks.

The significance of advanced feed network designs in mitigating mutual coupling is underscored by [19]–[21]. In [19], [20], an efficient Substrate Integrated Waveguide (SIW) feed network is proposed to effectively suppress mutual coupling within a slot array antenna, thereby enhancing overall array performance. Similarly, [21] presents a miniaturized, broadband array antenna incorporating a hybrid feed network that demonstrates improved radiation characteristics through reduced mutual coupling effects.

Decoupling and matching networks have been recognized as effective solutions for mitigating mutual coupling. For instance, reference [22] presents a decoupling and matching network design for a MIMO handset antenna, demonstrating improved antenna isolation and performance. In [23] and [24], Neutralizing lines have been used to reduce mutual coupling between the elements. The authors of [25] introduce a suitable matching and decoupling network for single and dual-band two-element array antennas to optimize performance by minimizing mutual coupling. Additionally, [12] applies a decoupling method to enhance element isolation in a dual-band array antenna, thereby improving overall array performance and reliability. In [26], a novel multipath decoupling circuit is introduced to effectively isolate a compact double-band MIMO receiver. To further enhance MIMO antenna performance, [26] proposes incorporating additional circuitry to mitigate coupling and balance operating bandwidths. Additionally, [28] explores the use of L-loaded E-shaped electromagnetic bandgap structures within array antennas to improve element isolation. These methods, while demonstrating varying degrees of success, highlight the ongoing pursuit of effective mutual coupling mitigation strategies.

Significant mutual coupling can adversely affect antenna array performance, leading to degraded spatial and pattern diversity, poor port isolation, reduced gain and efficiency, as well as increased correlation between elements [29], [30]. The effectiveness of the aforementioned mutual coupling reduction techniques in enhancing the gain and bandwidth of bi-layer beam-scanning array antennas has been studied. Researchers in [31] developed an improved Butler matrix feeding network for such antennas, while [32] focused on refining Butler matrix characteristics for millimeter-wave beam-steering arrays. These approaches also emphasize proper insulation and miniaturization for body-centric applications [33]–[35].

Mutual coupling between closely spaced antenna elements poses a significant challenge in the design of antenna arrays. This paper introduces a novel approach to mitigate this issue by strategically placing a parasitic element within a dual-element microstrip antenna configuration. By effectively redirecting surface currents, the proposed design achieves a substantial reduction in mutual coupling of -55 dB, while simultaneously expanding the operational bandwidth to cover the entire ISM band. This innovative combination of parasitic element integration and current path extension offers a promising solution for improving the performance and reliability of antenna arrays in wireless communication systems. One solution to antenna compression and thus reducing its operating frequency bands is to increase the antenna surface current path length. To reduce the resonant frequency, the current path should be increased. For this purpose, by meandering the modified antenna, a new structure can be achieved that considerably increases the current path. Hence, the antenna's resonant frequency is decreased.

The fundamental innovations of this research can be summarized as follows.

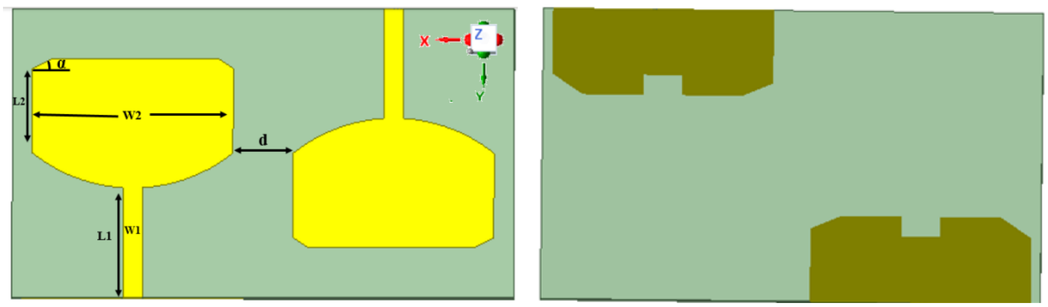
- Strategic placement of a parasitic element to significantly mitigate mutual coupling between antenna elements.
- Novel combination of current path extension and parasitic element integration for expanded bandwidth and reduced coupling.
- Substantial mutual coupling reduction of 55 dB achieved through the proposed design.
- Realization of an omnidirectional radiation pattern for the antenna array.

The subsequent sections of the article are described as follows:

Section 2 provides an elaborate description of the proposed structure, while Section 3 introduces a separator parasitic segment aimed at mitigating mutual coupling. Experimental findings and simulation results are subsequently provided in Section 4 to highlight the effectiveness of the proposed structure. The concluding section summarizes the key findings and implications of the study.

II. . GEOMETRY OF THE PROPOSED ARRAY ANTENNAS

The ISM band is widely used for a wide range of applications [36]. In this design, an antenna is selected that provides proper radiation performance in the given frequency band. Therefore, a two-element microstrip antenna structure is proposed. The initially designed structure was intended to be wideband. To achieve this, the lower edges of each array element were designed with a curved shape. This reduces field fringing at the edges where the feedline connects to the radiating element. Additionally, chamfers were incorporated into the upper corners. A grounded substrate configuration was employed. The substrate material was FR4 (50mm×30mm) with a thickness of 1.6 mm. The antenna arrangement is shown in Fig.1. The proposed structure dimensions are defined as W_1 = 2 mm, W_2 = 20 mm, L_1= 10 mm, L_2 = 12 mm, d= 3mm, alpha = 27°, and d= 2 mm.



