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Performance Enhancement of a Compact Tri-Band Microstrip Rectangular Patch Antenna for 5G Applications

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ABSTRACT

This paper presents a high-performance tri-band Microstrip Rectangular Patch Antenna (MRPA) designed for Fifth Generation (5G) applications. The design addresses the inherent limitations of conventional microstrip antennas, particularly their low gain and narrow bandwidth, while retaining a compact and lightweight structure. The antennas were designed and simulated in Computer Simulation Technology (CST) Studio Suite using a Rogers RT5880 substrate with a thickness of 0.508 mm^3, a relative permittivity of 2.2, and a loss tangent of 0.0009. To enhance performance, an I-shaped slot was strategically introduced in the patch between inverted T-slots, and Complementary Split Ring Resonators (CSRRs) were embedded in the Defected Ground Plane (DGP). This integration resulted in a 25% reduction in antenna size, alongside improvements in bandwidth. The reference MRPA with DGP and slots resonated at 10.08 GHz, 28.40 GHz, and 38.20 GHz, achieving bandwidths of 0.23 GHz, 0.74 GHz, and 1.97 GHz with gains of 6.32 dB, 9.08 dB, and 9.68 dB, respectively. After implementing the proposed modifications, the antenna resonated at 10.12 GHz, 28.72 GHz, and 38.20 GHz, with bandwidths increased to 0.25 GHz, 0.76 GHz, and 3.63 GHz (enhancements of 9%, 3%, and 84%), corresponding to gains of 6.45 dB, 9.21 dB, and 8.89 dB. A maximum radiation efficiency of 95% was recorded at 38.20 GHz in both antennas. These results demonstrate that the proposed DGP-Slotted and CSRR-loaded MRPA antenna significantly reduces size and increases bandwidth, making it a suitable choice for compact 5G wireless communication devices.

Keywords: Antenna Miniaturization; Antenna Gain; Bandwidth Enhancement; Complementary Split Ring Resonator; Computer Simulation Technology; Defected Ground Plane; Fifth Generation; Microstrip Patch Antenna; Radiation Efficiency; Slot Design.

1. Introduction

Over the past four decades, the wireless and mobile industry has experienced rapid growth, moving from analog 1G systems to digital 2G Global System for Mobile Communications (GSM), and then progressing to 3G, 3.5G, and 4G Long Time Evolution (LTE) systems, which offer high data rate cellular networks [1]. Initially, 1G devices were relatively lightweight but expensive compared to their predecessors. Then, 2G mobile phones implemented GSM technology, which utilized digital modulation to improve voice quality and offer limited data services. The introduction of 3G networks allowed users to use voice, graphics, and video on mobile devices. Modern 4G technology, found in current cell phones and handheld devices, has been widely adopted globally [2]. However, even in 4G systems, spectrum scarcity and power consumption remain challenges. Current 4G-LTE networks have the potential to achieve performance improvements exceeding 20 times their current levels. Still, radio propagation path loss models suggest that highly directional antenna systems are necessary for effective point-to-point communication. Research on 5G wireless systems began addressing these challenges in 2020 [3].

The current 5G wireless mobile communication system is expected to offer unique capabilities, such as higher data rates transmission and lower latency communication [4]. As the demand for wireless applications increases, spectrum scarcity remains an issue, prompting the exploration of new frequency bands. Present 5G networks have transformed the field by offering more services and benefits than 4G, globally connecting devices to form a worldwide wireless web [5]. This technology has enabled users to access high-bandwidth connections, opening new possibilities, such as connecting phones to laptops for broadband internet access. The Microstrip Patch Antenna

(MPA) is crucial in this rapidly expanding sector, and any progress in wireless communication is closely tied to advancements in microstrip antenna technology. To facilitate communication at higher frequency bands, antennas must be compact, conformal, cost-effective, and easy to fabricate. Printed antennas are favored for meeting these requirements [6].

Despite the significant advantages of MPA antennas, they have notable drawbacks, particularly their narrow bandwidth, which is typically between 3% and 6% of the operating frequency, with low gain and efficiency. These limitations reduce their suitability for many wireless applications, especially in handheld devices like smartphones [7]. To address these challenges, numerous researchers have proposed various techniques to improve the gain, bandwidth, and efficiency of MPAs. On the other hand, multi-band antenna designs offer notable benefits, including space saving, reduced interference, and improved signal quality. These advantages enhance communication reliability, making multi-band antennas essential for the seamless integration of 5G technology in portable devices [8].

For performance enhancement, [9] developed a tri-band MPA printed on Rogers RT substrate, with dimensions of 3.4 mm × 4.13 mm × 0.25 mm, achieving gains of 6.65 dB at 24.4 GHz, 7.02 dB at 28 GHz and 5.05 dB at 38 GHz, with efficiencies of 85.37%, 86.50%, and 73.30%, respectively, suitable for 5G applications. [2] designed a tri-band microstrip-line-fed MPA with dimensions of 20 mm × 16.5 mm × 0.508 mm for 5G applications, using a pair of inverted T slots and a partial ground plane technique, achieving gains of 5.67 dB at 10 GHz, 9.33 dB at 28 GHz, and 9.57 dB at 38 GHz, with a maximum efficiency of 92% at 38 GHz. [10] fabricated a CSRR-loaded T-shaped Multiple Input Multiple Output (MIMO) antenna with a gain of 6.4 dB at 28 GHz for 5G vehicular and cellular communications on a 12 mm x 25.4 mm x 0.8 mm Rogers RT substrate. [11] investigated a 15 mm × 15 mm × 1.52 mm high-gain CSRR-loaded MIMO patch antenna for wireless 5G devices, achieving gains of 8.65 dB at 28 GHz and 8.24 dB at 38 GHz. Moreover, [12] presented a tri-band MRPA using a binary-coded genetic algorithm, with computations and simulations performed using MATLAB and HFSS. The tri-band antenna operated at frequencies of 28 GHz, 40 GHz, and 47 GHz, providing peak directivities of 7.7 dB, 12.1 dB, and 8.2 dB and corresponding efficiencies of 61.2%, 44.5%, and 59.3%. In [13], a compact tri-band MPA was designed on Rogers RT substrate, measuring 12 mm × 12 mm × 0.8 mm, providing gains of 7.18 dB at 15.2 GHz, 5.79 dB at 23 GHz, and 6.72 dB at 29.8 GHz, with an overall efficiency of 95% for 5G applications.

