ISSN: 2229-6948(ONLINE)
DOI: 10.21917/ijct.2025.0532

DESIGN OF A MINIATURIZED CLUB-SHAPED MIMO ANTENNA WITH WIDEBAND PERFORMANCE FOR NEXT-GENERATION WIRELESS SYSTEMS

Soham Majumder
Department of Communication and Signal Processing Engineering, National Institute of Technology Silchar, India

Abstract

In this paper, a two port "club" shaped MIMO antenna is proposed for next generation wireless systems. In the proposed antenna design, slots were introduced in the ground plane and minimal spacing was maintained, which collectively contributed to enhanced overall performance. Furthermore, the proposed MIMO antenna is designed on Rogers RT/duroid 5870(tm) substrate with an overall dimension of 24mm × 12mm × 0.5mm (2.93λ_0 × 1.46λ_0 × 0.06λ_0, where λ_0 is the free space wavelength at the resonating frequency). The proposed antenna resonates at 36.63 GHz and achieves a wide bandwidth of 5.46 GHz (33.57 - 39.03 GHz). In addition to it, the proposed antenna achieves an isolation of < -27.27 dB, peak gain of > 5 dB and a high radiation efficiency of > 98%. Moreover, in terms of diversity parameters, the proposed MIMO antenna achieves acceptable results with envelope correlation coefficient < 0.0005 and diversity gain < 10dB. Thus, it can be concluded that our proposed antenna may be a suitable candidate for Ka band, 5G mm-wave and next generation wireless systems.

Keywords:

Wide Band Antenna, Club Shaped Antenna, Ka Band, 5G mm-Wave, Fractal Slot Antenna

1. INTRODUCTION

Due to scarcity of available bands in the sub-6 GHz frequency range, modern wireless communication (MWC) is shifting towards millimeter wave (mm-wave) spectrum. The mm-wave spectrum contains several frequency bands that are currently unallocated, as a result, these unallocated bands offer an accessible opportunity for deployment in MWC systems [1]. The Federal Communication Commission (FCC) has defined 30 - 300 GHz as the frequency band for mm-wave communication. However, with the increasing demands, the MWC is considering 24 - 100 GHz as the band for mm-wave communication [2]. With the advancements in MWC, there is a demand of higher data rate, wider bandwidth (BW), lower latency, lower interference in the system [3].

Thus, researchers are moving towards a better combination of Multiple Input Multiple Output (MIMO) system with wide BW technology. With MIMO system, there is an advantage of transmitting as well as receiving multiple signals at the same time. As the size of the hand-held devices are becoming compact so introducing MIMO systems in compact structure is quite hard. Placing antennas in proximity increases mutual coupling, which in turn degrades the overall performance [4]. Thus, to increase the performance by decreasing the mutual coupling, various methods have been implemented in recent years.

Some of the notable methods used by modern day researchers includes slotted ground, Defected Ground Structure (DGS), Electromagnetic Band Gap (EBG), Split Ring Resonator (SRR), Meta-Materials (MMT). But each method has its own drawbacks. In [5]-[8], the authors introduced multiple slots on the patch which helped in improving the overall performance of the antenna. However, the fabrication of such antennas becomes quite challenging as the number of slots increases. In [9] - [12], the authors implemented DGS to decrease the mutual coupling. Furthermore, in [13]-[15], the authors incorporated EBG structure to increase the overall performance. However, integrating DGS and EBG structures involves considerable complexity. Moreover, in [16]-[18] the authors introduced SRR to decrease the mutual coupling. Similarly, in [19], [20], authors had tried to use the concept of MMT and meta surface in their work. However, employing MMT and meta surfaces results in increased copper losses within the structure, which in turn reduces the overall efficiency. One important thing to note is that it is not mandatory to include any external methods to decrease the mutual coupling. There are works like [21], [22] which do not include any external technique(s), rather they have maintained sufficient inter-element spacing which helped in increasing the overall isolation. However, maintaining sufficient inter element spacing increases the overall size of the antenna.

In recent years, as technology is evolving, there has been not much work in open literature which achieves wideband or ultra-wide band in mm-wave systems. In [23], the authors had used ball grid array technology to achieve an ultra-wide band in the proposed work. Similarly, the concept of Butler matrix was used in [24] - [26] which helped to produce beams in a desired direction thereby increasing the overall BW. Furthermore, in [27], an elliptical slot was made on the patch which helped to enhance the BW and resonating frequency.