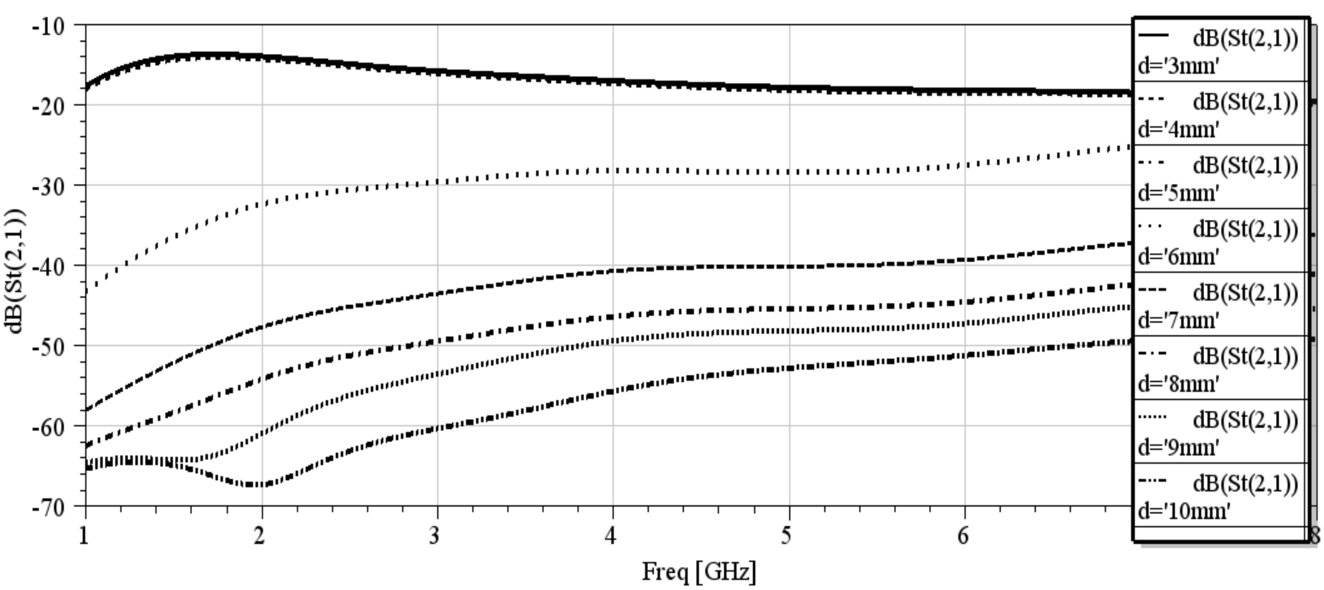
(a) (b)

Fig 1. Planned microstrip array antennas: (a) Top view, (b) Back view.

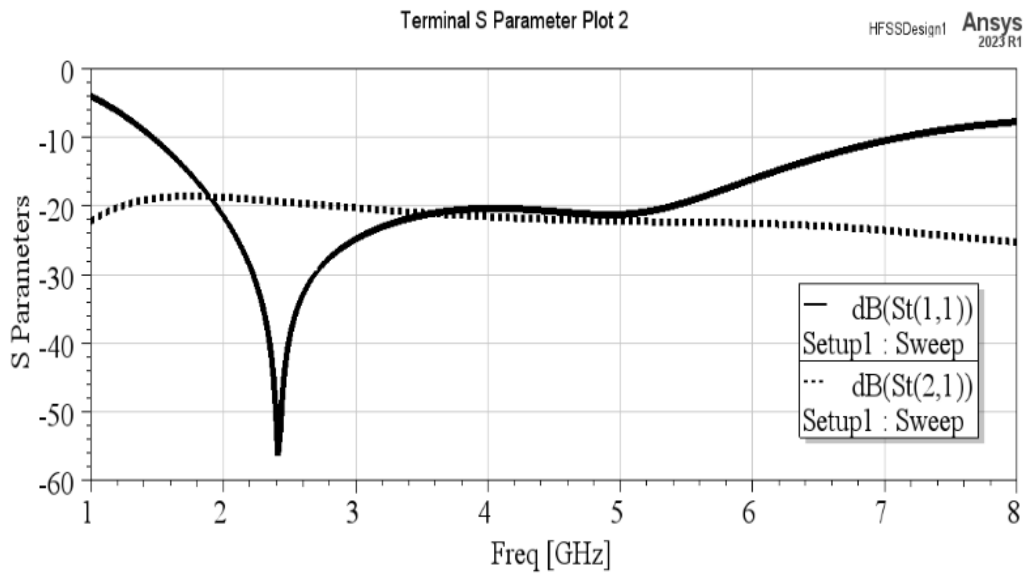
To facilitate a deeper understanding of mutual coupling, a brief definition is provided .As mentioned, the electromagnetic fields from one antenna element can induce currents in nearby elements when multiple antennas are in proximity.