In this study, an enhanced tri-band MRPA was developed to achieve high performance in the 10, 28, and 38 GHz bands for 5G portable devices. This improvement was achieved by modifying the design of [2]. The objective was to significantly enhance the antenna's bandwidth, efficiency, and gain by adding an extra I-slot in the patch and CSRRs in the ground, while optimizing the existing partial ground plane and inverted T-slots of the tri-band antenna. These modifications contributed to size reduction and improved overall performance. Finally, a comparative analysis was performed with previously developed multiband MPAs.

1.1. Study objectives

1. To design a tri-band DGP-Slotted MRPA antenna operating at 10 GHz, 28 GHz, and 38 GHz for 5G wireless communication.

2. To analyze the performance of the DGP-Slotted MRPA antenna in terms of bandwidth, gain and radiation efficiency using CST Studio Suite.

3. To integrate CSRRs into the DGP of the Slotted MRPA antenna using CST Studio Suite.

4. To evaluate the impact of the integrated slots and CSRRs into a unified MRPA design on antenna size reduction, gain enhancement, and bandwidth improvement for 5G applications.

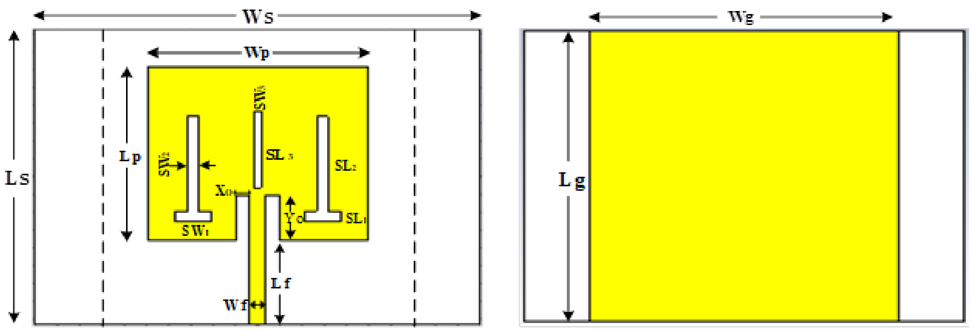
5. To compare the simulated results of the DGP-Slotted MRPA with the integrated MRPA and other previous work in literature to identify the most suitable configuration for 5G applications.

2. Antenna Design

This study utilized a design approach based on rectangular patch antennas, similar to [2], [8], [14], [15]. The selected antennas feature rectangular patches with slots in inverted T and I combinations, along with partial ground planes to improve control over gain and other radiation characteristics. Inset feeding was selected among various feeding methods for MPAs to achieve optimal impedance matching between the feed line and the radiating patch. These antennas were designed using CST Studio Suite 2018 with a Rogers RT5880 substrate, which has a relative dielectric permittivity (ε_r) of 2.2 and a loss tangent (tan δ) of 0.0009. For further details on the properties of the Rogers RT5880 substrate, refer to [2], [16].

Table 1. Optimal dimensions of the inset fed, DGP, and slots of the antenna design (in millimeters)

Parameter	Ls=Lg	Ws	Wg	L_p	W_p	L_f	W_f	SL_I	SW_I	SL_2	SW_2	SL_3	SW_3	Y_O	X_O
Dimension	16.50	20.00	14.00	9.6	10.0	4.75	0.7	0.60	1.60	5.30	0.50	5.30	0.30	4.75	0.70



(a) Front view (b) Back view

Figure 1(a-b). The design geometry of the proposed tri-band 5G antenna

Figure 1(a-b) shows the DGP-slotted MRPA designed on a 20 mm × 16.5 mm × 0.508 mm Rogers RT substrate. The rectangular patch measuring 9.7 mm × 9.9 mm is fed by a microstrip line with a width of 0.7 mm and a length of 4.75 mm at 50 Ω. A partial ground plane is centered opposite the patch on the back of the substrate. Table 1 contains the optimized dimensions of the partial ground plane, different slots, and the inset feed of the proposed tri-band antenna.