All the above-mentioned works are good, but when it comes to practical implementation, they hold some strong drawbacks. Thus, to mitigate these drawbacks, this paper presents a compact two-port MIMO antenna design featuring strategically introduced slots on the ground plane with minimal inter-element spacing. These design choices contribute to enhanced overall performance. The proposed antenna demonstrates satisfactory results and achieves a wide BW, making it a suitable candidate for applications in the Ka band, 5G mm-wave and next generation wireless systems.

The rest of the paper is organized as follows:

Section 2 describes the overall geometry, mathematical analysis of the antenna geometry as well as the step wise evolution of the proposed MIMO antenna. Section 3 describes the various results like scattering parameters, isolation, voltage standing wave ratio, peak gain, radiation efficiency, surface current distribution, radiation characteristics. It also describes the MIMO diversity parameters like envelope correlation coefficient and diversity gain. Section 4 describes the state-of-the-art-comparison of the proposed antenna with some of the latest works. Finally, conclusions are drawn in section 5.

2. ANTENNA GEOMETRY AND EVOLUTION

This section describes the overall geometry, mathematical analysis of the antenna geometry as well as the step wise evolution of the proposed MIMO antenna.

2.1 ANTENNA GEOMETRY

The top view and the bottom view of the proposed MIMO antenna along with its dimensional values are shown in Fig.1(a) and 1(b) respectively. Furthermore, the detailed dimensional analysis of the single port is shown in Fig.1(c). For clarity in the dimensions, all the dimensional values are tabulated in Table.1. The proposed antenna is designed on Rogers RT/duroid 5870(tm) substrate ($\varepsilon_r = 2.33, \tan\delta = 0.0009$). The proposed MIMO antenna has an overall dimension of 24mm × 12mm × 0.5mm ($2.93\lambda_0 \times 1.46\lambda_0 \times 0.06\lambda_0$, where λ_0 is the free space wavelength at the resonating frequency). All the antenna simulations were done in Ansys HFSS 2023 R2 software.

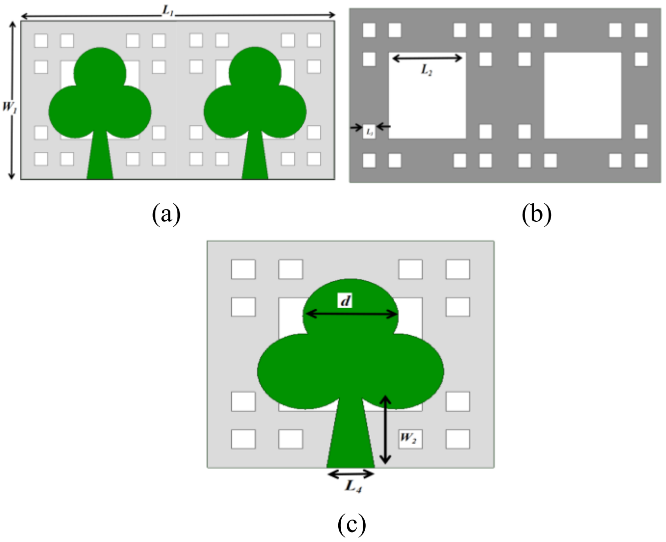


Fig.1. (a) top view of the proposed MIMO antenna (b) bottom view of the proposed MIMO antenna (c) Single port of the MIMO antenna

Table.1. Dimensional values of the proposed antenna

Parameter	Value (mm)	Parameter	Value (mm)
L_1	24	L_4	2
W_1	12	W_2	3.7
L_2	6	d	4
L_3	1	Height	0.5

2.2 MATHEMATICAL ANALYSIS OF THE ANTENNA GEOMETRY

The proposed MIMO antenna features a three-layered structure, comprising a patch on the top layer and a ground plane on the bottom layer, with the substrate sandwiched between them. The dimensions of each layer can be calculated using the equations mentioned in [28]:

Substrate height (H) can be calculated as:

$$H \le \frac{0.3c}{2\times 3.14 f_r \sqrt{\varepsilon_r}} \quad (1)$$

The length of the patch (L) can be calculated as:

$$L = \frac{c}{\sqrt{2\varepsilon_r^{\text{eff}}}\, f_r} - 2\Delta L \quad (2)$$

The width of the patch (W) can be calculated as:

$$W = \frac{c}{2f_r}\sqrt{\frac{2}{\varepsilon_r + 1}} \quad (3)$$

The effective dielectric constant $\varepsilon_r^{\text{eff}}$ can be calculated as:

$$\varepsilon_r^{\text{eff}} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + \frac{12H}{W}\right)^{-1/2} \quad (4)$$