Typically, the mutual coupling between elements *i* and *j* is assumed to be proportional to the parameter *S* between the corresponding elements. Considering an array, let us denote its scattering matrix $[S]$, $S_{ij}(i \neq j)$ indicates the mutual coupling, which ideally should be $S_{ij}(i \neq j) = 0$ for $i, j = \{0,1,2,3,\dots\}$. In this case, the array elements would operate independently, demonstrating the best radiation characteristics. However, achieving a zero value for the scattering parameter on the off-diagonal elements of the scattering matrix is not feasible in practice. Therefore, by altering the structure, reducing this value as close to zero as possible will significantly minimize the coupling between elements.

where *d* represents the distance between the two elements. To achieve the smallest possible structure, the distance *d* is set to its minimum possible value. Furthermore, the variation in the scattering parameter with different values of *d* is shown in Fig.2.



(a)



(b)

Fig 2. The simulation outcomes of the proposed array antenna, (a) Simulation results coupling *S*-parameter variations for different ES, (b) Scattering parameter analysis (*d*=3mm).

Fig.2. The simulation outcomes of the proposed array antenna, (a) Simulation results coupling *S*-parameter variations for different ES, (b) Scattering parameter analysis (*d*=3mm).

To evaluate the effectiveness of the proposed coupling reduction technique, the element spacing has been initially set to maximize initial coupling between the elements. As shown in Fig.2., the maximum mutual coupling occurs at d=3m. Subsequently, by employing the techniques introduced in the following sections, this coupling was significantly reduced. The current distribution of the two elements must be analyzed in order to reduce the bandwidth and adjust it to the desired frequency.

A. Current Distribution Analysis

Analyzing the current distribution of the elements provides valuable information, including identifying regions of high and low current concentration and understanding mutual coupling effects between array elements, enabling the design of appropriate structures to reduce coupling. The current distribution of the elements offers insights into the radiation characteristics of the antenna, including regions of high and low current density. This information is crucial for understanding mutual coupling effects and designing effective coupling-reduction techniques. Fig. 3. shows the current distribution on the antenna surfaces at 2.4 GHz.

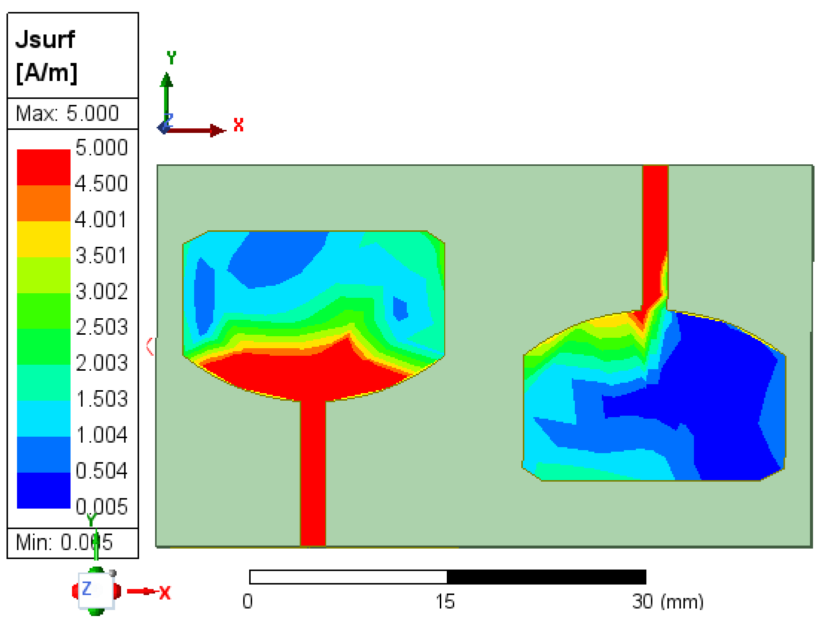


Fig 3. The current distribution of the antenna surfaces at 2.4 GHz.

Current distribution analysis indicates minimal current density at the target resonant frequency. Removing elements with negligible radiation impact is anticipated to have minimal influence on the overall radiation pattern. By extending the current path through a meandering configuration, the operating bandwidth can be reduced while preserving a compact form factor.

B. Proposed Meandered Structure

To reduce bandwidth, as previously mentioned, parts that have less impact on radiation and where the current distribution is less concentrated can be removed. By meandering the structure, the current can be passed through the removed areas without increasing the antenna size, but it increases the current path. In Fig. 4, the meandered antenna configuration and its current distribution are shown.

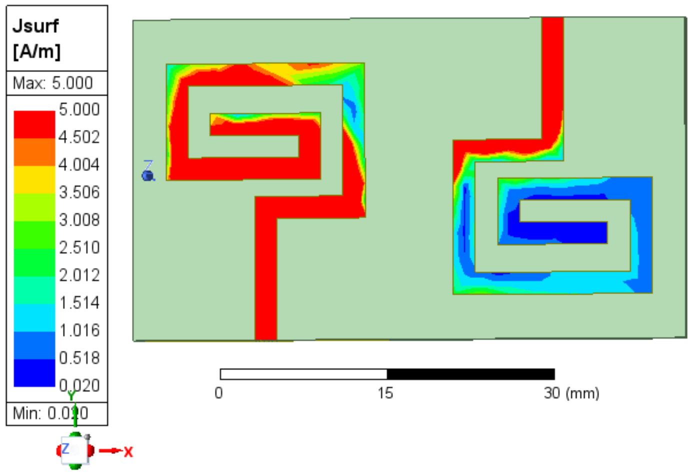


Fig 4. The current distribution of the meandered array antenna.