Figure 2(a-c) presents the integrated slots and CSRR-loaded MRPA designed on a 15.5 mm × 16 mm × 0.508 mm Rogers RT5880 substrate. The rectangular patch measures 9.6 mm × 10.0 mm × 0.035 mm, and is fed by a 4.75 mm

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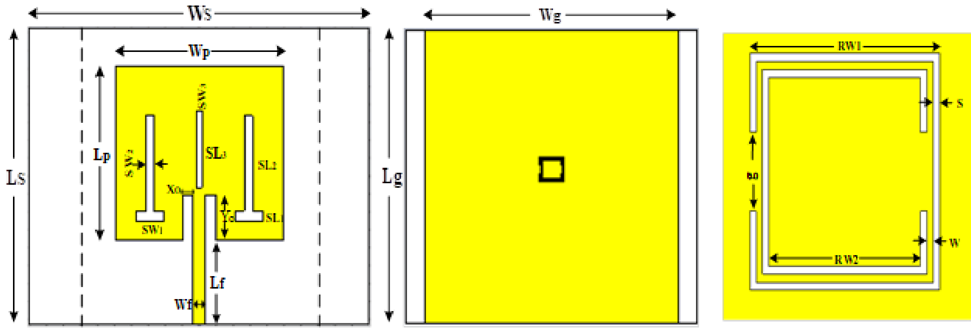
long, 0.7 mm wide microstrip feed line. Table 2 presents measurements of the ⊥LL-shaped slots and CSRR-loaded MRPA depicted in Figure 2(a-c).

Table 2. Measurements of the DGP-slotted MRPA integrated with CSRRs (in millimeters)

Parameter	Ls=Lg	Ws	Wg	L_p	W_p	L_f	W_f	Y_O	X_O	RW_1	RW_2	s	w	g
Dimension	15.5	16.0	14.0	9.6	10.0	4.75	0.7	4.75	0.70	1.3	1.1	0.1	0.1	0.5

To reduce the antenna's size, expand its bandwidth, and improve gain, slots and CSRRs were etched into the patch and ground layers of the antenna, as presented in Figure 2(a-c).



(a) Front view (b) Back view with CSRRs (c) CSRRs

Figure 2(a-c). The geometric design of the DGP-slotted MRPA loaded with the CSRRs structure

3. Results and Discussion

This section presents the key findings of the DGP-Slotted tri-band MRPA and the novel DGP-Slotted MRPA integrated with CSRRs. The results are provided in terms of return loss (S11), bandwidth, Voltage Standing Wave Ratio (VSWR), gain, directivity, and efficiency. The performance is evaluated and compared based on size, bandwidth, gain, and efficiency.

3.1. Performance of the designed DGP-slotted tri-band MRPA antenna

Table 3 presents the results of the DGP-Slotted MRPA antenna shown in Figure 1(a-b). The antenna exhibited excellent performance, particularly with its low S_{11} value, good gain, and efficiency in the 10, 28, and 38 GHz bands. However, to meet the modern 5G design specifications for mobile communication systems, the antenna size needs to be reduced, while its bandwidth and gain performance should be improved.

Table 3. Simulated results of the DGP-Slotted MRPA design depicted in Figure 1(a-b)

Resonance Frequency (GHz)	Return loss S_{11} (dB)	Bandwidth (GHz)	VSWR	Gain (dB)	Directivity (dBi)	Efficiency (%)
10.08	-20.85	0.23	1.20	6.32	7.09	89.00
28.40	-35.70	0.74	1.03	9.08	10.00	91.00
38.20	-40.11	1.97	1.02	9.68	10.17	95.00

The S_{11} values, as shown in Figure 3, are well below the -10 dB threshold across all bands. Although the bandwidths for the frequencies 10.08 and 28.40 GHz, as listed in Table 3, are not very wide, they are still sufficient for 5G applications. Figure 4 shows the bandwidth for the three bands. The VSWR, as presented in Figure 5, indicates good impedance matching between the antenna and its feeding system.

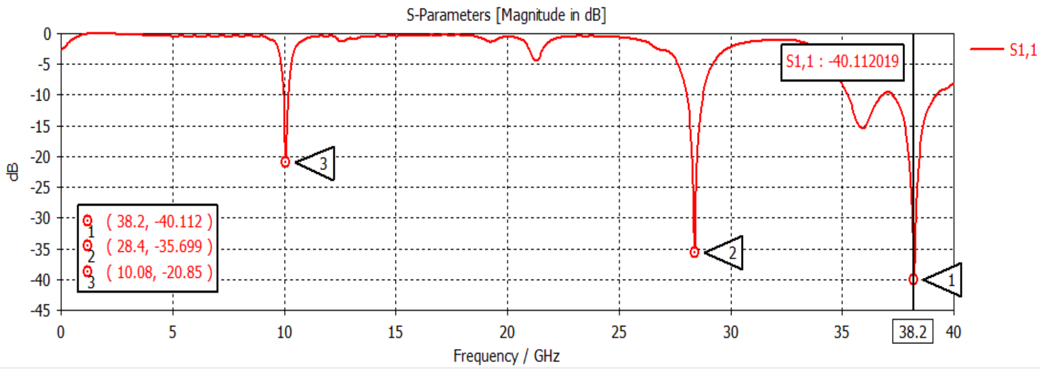


Figure 3. Simulated Return loss (S_{11}) of the DGP-Slotted tri-band 5G MRPA antenna