The length extension (ΔL) can be calculated as:

$$\frac{\Delta L}{H} = 0.412\frac{\left(\varepsilon_r^{\text{eff}} + 0.3\right)\left(\frac{W}{H} + 0.264\right)}{\left(\frac{W}{H} + 0.8\right)\left(\varepsilon_r^{\text{eff}} - 0.258\right)} \quad (5)$$

where, $\in_r$: dielectric constant of the substrate, c: velocity of light in free space f_r: resonant frequency

2.3 STEPWISE EVOLUTION

This section outlines the key steps undertaken prior to finalizing the design of the proposed antenna. There is a total of four steps that were done to finalize the antenna. The step wise evolution of the proposed antenna is shown in Fig.2(a-d) while the scattering parameter plot for each step is shown in Fig.2(e). In any microstrip antenna, every parametric value plays an important role in the overall performance. Changing one parameter can change the overall performance, thus a careful approach should be taken while performing the step wise evolution.

In *design step-1,* a full ground of 12mm × 12mm was taken and above it, a substrate of height 0.5mm, material: Rogers RT/duroid 5870 (tm) was placed. Above the substrate a isosceles triangular strip of height 3.7mm and base width of 2mm was placed. When this step was simulated, the antenna could not cover the -10 dB impedance BW. Thus, further modifications were made.

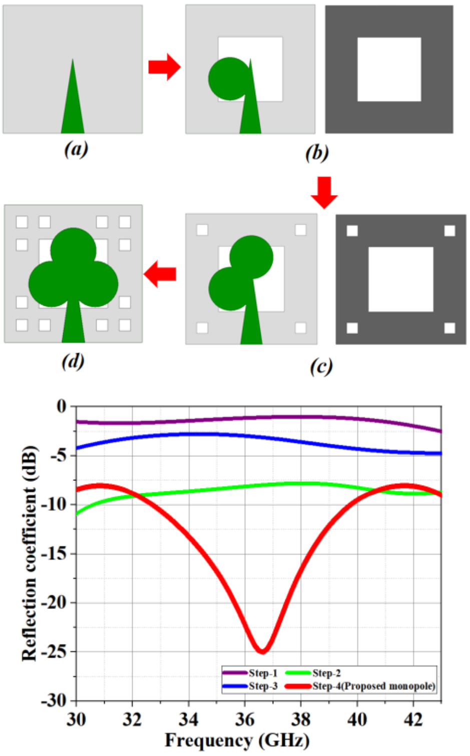
In *design step-2*, a square of side 6mm was removed from the middle of the ground and a circle of radius 2mm was added on the left side of the triangular patch. When this step was simulated, the antenna was still unable to cover the -10 dB impedance BW. Thus, further modifications were made.

In *design step-3*, four square shaped slots of side 1mm were removed from each corner of the ground and another circle of radius 2mm was added on the top of the patch. When this step was simulated, the antenna was still unable to cover the -10 dB impedance BW. Thus, further modifications were still required.

In *design step-4*, two squares of side 1mm were removed from each corner of the ground (total 8 squares were removed) and another circle of radius 2mm was added on the right side of the patch. When this step was simulated, the antenna was able to cover the -10 dB impedance bandwidth. In this step, the antenna resonated at 36.63 GHz and achieved a wide bandwidth of 5.46

GHz. Since this step achieved acceptable result, thus we finalized this step as the proposed antenna for our work.

With the advancements in MWC there is a strong need for MIMO antennas to have a higher data rate and a wide bandwidth. Thus, to fulfill this need, the single port antenna presented in this paper was converted to two port MIMO antenna as shown in Fig.1(a). It should be noted that sufficient yet minimum spacing was maintained between the ports of the antenna which helped in achieving a lower mutual coupling and a higher isolation between the antenna elements.



(e)

Fig.2. (a-d) step wise evolution of the proposed antenna (e) scattering parameter plot for each step in the step-wise evolution.

3. RESULTS AND DISCUSSION

This section describes the various results that were obtained while simulating the proposed MIMO antenna. The various results such as scattering parameters, peak gain, radiation efficiency, voltage standing wave ratio, radiation characteristics, and surface current distribution were obtained. Furthermore, MIMO diversity parameters such as envelope correlation coefficient, diversity gain were also explored. It should be noted that, the MIMO antenna is symmetrical and thus the plots overlap each other.