It is clearly observed that the current which flows on the surface of the meandered elements, leading to an improvement in the radiation characteristics. The scattering parameter plots are shown in Fig. 5(a). However, it is still observed that when port 1 is turned on, electric current is injected into element 2, and the S_{21} parameter, which indicates the mutual coupling between the two elements, has a high value, which is undesirable. The simulation results are as follow: minimum S_{11}=-48 dB (at 4.38GHz), minimum S_{21}=-19dB, Bandwidth= 4.15GHz and maximum Gain=5.95 dB (at 2.4 GHz).

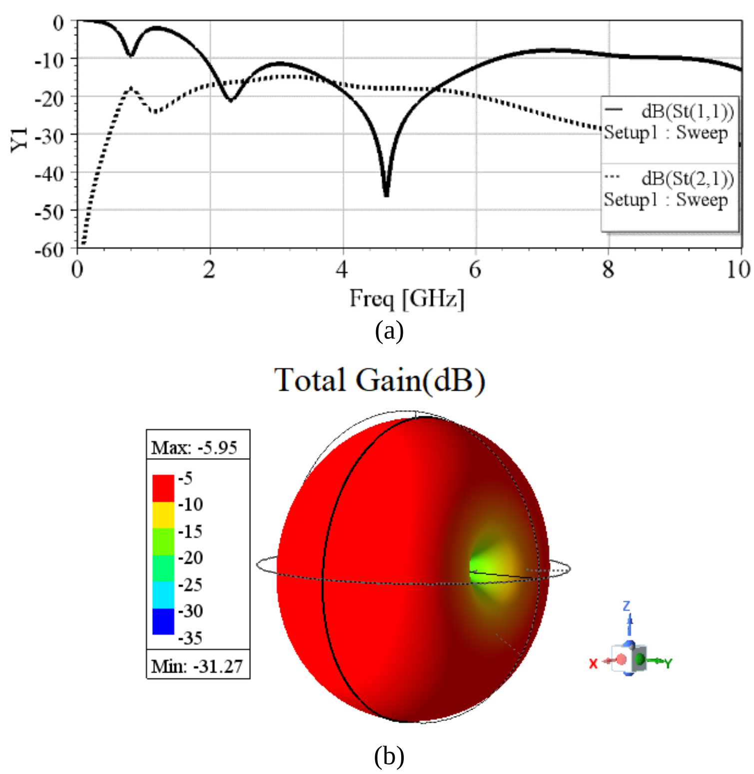


Fig 5. The simulation outcomes of the meandered array antenna at 2.4 GHz: (a) Scattering parameter analysis, (b) Radiation pattern analysis.

In the next section, the application of the technique used in this paper and the reduction of mutual coupling effects will be described.

III. Mutual Coupling Reduction via Parasitic Element Insertion

As previously mentioned, one method to reduce mutual coupling between two elements in an antenna array is to place a parasitic element between them. This parasitic element, by absorbing part of the energy, reduces interference between the two main elements, thereby reducing mutual coupling effects in the optimized structure. A parasitic element is placed between the antennas to prevent surface current leakage. The parasitic element acts as a shield between the two elements, creating a parallel path for the induced surface current. The dimensions of the parameters defined in the proposed structure are described in Table I.

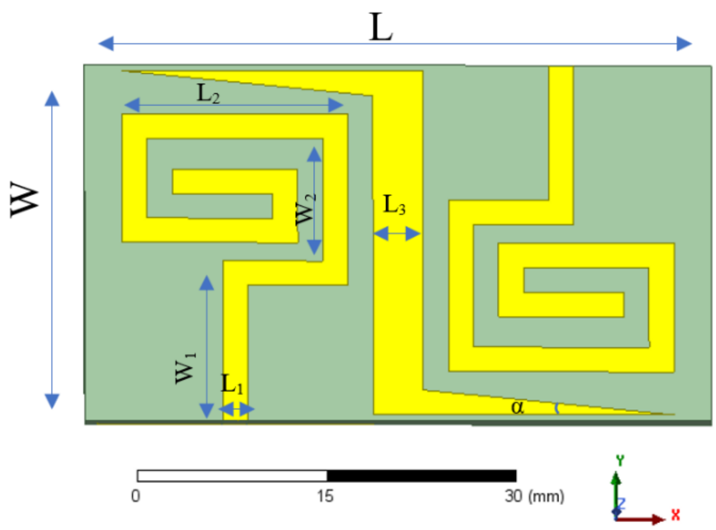
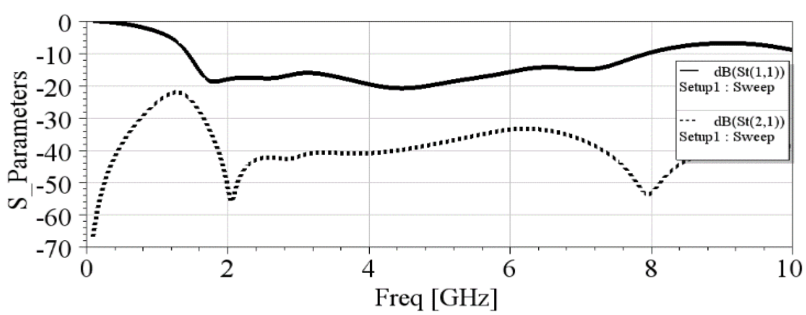


Fig 6. The structure of the proposed array antenna with the placement of parasitic element.