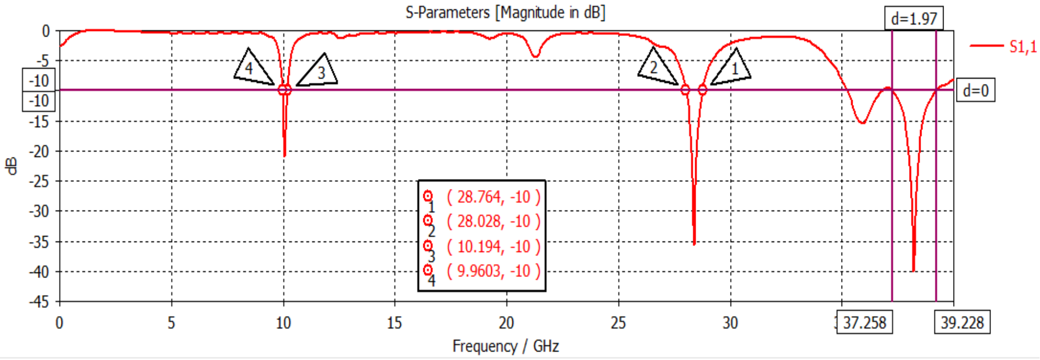


Figure 4. Simulated Bandwidth of the DGP-Slotted tri-band 5G MRPA antenna

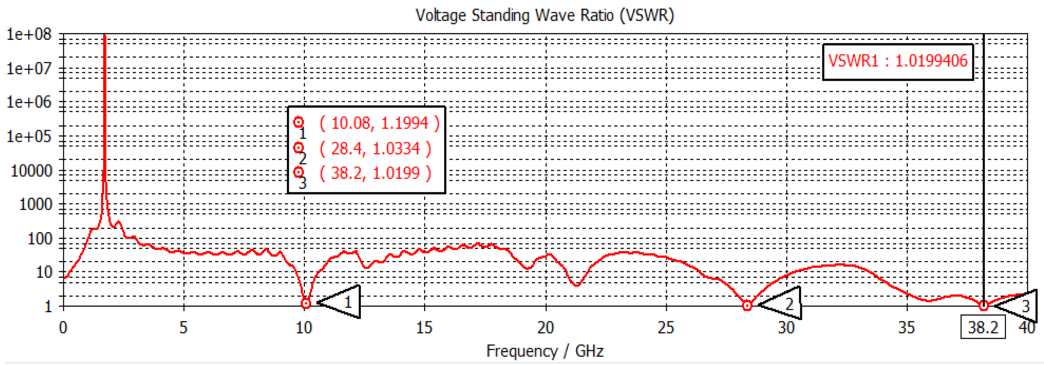


Figure 5. Simulated VSWR of the proposed DGP-Slotted tri-band 5G MRPA antenna

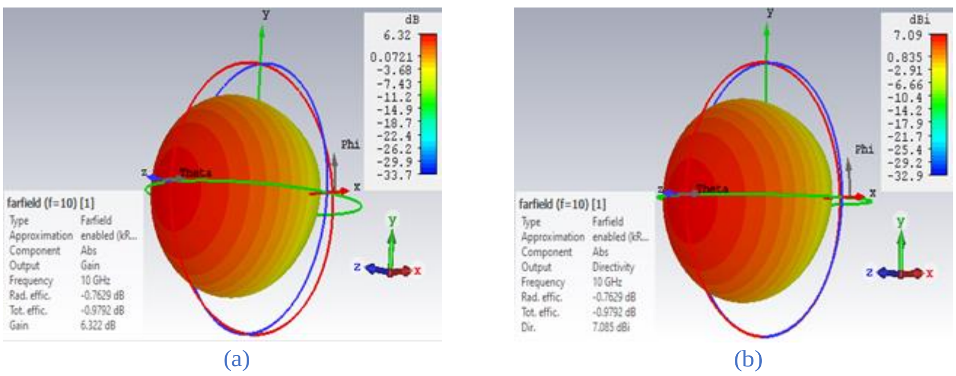


Figure 6(a-b). Simulated gain and directivity of the tri-band 5G antenna at 10 GHz

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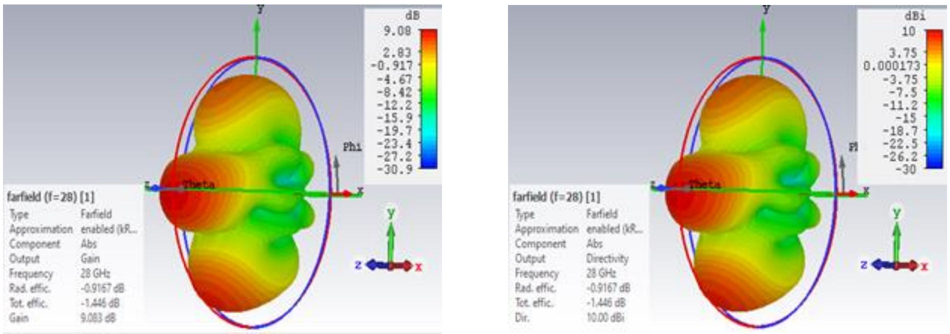
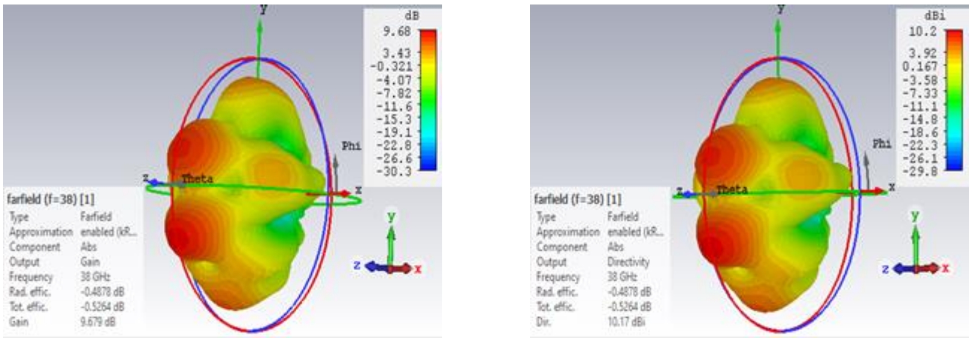
Figure 6(a) and Figure 6(b) show the gain and directivity at 10 GHz, Figure 7(a) and Figure 7(b) show the gain and directivity at 28 GHz, and Figure 8(a) and Figure 8(b) show the gain and directivity at 38 GHz, respectively.