Scattering parameters (S-parameters) is used to find the relationship between the input port(s) and output port(s) of any antenna system [29]. For an antenna to be suitable for modern day applications, the S-parameter should lie below -10 dB in the entire frequency of interest. The S-parameter plot of the proposed MIMO antenna is shown in Fig.3. From the figure, it can be noted that the proposed antenna resonates at 36.63 GHz and achieves a wide bandwidth of 5.46 GHz (33.57 GHz - 39.03 GHz) which makes it suitable for 5G mm-wave, Ka band and next generation wireless systems.

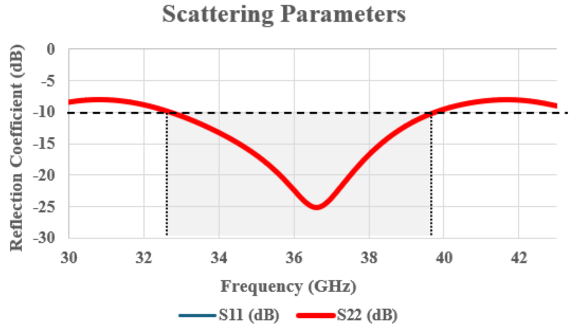


Fig.3. Scattering parameters plot of the proposed MIMO antenna

Isolation tells the amount of mutual coupling that exists between the multiple ports of any multi antenna system. For an antenna to be suitable for modern day applications, the isolation should lie below -15 dB in the entire frequency of interest. The isolation plot of the proposed MIMO antenna is shown in Fig.4. From the figure, the proposed antenna achieves a high isolation of <-27.27 dB in the operating band. It can also be noted that due to incorporation of slots on the ground, the proposed antenna achieves a high value of isolation.

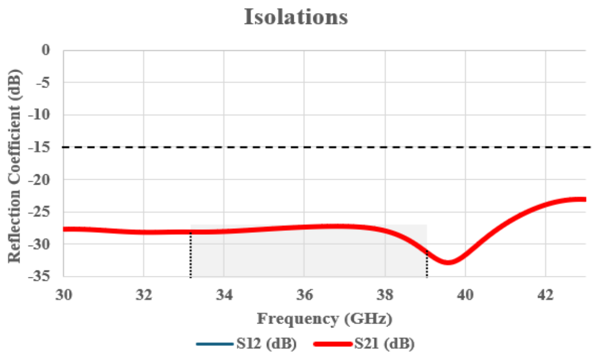


Fig.4. Isolation plot of the proposed MIMO antenna

Voltage Standing Wave Ratio (VSWR) describes the amount of power that is reflected from the antenna [30]. The simulated VSWR plot for the proposed antenna is shown in Fig.5. From the VSWR plot, it can be noted that, the VSWR values lie below 2 in the entire frequency band of interest.

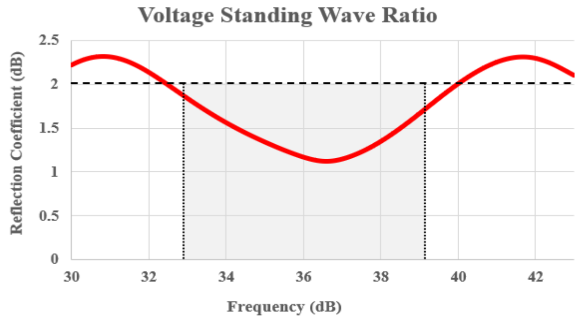


Fig.5. VSWR plot of the proposed MIMO antenna

Peak gain tells the degree of directivity of antenna's radiation pattern or in other words, it is the amount of input power concentration in the main beam direction with respect to isotropic antenna [31]. It should be noted that peak gain of an antenna should always be positive which implies that the antenna possesses minimum loss or lossless. The peak gain of the proposed MIMO antenna is shown in Fig.6. From the figure, it can be noted that, the proposed antenna achieves a high gain of > 5 dB in the entire band of interest.