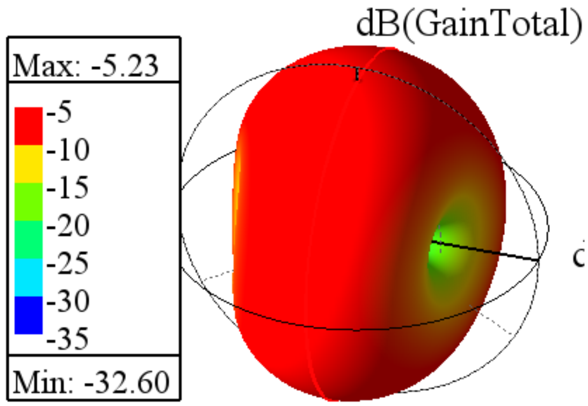
TABLE I
The Dimension of the Proposed Structure

Parameters	Value	Parameters	Value
L	50mm	L3	4mm
W	30mm	W1	13mm
L1	2mm	W2	10mm
L2	18mm	α	15^0

When element 1 is radiating, the parasitic current in element 2 is very low, and the parasitic element effectively reduces the interference between the two elements. The microstrip patch antenna array is simulated in HFSS software. Fig. 7a illustrates the scattering matrix results obtained from the simulation. The S_{11} and S_{21} parameters represent the reflection and transmission coefficients, respectively. As shown in Fig. 7, the antenna exhibits a good match to the transmission line at the frequency band. The final design demonstrates an Ultra-Wide Bandwidth (UWB), thereby fully covering the ISM band. The minimum S_{11} and S_{21} are -20 dB and -55 dB, respectively, and the bandwidth is 6.3 GHz. Also, the maximum Gain is -5.23 dB, and the radiation pattern is omnidirectional at 2.4 GHz.



(a)



(b)

Fig 7. The simulation outcomes of the final structure at 2.4 GHz: (a) Scattering parameter analysis, (b) Radiation pattern analysis.

To clarify, the gain of the antenna prior to applying the coupling-reduction technique was −5.95 dB, and after implementing the proposed method, it improved to −5.23 dB. This 0.72 dB increase demonstrates that, unlike certain decoupling techniques that inherently lead to noticeable gain degradation, the proposed approach effectively preserves the antenna gain while reducing coupling. Maintaining the gain at an acceptable level ensures the overall performance of the system, as energy losses are minimized and radiation in the desired directions is reinforced. It is also worth noting that the achieved gain values fully meet the requirements for in-body medical applications.

To evaluate the effectiveness of the applied method, the current distribution on the conductor surfaces was simulated. As shown in Fig. 8, the placement of the element between the two antennas has effectively prevented current leakage to the adjacent element.

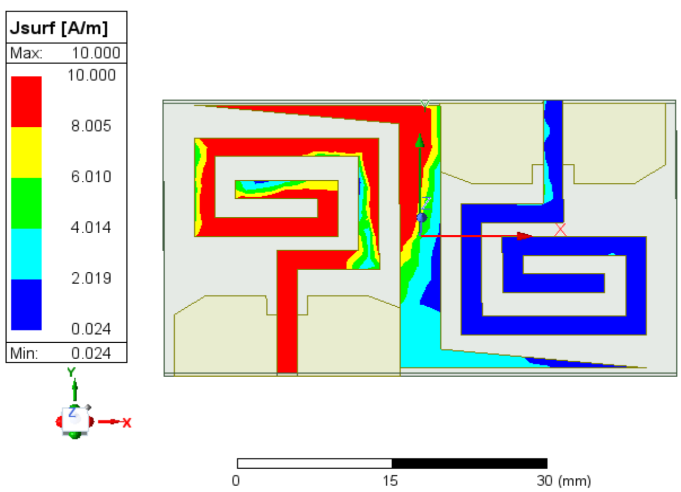


Fig 8. The current distribution of the proposed decoupled array antenna.

As shown in Fig. 7, when element 1 is radiating, the parasitic current in element 2 is very low, and the parasitic element effectively reduces the interference between the two elements.

The results show that in the initial structure, the current paths are clearly directed toward the adjacent antenna element, indicating the presence of significant mutual coupling. After introducing the neutralization line between the two antenna elements, the surface current on the neighboring antenna is considerably reduced. This technique effectively optimizes the undesired current paths, leading to a noticeable reduction in the leaked currents in the region between the antennas. Furthermore, the current on the excited element (main antenna) remains strong, while the unwanted coupled currents are significantly suppressed. These observations confirm the effectiveness of the proposed decoupling structure.