(a) (b)

Figure 7(a-b). Simulated gain and directivity of the tri-band 5G antenna at 28 GHz



(a) (b)

Figure 8(a-b). Simulated gain and directivity of the tri-band 5G antenna at 38 GHz

3.2. Performance of the DGP-slotted tri-band MRPA integrated with CSRRs

According to the results in Table 4, the DGP-Slotted tri-band MRPA integrated with CSRRs shows improved radiation performance by increasing bandwidth at all frequencies. The gain improves slightly at 10 and 28 GHz. In contrast, efficiency improves only at 10 GHz.

Table 4. Simulated results of the DGP-Slotted MRPA with CSRRs depicted in Figure 2(a-b)

Resonance Frequency (GHz)	Return loss S_{11} (dB)	Bandwidth (GHz)	VSWR	Gain (dB)	Directivity (dBi)	Efficiency (%)
10.12	-21.25	0.25	1.20	6.45	7.10	91.00
28.72	-34.93	0.76	1.04	9.21	10.20	90.00
38.20	-22.16	3.63	1.17	8.89	9.35	95.00

The S_{11} values, as shown in Figure 9, are well below the -10 dB threshold across all bands. The bandwidth at 28.20 as shown in Table 4, is very wide, well sufficient for applications in 5G portable devices. Figure 10 shows the bandwidth for the three bands. The VSWR, as presented in Figure 11, indicates good impedance matching between the antenna and its feeding system. Figure 12(a) and Figure 12(b) show the gain and directivity at 10 GHz, Figure 13(a) and Figure 13(b) show the gain and directivity at 28 GHz, and Figure 14(a) and Figure 14(b) show the gain and directivity at 38 GHz, respectively.

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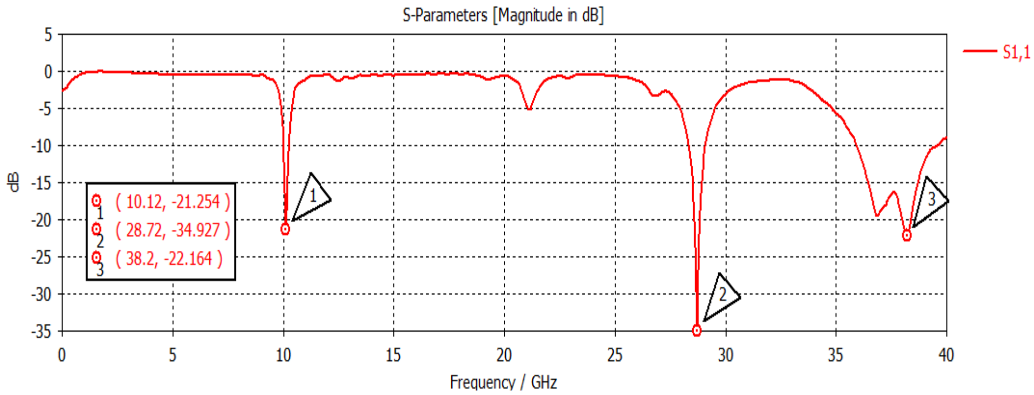

Figure 9. Simulated Return loss (S_{11}) of the tri-band DGP-Slotted MRPA with CSRRs