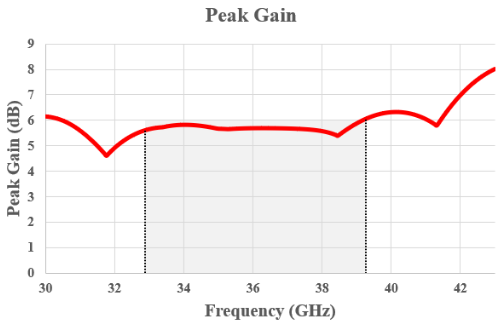


Fig.6. Peak gain plot of the proposed MIMO antenna

Radiation efficiency tells the how efficiently the antenna can convert the fed radio frequency power into radiated power. The radiation efficiency of the proposed MIMO antenna is shown in Fig.7. From the figure, it can be concluded that, the proposed antenna achieves a high radiation efficiency of >98% in the entire operating band of interest.

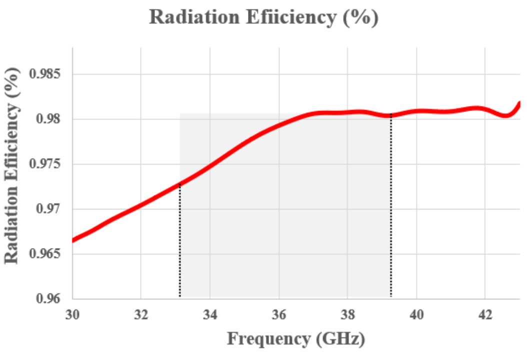


Fig.7. Radiation efficiency plot of the proposed MIMO antenna

Surface current distribution (SCD) tells how the current is distributed on the conducting surface of any antenna. The SCD on the patch at the resonating frequency is shown in Fig.8. From the figure, it can be noted that, as port 1 is excited, the current distribution near port 1 is maximum and as we move away from port 1, the current distribution decreases. The proposed MIMO antenna achieves a minimum current distribution of 0.009 dB while a maximum current distribution of 58.210 dB at the resonating frequency.

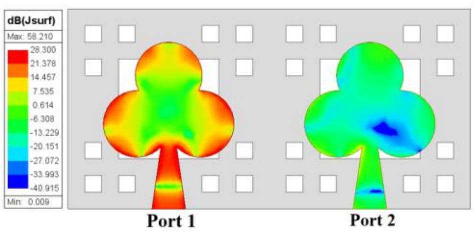


Fig.8. Surface current distribution of the proposed MIMO antenna

Radiation mechanism tells how the antenna radiates in free space. From the radiation pattern generally two types of polarizations are observed: cross-polarization ($\varphi = 0^0$, which is undesired) and co-polarization ($\varphi = 90^0$, which is desired). The simulated radiation patterns (E plane and H plane) at the resonating frequency are shown in Fig.9 and Fig.10. From the figures it can be noted that the proposed antenna achieves an omnidirectional radiation pattern in both the E-plane and H-plane respectively.

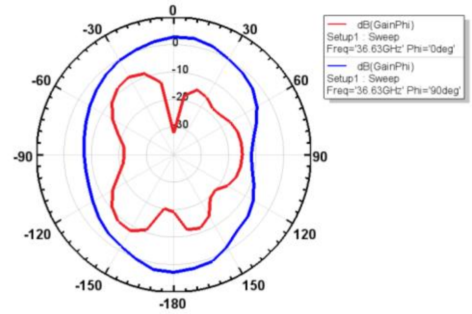


Fig.9. E-plane cross and co-polarization of the proposed MIMO antenna

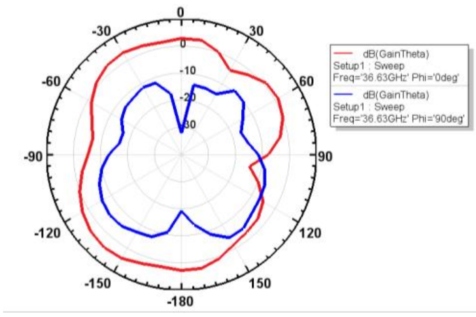


Fig.10. H-plane cross and co-polarization of the proposed MIMO antenna

Envelope Correlation Coefficient (ECC) describes the correlation between two ports in a multi-port antenna system [32]. ECC can be calculated using S-parameter which is given by Eq.(6):

$$ECC_{ij} = \frac{|S_{11}^* S_{12} + S_{21}^* S_{22}|^2}{\left(1 - |S_{11}|^2 - |S_{21}|^2\right)\left(1 - |S_{22}|^2 - |S_{12}|^2\right)} \quad (6)$$

where i and j are port numbers.