IV. Implementation

To validate the simulation results, the designed microstrip array antenna was fabricated and tested. The measured results demonstrate excellent agreement with the simulated results. This confirms the accuracy of the simulation model and the effectiveness of the design approach.

Fig 9. Implementation of final proposed structure and test processing.

The measurement outcomes demonstrate the effectiveness of this methodology on practical antennas, as shown in Fig. 10. The empirical findings support the simulation results, confirming the desired accuracy of the method. It is worth mentioning that the measured outcomes of the scattering parameters (rather than the frequency response of the structure) differ slightly from the simulations. This discrepancy can be attributed to testing conditions such as the connected connector and fabrication precision.

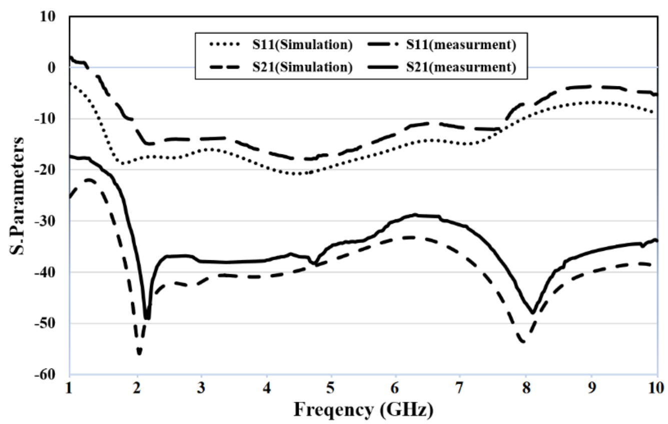


Fig 10. *S*-parameters results, including S_{21} and S_{11} simulated and measurement results.

In Table II, the results of the suggested decoupling method have been compared with those from another reported research with different Coupling Reduction Methods (CRM). Consequently, the technique proposed in this paper effectively suppresses the mutual coupling phenomena and offers compact structures suitable for certain aperture distributions.

TABLE II
Comparison of the Suggested Mutual Coupling Reduction with Another Published Research

Ref.	Year	ES (λ)	S_{21} improvement (dB)	Array	CRM
Proposed	2024	0.16	-55	1 × 2	Parasitic element Adding
[2]	2022	0.09	-21	1 × 2	H-shape parasitic structures
[6]	2024	0.18	-36	1 × 2	EBG and DGS
[23]	2025	0.16	-27	1 × 2	Neutralizing line
[24]	2025	0.13	-32.84	1 × 8	Neutralizing line
[37]	2024	0.16	-22 (2.45 GHz) -27 (5.4 GHz)	1 × 2	Parasitic element adding (Dual bands)
[38]	2017	0.83	-16	1 × 2	Metamaterial
[39]	2017	0.08	-30	1 × 2	ADS
[40]	2016	0.72	-20	7 × 3	Asymmetrical coplanar strip wall
[41]	2014	0.05	< -40	1 × 2	Slot-combined CSRR
[42]	2011	0.50	< -20	1 × 2	FSRR
[43]	2011	0.72	< -20	7 × 3	Metamaterial

V. Conclusion

This paper presented a novel approach to mitigating mutual coupling in dual-element antenna arrays operating within the ISM band. By strategically incorporating a parasitic element and optimizing the current path, a significant reduction in mutual coupling was achieved. Increasing the current path is investigated by examining the current distribution in the primary structure and by using the meander technique on the radiating element .The resulting antenna design exhibited desirable characteristics such as wide bandwidth (1.7GHz – 8GHz), minimum mutual coupling -55dB, and omnidirectional radiation patterns (maximum gain -5.23 dB). The proposed methodology offered a promising solution for addressing mutual coupling challenges in compact antenna systems, with potential for further exploration and refinement in future research.

Acknowledgments

This research was supported by Semnan University. The authors would like to thank all the members of the antenna laboratory at the Iran Telecommunication Research Center (ITRC) for their cooperation. Also, the authors would like to thank the editor and reviewers for their constructive comments.

Disclosure statement

The authors reported no potential conflict of interest.

Funding

No funding was received for this research.