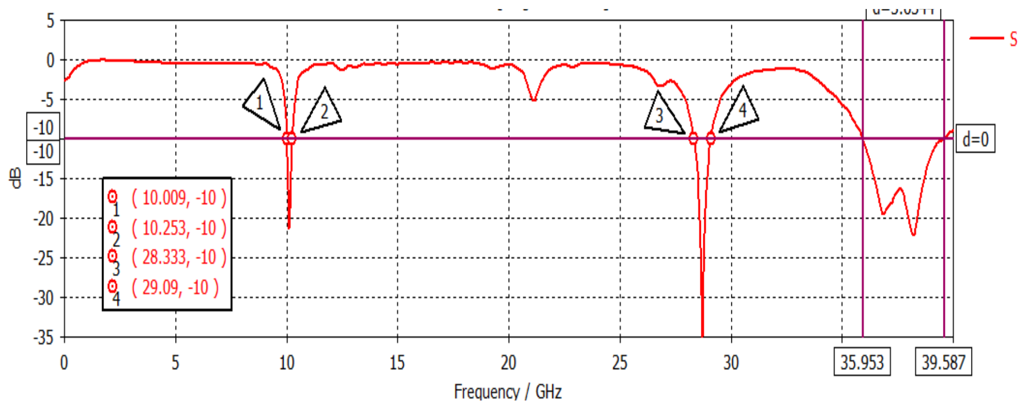

Figure 10. Simulated Bandwidth of the tri-band DGP-Slotted MRPA with CSRRs

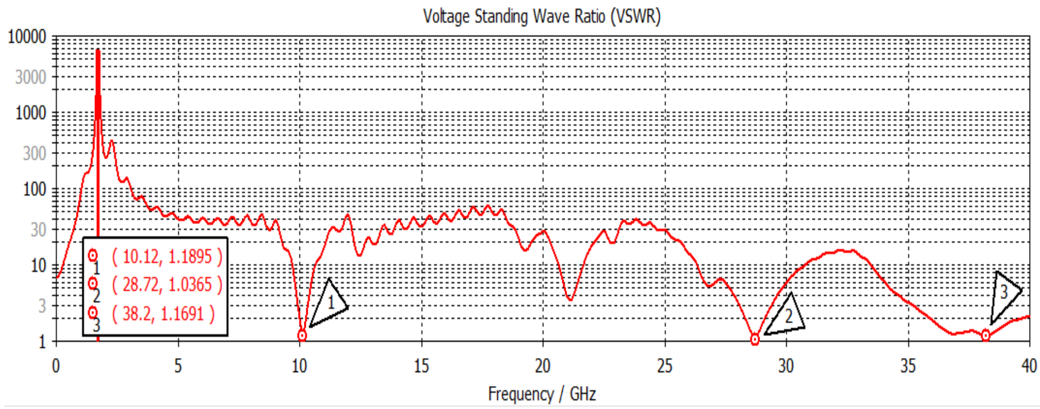

Figure 11. Simulated VSWR of tri-band DGP-Slotted MRPA with CSRRs

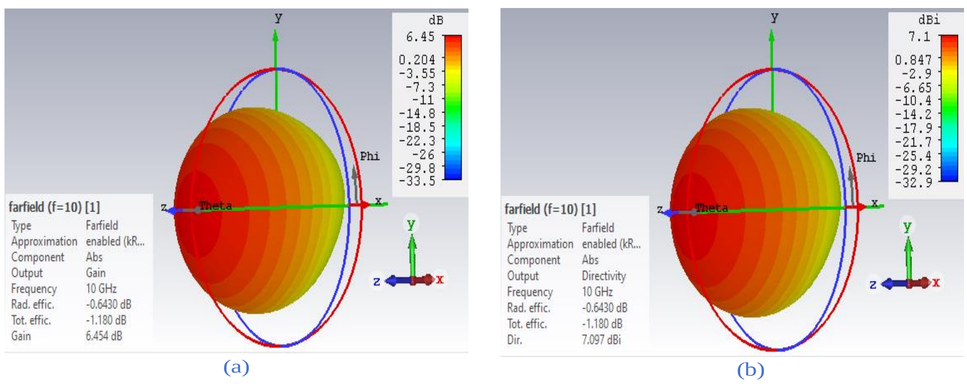

Figure 12(a-b). Simulated gain and directivity of the tri-band 5G antenna at 10 GHz

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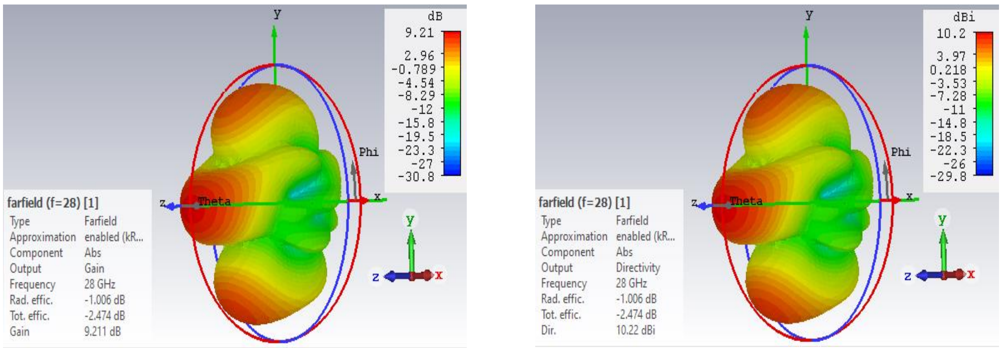
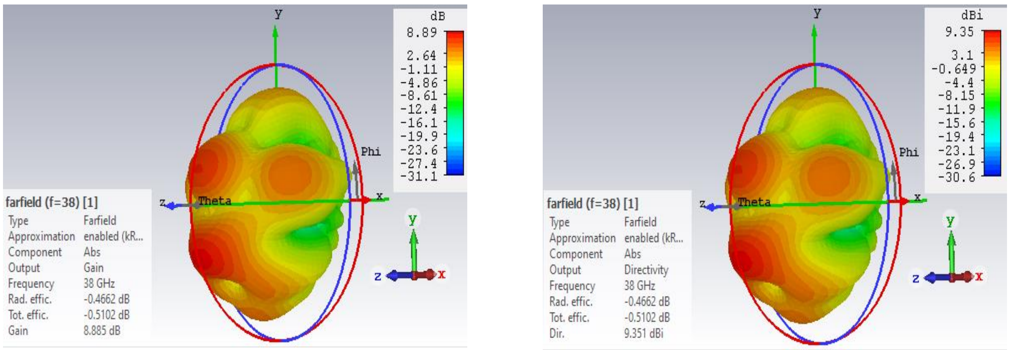


(a) (b)

Figure 13(a-b). Simulated gain and directivity of the tri-band 5G antenna at 28 GHz



(a) (b)

Figure 14(a-b). Simulated gain and directivity of the tri-band 5G antenna at 38 GHz