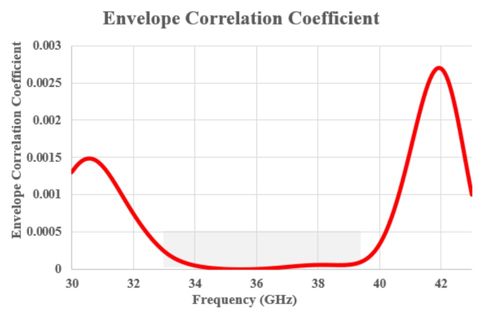


Fig.11. Envelope correlation coefficient plot of the proposed MIMO antenna

For a MIMO antenna system, the ECC should lie between 0 and 1. If ECC value is 1: then antennas are highly correlated. If ECC value is 0: then antennas are highly uncorrelated. If ECC value is less than 0.5: it is suitable for practical applications. The simulated ECC plot for the proposed antenna is shown in Fig.11. From the figure, it can be concluded that the ECC for the proposed antenna lies below 0.0005 which is within the acceptable range defined for ECC.

Diversity gain (DG) is the measure for the reduction in the transmitted power when the channel experiences noise [33]. DG can be calculated using ECC values which is given by Eq.(7):

$$DG_{ij} = 10\sqrt{1 - |ECC_{ij}|^2} \quad (7)$$

where, ECC_{ij} are the simulated ECC values.

For a MIMO antenna system, the DG should lie below 10 dB. The simulated DG plot for the proposed antenna is shown in Fig.12. From the figure, it can be concluded that the DG for the proposed antenna lies < 10 dB which is within the acceptable range defined for DG.

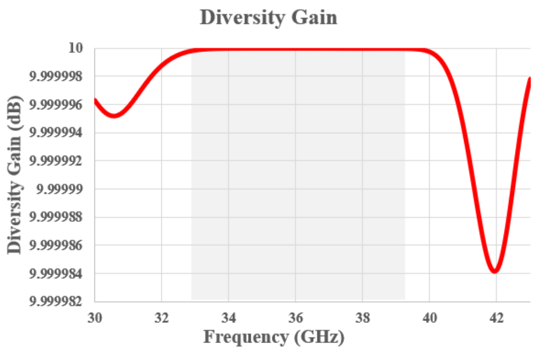


Fig.12. Diversity gain plot of the proposed MIMO antenna

3.1 STATE-OF-ART-COMPARISON

The Table.2 presents a state-of-the-art comparison between the proposed antenna and several recent designs reported in the literature. As observed, the proposed antenna exhibits a significantly wider BW than all referenced works. Additionally, it demonstrates superior isolation performance, indicating that simultaneous operation of both antenna elements will not degrade overall performance due to mutual coupling. Furthermore, the proposed design achieves higher gain and radiation efficiency compared to the other designs. Based on the comparative analysis, it can be concluded that the proposed antenna offers enhanced performance across multiple key parameters.

Table.2. State-of-the-art-comparison

Ref.	Overall dimensions (λ_0)	B.W (GHz)	Isolations (dB)	Gain (dB)	Rad. Eff.
[7]	$5.959\lambda_0 \times 5.959\lambda_0 \times 1.4\lambda_0$	1.76	NA	0.1573	NR
[8]	$0.56\lambda_0 \times 0.74\lambda_0 \times 0.023\lambda_0$	3.56, 5.39	NA	4.5	80%
[9]	$1.84\lambda_0 \times 1.58\lambda_0 \times 0.05\lambda_0$	2.55, 2.1	NA	1.83	78%
[34]	$1.12\lambda_0 \times 1.12\lambda_0 \times 0.11\lambda_0$	3.7, 3.23	NA	4.3	73.2
[35]	$1.68\lambda_0 \times 0.79\lambda_0 \times 0.02\lambda_0$	0.54, 0.5	<-20	4.15	80.13
[36]	$0.65\lambda_0 \times 1.4\lambda_0 \times 0.07\lambda_0$	5	-22	2.7	NR
[37]	$0.54\lambda_0 \times 0.31\lambda_0 \times 0.01\lambda_0$	3.38	NR	4.85	NR
Prop. Work	$\mathbf{2.93\lambda_0 \times 1.46\lambda_0 \times 0.06\lambda_0}$	**5.46**	**>-27.27**	> 5	**> 98**

Note: Prop. Work: Proposed antenna, NA: Not Applicable, NR: Not Reported and B.W: Bandwidth