REFERENCES

[1]P. K. Choudhury and M. A. El-Nasr, “Massive MIMO toward 5G,” *J. Electromagn. Waves Appl.*, vol. 34, no. 9, pp. 1091–1094, Jun. 2020.
[2]D. Jing and H. Li, “A Compact Dual-Band Two-Element Implantable MIMO Antenna for Biotelemetric Applications,” *IEEE MTT-S Int. Microw. Work. Ser. Adv. Mater. Process. RF THz Appl. IMWS-AMP 2022 - Proc.*, 2022.
[3]C. S. Ankireddy, T. S. Reddy, and B. T. P. Madhav, “Design and verification of an umbrella shaped narrow band - UWB antenna pair for MIMO applications using characteristic mode analysis,” *e-Prime - Adv. Electr. Eng. Electron. Energy*, vol. 8, p. 100545, Jun. 2024.
[4]G. Hu, Q. Wu, K. Xu, J. Si, and N. Al-Dhahir, “Secure Wireless Communication via Movable-Antenna Array,” *IEEE Signal Process. Lett.*, vol. 31, pp. 516–520, 2024.
[5]P. Rezaei, A. Valizade, J. Nourinia, M. Solimanejad, F. Alizadeh, B. Mohammadi, "Design of a triple-band compact microstrip monopole antenna using multiple bent-lines with low correlation for MIMO applications," 24th Iranian Conf. on Electrical Engineering, Shiraz, Iran, pp. 768-771, May 2016.
[6]W. Chang, S. Chen, K. Chen, P. Yu, and Q. H. Liu, “Mutual coupling reduction in antenna arrays using the novel mushroom electromagnetic band gap and defected ground structure,” *Microw. Opt. Technol. Lett.*, vol. 66, no. 2, p. e34084, Feb. 2024.
[7]H. Nimehvari Varcheh and P. Rezaei, “Integration of the modified Butler matrix and decoupling network for beam-steering antenna array,” *Int. J. RF Microw. Comput. Eng.*, vol. 32, no. 3, 2022.
[8]Y. A. S. Dama *et al.*, “An envelope correlation formula for (N, N) MIMO antenna arrays using input scattering parameters, and including power losses,” *Int. J. Antennas Propag.*, vol. 2011, 2011.
[9]S. Khani, M. Danaie, P. Rezaei, A. Shahzadi, “Compact ultra-wide upper stopband microstrip dual-band BPF using tapered and octagonal loop resonators,” Frequenz, vol. 74, no. 1-2, pp. 61-71, Jan. 2020.
[10] A. Habibi Daronkola, F. Tavakol Hamedani, P. Rezaei, A. Pesarakloo, S. A. Khatami, “Studying superposition of multiple OAM modes for beam concentration using circular arrays for long-range communication,” Int. J. of RF Microwav. Computer-Aided Eng., vol. 32, no. 11, 23331, November 2022.
[11] A. Habibi Daronkola, F. Tavakkol Hamedani, P. Rezaei, and N. Montaseri, “Mutual coupling reduction using plane spiral orbital angular momentum electromagnetic wave,” *J. Electromag. Waves Appl.*, vol. 36, no. 3, 2022.
[12] E. Atashpanjeh and P. Rezaei, “Applying decoupling method to a dual-band antenna array for element isolation.,” *Model. Simul. Electr. Electron. Eng.*, vol. 1, no. 4, pp. 1–5, 2022.
[13] Z. Wang, Z. Wang, H. Liu, and S. Fang, “Differential Negative Group Delay Circuit Topology with Reverse Nested Double U-Shaped Defected Ground Structure,” *Prog. Electromagn. Res. C*, vol. 132, 2023.
[14] W. Yuan, X. Liu, H. Lu, W. Wu, and N. Yuan, “Flexible Design Method for Microstrip Bandstop, Highpass, and Bandpass Filters Using Similar Defected Ground Structures,” *IEEE Access*, vol. 7, 2019.
[15] A. Kumar, A. Q. Ansari, B. K. Kanaujia, J. Kishor, and L. Matekovits, “A Review on Different Techniques of Mutual Coupling Reduction Between Elements of Any MIMO Antenna. Part 1: DGSs and Parasitic Structures,” *Radio Science*, vol. 56, no. 3. 2021.
[16] O. Elalaouy, M. El Ghzaoui, and J. Foshi, “Mutual coupling reduction of a two-port MIMO antenna using defected ground structure,” *e-Prime - Adv. Electr. Eng. Electron. Energy*, vol. 8, p. 100557, Jun. 2024, doi: 10.1016/J.PRIME.2024.100557.
[17] A. S. Adesoye, J. J. Popoola, and A. O. Fadamiro, “Mutual coupling in a collocated dipole antenna setup: a comprehensive review,” *J. Multidiscip. Eng. Sci. Technol.*, vol. 8, pp. 2458–9403, 2022.
[18] B. R. Devi, C. Niharika, A. M. Lakshmi, D. Jayaram, and B. Tarun, “Design of a Millimeter Wave Antenna Using MIMO for 5G Applications,” in *IEEE 2nd International Conference on Applied Electromagnetics, Signal Processing, and Communication, AESPC 2021 - Proceedings*, 2021, pp. 1–7.
[19] A. A. Diman *et al.*, “Efficient SIW-feed network suppressing mutual coupling of slot antenna array,” *IEEE Trans. Antennas Propag.*, vol. 69, no. 9, 2021.
[20] T. Kumar, M. Agrawal, and K. Saraswat, “A substrate-integrated waveguide-based wideband circularly polarized slot antenna using the parasitic square patch array,” *J. Electromagn. Waves Appl.*, 2024.
[21] Z. Mousavi Razi, P. Rezaei, “Fabry Perot cavity antenna based on capacitive loaded strips superstrate for X-band satellite communication,” Advanced Radar Systems Journal, vol. 2, no. 1, pp. 26-30, Dec. 2013.
[22] R. Kormilainen, R. Luomaniemi, A. Lehtovuori, and V. Viikari, “A Lumped-Element Decoupling and Matching Network for a Four-Element Mobile Handset MIMO Antenna,” *Int. J. Antennas Propag.*, vol. 2019, 2019.
[23] E. Atashpanjeh and P. Rezaei, “Innovative design for mutual coupling reduction in dual-element array antennas for ISM applications using whale optimization algorithm,” Prog. Electromagn. Res. C, 152, (2025): 121–129.
[24] E. Atashpanjeh, P. Rezaei. "Chebyshev antenna array miniaturization with aperture feeding based on effective neutralizing line design for mutual coupling reduction." Journal of Modeling in Engineering, 2026.
[25] K. Da Xu, H. Luyen, and N. Behdad, “A Decoupling and Matching Network Design for Single-and Dual-Band Two-Element Antenna Arrays,” *IEEE Trans. Microw. Theory Tech.*, vol. 68, no. 9, 2020.
[26] H. V. Singh, D. V. S. Prasad, and S. Tripathi, “Dual-band MIMO antenna decoupling using vias based multipath decoupling circuit,” *Microw. Opt. Technol. Lett.*, vol. 64, no. 4, 2022.
[27] A. Omidvar, P. Rezaei, and E. Atashpanjeh, “Mutual coupling reduction with Peyton Turtle pattern nearfield surface for MIMO patch antenna,” *Frequenz*, vol. 77, no. 7–8, 2023.
[28] T. Jiang, T. Jiao, and Y. Li, “Array Mutual Coupling Reduction Using