Table 5. Comparison of DGP-Slotted MRPA with ⊥I⊥-shape slotted MRPA with CSRRs

Frequency (GHz)	**Parameters**	**DGP + Slotting (330 mm²)**	**DGP + Slot + CSRRs (248 mm²)**	**Annotation**
	Antenna size	16.5×20 mm² (330 mm²)	15.5×16 mm² (248 mm²)	Reduction = 25%
10.00	Bandwidth	0.23 GHz	0.25 GHz	Enhancement = 8.70%
	Gain	6.32 dB	6.45 dB	Enhancement = 2.06%
	Efficiency	89.00 %	91.00 %	Enhancement = 2.25%
28.00	Bandwidth	0.74 GHz	0.76 GHz	Enhancement = 2.70%
	Gain	9.08 dB	9.21 dB	Enhancement = 1.43%
	Efficiency	91.00 %	90.00 %	Reduction = 1.10%
38.00	Bandwidth	1.97 GHz	3.63 GHz	Enhancement = 84.26%
	Gain	9.68 dB	8.89 dB	Reduction = 8.16%
	Efficiency	95.00 %	95.00 %	No change

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Table 5 shows how the DGP-slotted MRPA loaded with CSRRs compares with the DGP-slotted MRPA in terms of size, bandwidth, gain, and efficiency at 10, 28, and 38 GHz. The integration of CSRRs helped reduce the antenna size by 25%, making it more compact, with an enhanced bandwidth of up to 84% at 38.20 GHz.

Table 6 presents a comparison between our proposed tri-band 5G MRPAs and other antenna designs mentioned in the literature. The best-performing design has a partial ground plane with integrated CSRRs and slots, offering a compact size and high performance for 5G applications. The results are organized by bandwidth and efficiency values for easy comparison.

Table 6. Comparison of our work with previously published works in the literature

References	Size (mm^3)	Fr (GHz)	S_{11} (dB)	BW (GHz)	VSWR	Gain (dB)	Directivity (dBi)	Efficiency %
This work (DGP+Slots+ CSRRs)	5.5×16×0.508	10.12	-21.25	0.25	1.20	6.45	7.10	91.00
		28.72	-34.93	0.76	1.04	9.21	10.20	90.00
		38.20	-22.16	3.63	1.17	8.89	9.35	95.00
This work (DGP+Slots)	20×16.5×0.508	10.08	-20.85	0.23	1.20	6.32	7.09	89.00
		28.40	-35.70	0.74	1.03	9.08	10.00	91.00
		38.20	-40.11	1.97	1.02	9.68	10.17	95.00
[13]	12×12×0.8	15.20	-23.95	-	1.14	7.18	-	-
		23.00	-23.64	-	1.14	5.79	-	-
		29.80	-31.81	-	1.07	6.72	-	95.00
[2]	20×16.5×0.508	10.00	-25.80	0.34	1.10	5.67	-	74.47
		28.00	-24.90	0.76	1.12	9.33	-	87.20
		38.00	-32.90	1.50	1.03	9.57	-	92.00
[17]	55×115×0.508	28.02	-30.02	2.31	1.08	6.63	7.10	90.03
		37.83	-20.15	3.65	1.27	8.58	9.20	90.32
[9]	3.4×4.13×0.25	24.40	-14.70	0.53	1.50	6.65	7.49	85.37
		28.00	-19.30	0.90	1.24	7.02	7.69	86.50
		38.00	-18.70	0.48	1.27	5.05	6.46	73.30
[18]	7.91×7.85×0.648	28.00	-50.97	7.20	1.02	6.00	-	75.46
		38.00	-16.65	4.17	1.35	4.15	-	88.62
[12]	8.2×10.2×0.6	28.00	-18.80	0.50	-	-	7.70	62.20
		40.00	-48.10	2.20	-	-	12.10	45.10
		47.00	-26.90	0.40	-	-	8.20	61.90

As shown in Table 6, the proposed designs surpass previously reported antennas, achieving a maximum gain of 9.68 dB at 38.20 GHz with the DGP-Slotted design and a peak bandwidth of 3.63 GHz at the same frequency with the integrated design. Although [17], [18] reported a larger bandwidth, but it was accompanied by reduced gain and efficiency, with operation limited to dual-band. Other parameters, including return loss, VSWR, and efficiency, also demonstrate strong performance compared to alternative designs.

4. Conclusion

This paper presents a modified tri-band MRPA designed for high performance within the 10, 28, and 38 GHz bands for 5G wireless applications using CST simulation software. By introducing an I-slot to the patch and optimizing the existing inverted T-slots, the numerical gain and efficiency of the tri-band MRPA were improved compared to the values reported by [2]: 5.67 dB at 10 GHz, 9.33 dB at 28 GHz, and 9.57 dB at 38 GHz, with a maximum efficiency of 92%, to 6.32 dB at 10.08 GHz, 9.08 dB at 28.40 GHz, and 9.68 dB at 38.20 GHz, with a maximum efficiency of 95%. Although the gain at 28.40 GHz is slightly lower, it remains adequate for 5G applications. Further modification of the DGP-Slotted MRPA through the integration of CSRRs into the DGP reduced the antenna size by 25% and increased the bandwidth by 84% at 38.20 GHz, while maintaining an efficiency of 95%. Other radiation characteristics also exhibited strong performance. These results confirm that the proposed tri-band DGP-slotted MRPA integrated with CSRRs is compact, cost-effective, and simple, making it suitable for seamless integration into mobile devices for 5G wireless communications.

- Future work should include the fabrication and experimental validation of the proposed MRPA designs to verify the simulated results and assess the impact of fabrication tolerances or environmental effects.