4. CONCLUSIONS

With the increase in demand of higher data rate, lower latency, higher BW, single antenna systems are no longer suitable. Thus, researchers are moving towards a multiple antenna system. Mainly two bands are common in today's world: sub 6 GHz and mm-wave band. In sub 6 GHz, there is a scarcity of available bands, thus researchers are moving towards mm-wave band, where a lot of unallocated bands are present. So, mm-wave band becomes suitable to fulfill all the modern-day demands. In this proposed work, we have also tried to explore the mm-wave band by designing a two port MIMO antenna where slots were made on the ground and a minimum spacing was maintained which helped in increasing the overall performance. The proposed antenna resonates at 36.63 GHz and achieves a wide BW of 5.46 GHz (33.57 - 39.03 GHz). In addition to it, the proposed antenna achieves an isolation of < -27.27 dB, peak gain > 5 dB and radiation efficiency of > 98%. Furthermore, the proposed antenna also achieves an acceptable result for the diversity parameters with envelope correlation coefficient of < 0.0005 and diversity gain of < 10 dB. Thus, we can conclude that our proposed MIMO antenna may be a suitable candidate for Ka band, 5G mm-wave and next generation wireless systems.

REFERENCES

[1] G. Chittimoju and U.D. Yalavarthi, "A Comprehensive Review on Millimeter Waves Applications and Antennas", *Journal of Physics*, Vol. 1804, No. 1, pp. 1-6, 2021.

[2] H. Zhang, Y. Zhang, J. Cosmas, N. Jawad, W. Li, R. Muller and T. Jiang, "mmWave Indoor Channel Measurement Campaign for 5G New Radio Indoor Broadcasting", *IEEE Transactions on Broadcasting*, Vol. 68, No. 2, pp. 331-344, 2022.

[3] A. Patil and R.S. Bhadade, "A Literature Survey on MIMO Antenna", *Proceedings of International Conference on IoT based Control Networks and Intelligent Systems*, pp. 1-10, 2021.

[4] A.C. Malathi and D. Thiripurasundari, "Review on Isolation Techniques in MIMO Antenna Systems", *Indian Journal of Science and Technology*, Vol. 9, No. 35, pp. 1-10, 2016.

[5] V. Karthikeyan, S. Vignesh, K.A. Reddy, G.B. Reddy and R.A. Sekhar, "A Millimeter Wave based Circular Slot Loaded Microstrip Patch Antenna for 5G Communication",

Materials Science and Engineering, Vol. 590, No. 1, pp. 1-7, 2019.

[6] O. Sokunbi, H. Attia, A. Hamza, A. Shamim, Y. Yu and A.A. Kishk, "New Self-Isolated Wideband MIMO Antenna System for 5G mm-Wave Applications using Slot Characteristics", *IEEE Open Journal of Antennas and Propagation*, Vol. 5, No. 4, pp. 81-90, 2023.

[7] P. Kumawat, "Design of 28/38 GHz Dual-Band SIW Slot Antenna for 5GApplications", *International Journal of Engineering Research and Technology*, Vol. 18, No. 17, pp. 1-20, 2020.

[8] S.M. Umar, W.U. Khan, S. Ullah, M. Khan and S. Bashir, "Design and Analysis of a Slotted Patch Antenna for Dualband Millimeter-Wave Applications: Design and Analysis of a Slotted Patch Antenna", *Proceedings of the Pakistan Academy of Sciences: A. Physical and Computational Sciences*, Vol. 57, No. 1, pp. 31-36, 2020.

[9] A. Djouimaa and K. Bencherif, "Design of a Compact Circular Microstrip Patch Antenna for 5G Applications", *Engineering, Technology and Applied Science Research*, Vol. 14, No. 4, pp. 16020-16024, 2024.

[10] A.K. Gondi, A.D. Jaiswal, S.J. Vignesh and D. Yadav, "High Directivity and High Gain Microstrip Patch Antenna for 5G Application with Defective and Suspended Ground Plane", *Proceedings of International Conference on Electronics, Materials Engineering and Nano-Technology*, pp. 1-5, 2021.

[11] C. Guler and S.E. Bayer Keskin, "A Novel High Isolation 4-Port Compact MIMO Antenna with DGS for 5G Applications", *Micromachines*, Vol. 14, No. 7, pp. 1-17, 2023.

[12] J.R. Abraham and A. Bhargava, "Fractal Microstrip Patch Antenna with Defected Ground Structure for 5G Wireless Communication Applications", *Journal of Emerging Technologies and Innovative Research*, Vol. 7, No. 9, pp. 375-381, 2020.