L-Loading E-Shaped Electromagnetic Band Gap Structures," *Int. J. Antennas Propag.*, vol. 2016, 2016.

[29] W. J. Wu, Y. F. Cheng, S. Chen, C. Wei, and G. Wang, "Decoupling and bandwidth equalization for MIMO antennas by using novel network design," *Microw. Opt. Technol. Lett.*, vol. 64, no. 8, 2022.

[30] K. H. Chen and J. F. Kiang, "Effect of mutual coupling on the channel capacity of MIMO systems," *IEEE Trans. Veh. Technol.*, vol. 65, no. 1, 2016.

[31] A. Parsa, P. Rezaei, A. AmneElahi, S.A. Khatami, Z. MousaviRazi, "Efficient transition from SMA to ESIW for planar slot array antennas in wireless systems," Analog Integrated Circuits and Signal Processing, vol. 125, no. 1, pp. 18, 2025.

[32] Z. MousaviRazi and P. Rezaei, "Millimetre-wave beam-steering array antenna by emphasising on improvement of Butler matrix features," *IET Microwaves, Antennas Propag.*, vol. 13, no. 9, 2019.

[33] E. Atashpanjeh and A. Pirhadi, "Design of wideband monopole antenna loaded with small spiral for using in wireless capsule endoscopy systems," *Prog. Electromagn. Res. C*, vol. 59, 2015.

[34] E. Atashpanjeh and P. Rezaei, "Broadband Conformal Monopole Antenna Loaded with Meandered Arms for Wireless Capsule Endoscopy," *Wirel. Pers. Commun.*, vol. 110, no. 4, 2020.

[35] M. Karami, P. Rezaei, S. Kiani, R.A. Sadeghzadeh, "Modified planar sensor for measuring dielectric constant of liquid materials," Electronics Letters, vol. 53, no. 19, pp. 1300–1302, Sep. 2017.

[36] S. Majumder *et al.*, "Isolation enhancement of the F-shaped four-port MIMO antenna for WiMAX, Wi-Fi, WLAN and ISM band applications using dielectric material," *J. Electromagn. Waves Appl.*, 2024.

[37] W. A. Awan, T. Islam, F. N. Alsunaydih, F. Alsaleem, and K. Alhassoonc, "Dual-band MIMO antenna with low mutual coupling for 2.4/5.8 GHz communication and wearable technologies," *PLoS One*, vol. 19, no. 4, p. e0301924, Apr. 2024.

[38] X. Zhu, X. Yang, Q. Song, and B. Lui, "Compact UWB-MIMO antenna with metamaterial FSS decoupling structure," *EURASIP J. Wirel. Commun. Netw.*, vol. 2017, no. 1, p. 115, Dec. 2017.

[39] K.-L. Wu, C. Wei, X. Mei, and Z.-Y. Zhang, "Array-Antenna Decoupling Surface," *IEEE Trans. Antennas Propag.*, vol. 65, no. 12, pp. 6728–6738, Dec. 2017.

[40] H. Qi, L. Liu, X. Yin, H. Zhao, and W. J. Kulesza, "Mutual Coupling Suppression between Two Closely Spaced Microstrip Antennas with an Asymmetrical Coplanar Strip Wall," *IEEE Antennas Wirel. Propag. Lett.*, vol. 15, 2016.

[41] Z. Qamar, L. Riaz, M. Chongcheawchamnan, S. A. Khan, and M. F. Shafique, "Slot combined complementary split ring resonators for mutual coupling suppression in microstrip phased arrays," *IET Microwaves, Antennas Propag.*, vol. 8, no. 15, 2014.

[42] A. Habashi, J. Nourinia, and C. Ghobadi, "Mutual coupling reduction between very closely spaced patch antennas using low-profile folded split-ring resonators (FSRRs)," *IEEE Antennas Wirel. Propag. Lett.*, vol. 10, 2011.

[43] M. C. Tang, S. Xiao, B. Wang, J. Guan, and T. Deng, "Improved performance of a microstrip phased array using broadband and ultra-low-loss metamaterial slabs," in *IEEE Antennas and Propagation Magazine*, 2011, vol. 53, no. 6.