- Research could also explore alternative substrates with improved dielectric or thermal properties to enhance performance at 10, 28 and 38 GHz for 5G applications.

- Additionally, incorporating tunable elements like varactor diodes or Micro-Electro-Mechanical Systems (MEMS) switches could enable reconfigurable frequency and bandwidth, enhancing adaptability to evolving wireless standards.

- Lastly, thermal and mechanical reliability tests are necessary to ensure durability in practical mobile and embedded applications.

Declarations

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Competing Interests Statement

The authors declare that they have no competing interests related to this work.

Consent for publication

The authors declare that they consented to the publication of this study.

Authors' contributions

Both the authors took part in literature review, analysis, and manuscript writing equally.

Availability of data and materials

Supplementary information is available from the authors upon reasonable request.

Institutional Review Board Statement

Not applicable for this study.

Informed Consent

Not applicable for this study.

References

[1] Bhalla, M.R., & Bhalla A.V. (2010). Generations of Mobile Wireless Technology: A Survey. Int J Comput Appl., 5(4): 26–32.

[2] Abdelaziz, A., & Hamad, E.K.I. (2019). Design of a Compact High-Gain Microstrip Patch Antenna for Tri-Band 5G Wireless Communication. Frequenz., 73(1–2): 45–52.

[3] Ahmed Solyman, A.A., & Yahya, K. (2022). Evolution of wireless communication networks: from 1G to 6G and future perspective. Int J Electr Comput Eng., 12(4): 3943–3950.

[4] Nafea, S.N., & Khamiss, N.N. (2023). For 5G applications, high-gain patch antenna in Ka-Band. Indones J Electr Eng Comput Sci., 31(2): 802–809.

[5] Agiwal, M., Roy, A., & Saxena, N. (2016). Next Generation 5G Wireless Networks: A Comprehensive Survey. IEEE Commun Surv Tutorials, Third Quart., 18(3): 1617–1655.

[6] Thi, N., & Lan, M. (2023). Evolution of Wireless Technology: From 1G to 5G. Asian J Appl Sci Technol., 7(4): 68–73. https://doi.org/10.38177/ajast.2023.7408.

[7] Khan, M.U., Sharawi, M.S., & Mittra, R. (2015). Microstrip patch antenna miniaturisation techniques: A review. IET Microwaves, Antennas Propag., 9(9): 913–922.

[8] Yusuf, M.A., & Ali, M.H. (2025). Integration of Slots and Complementary Split Ring Resonators (CSRRs) for High-Gain Dual-Band Compact Microstrip Patch Antennas for 5G Applications. Int J Adv Res Sci Technol., 14(04): 1576–1588.

[9] Kamal, M.S., Islam, M.J., Uddin, M.J., & Imran, A.Z.M. (2018). Design of a Tri-Band Microstrip Patch Antenna for 5G Application. Int Conf Comput Commun Chem Mater Electron Eng IC4ME2, Pages 1–5.

[10] Venkateswara Rao, M., Madhav, B.T.P., Krishna, J., Usha Devi, Y., Anilkumar, T., & Prudhvi Nadh, B. (2019). CSRR-loaded T-shaped MIMO antenna for 5G cellular networks and vehicular communications. Int J RF Microw Comput Eng., 29(8): 1–14.

[11] Singh, M., Singh, S., & Tariqul, M. (2022). CSRR loaded high gained 28/38GHz printed MIMO patch antenna array for 5G millimeter wave wireless devices. Microelectron Eng., 262(1): 1–11. https://doi.org/10.1016/j.mee.2022.111829.

[12] Dejen, A., Jayasinghe, J., Ridwan, M., & Anguera, J. (2022). Genetically engineered tri-band microstrip antenna with improved directivity for mm-wave wireless applications. AIMS Electron Electr Eng., 6(1): 1–15.

[13] Sengar, S., & Malik, P.K. (2023). A Compact Tri-band Microstrip Patch Antenna Design for 5G millimeter wave applications. In 14th ICCCNT IEEE Conf IIT - Delhi, Delhi, India. https://doi.org/10.1109/icccnt56998.2023.10308282.

[14] Alshaikhli, N.Q.A., Neamah, M.A., & Aal-Nouman, M.I. (2022). Design of triband antenna for telecommunications and network applications. Bull Electr Eng Informatics, 11(2): 1084–1090. https://doi.org/10.11591/eei.v11i2.3233.

[15] Nahas, M.A. (2024). High-Gain Dual-Band Slotted Microstrip Patch Antenna for 5G Cellular Mobile Phones. Eng Technol Appl Sci Res., 14(3): 14504–14508. https://doi.org/10.48084/etasr.7410.

[16] Vythee, E., & Jugumauth, R. (2020). Microstrip Patch Antenna Design and Analysis with Varying Substrates for 5G. In the 3rd Int Conf Emerg Trends Electr Electron Commun Eng., Pages 141–146. https://doi.org/10.1109/elecom49001.2020.9296991.

[17] Marzouk, H.M., Shaalan, A., & Ahmed, M.I. (2020). Two-Element Microstrip Antenna 28/38 GHz for 5G Mobile Applications. Delta Univ Sci J., 3(1): 1–8. https://doi.org/10.35360/njes.34.

[18] Ayalew, L.G., & Asmare, F.M. (2022). Design and optimization of Pi-slotted dual-band rectangular Microstrip Patch Antenna using Surface Response Methodology for 5G Applications. Heliyon, 8: 1–14. https://doi.org/10.1016/j.heliyon.2022.e12030.