[13] X. Shen, Y. Liu, L. Zhao, G.L. Huang, X. Shi and Q. Huang, "A Miniaturized Microstrip Antenna Array at 5G Millimeter-Wave Band", *IEEE Antennas and Wireless Propagation Letters*, Vol. 18, No. 8, pp. 1671-1675, 2019.

[14] A.T. Devapriya and S. Robinson, "Design and Development of Microstrip Patch Antenna using EBG Structures for S-Band Communication", *ICTACT Journal on Microelectronics*, Vol. 5, No. 1, pp. 738-743, 2019.

[15] R. Kumar, G. Mathai and J.P. Shinde, "Design of Compact Multiband EBG and Effect on Antenna Performance", *International Journal of Recent Trends in Engineering*, Vol. 2, No. 5, pp. 254-258, 2009.

[16] S. Angadi, T. Sabapathy, N.S. Raghava, M. Jusoh, H. Vettikalladi, A.M. Almuhlafi and M. Himdi, "A Compact Wideband SRR-based C-Shaped Antenna for 5G New Radio Band n258", pp. 1-14, 2023.

[17] Z. Wang, Y. Dong and T. Itoh, "Miniaturized Wideband CP Antenna based on Metaresonator and CRLH-TLs for 5G New Radio Applications", *IEEE Transactions on Antennas and Propagation*, Vol. 69, No. 1, pp. 74-83, 2020.

[18] S. Robinson, "Design and Analysis of Split Ring Resonator based Microstrip Patch Antenna for X-Band Applications", *ICTACT Journal on Microelectronics*, Vol. 4, No. 4, pp. 687-692, 2019.

[19] M.L. Hakim, T. Alam, M.T. Islam, N.B. Sahar, M.S. Singh, H. Alsaif and M.S. Soliman, "Metamaterial Physical Property Utilized Antenna Radiation Pattern Deflection for Angular Coverage and Isolation Enhancement of mm-Wave 5G Mimo Antenna System", *Radiation Physics and Chemistry*, Vol. 209, pp. 1-7, 2023.

[20] M. Singh and M.S. Parihar, "Gain Improvement of Vivaldi MIMO Antenna With Pattern Diversity using Bi-Axial Anisotropic Metasurface for Millimeter-Wave Band Application", *IEEE Antennas and Wireless Propagation Letters*, Vol. 22, No. 3, pp. 621-625, 2022.

[21] T. Upadhyaya, V. Sorathiya, S. Al-Shathri, W. El-Shafai, U. Patel, K.V. Pandya and A. Armghan, "Quad-Port MIMO Antenna with High Isolation Characteristics for Sub 6-GHz 5G NR Communication", *Scientific Reports*, Vol. 13, No. 1, pp. 1-14, 2023.

[22] A.A. Ibrahim and M.F. Abo Sree, "UWB MIMO Antenna with 4-Element, Compact Size, High Isolation and Single Band Rejection for High-Speed Wireless Networks", *Wireless Networks*, Vol. 28, No. 7, pp. 3143-3155, 2022.

[23] X. Liu, W. Zhang, D. Hao and Y. Liu, "Cost-Effective Surface-Mount Magnetoelectric Dipole Antenna based on Ball Grid Array Packaging Technology for 5G Millimeter-Wave New Radio Band Applications", *IEEE Transactions on Components, Packaging and Manufacturing Technology*, Vol. 12, No. 9, pp. 1567-1574, 2022.

[24] Z. Xu, Y. Shen, S. Xue and S. Hu, "Fully Planar 2-D Multibeam Millimeter-Wave Antenna With Via-based Phase Shifters", *IEEE Antennas and Wireless Propagation Letters*, Vol. 21, No. 11, pp. 2234-2238, 2022.

[25] J. Wang, Y. Wu, W. Wang and L. Ma, "Wideband mm-Wave High-Gain Multibeam Antenna Array Fed by 4×4 Groove Gap Waveguide Butler Matrix with Modified Crossover", *AEU-International Journal of Electronics and Communications*, Vol. 154, pp. 1-7, 2022.

[26] N. Ashraf, A.R. Sebak and A.A. Kishk, "PMC Packaged Single-Substrate 4×4 Butler Matrix and Double-Ridge Gap Waveguide Horn Antenna Array for Multibeam Applications", *IEEE Transactions on Microwave Theory and Techniques*, Vol. 69, No. 1, pp. 248-261, 2020.

[27] P. Kumar, T. Ali, O.P. Kumar, S. Vincent, P. Kumar, Y. Nanjappa and S. Pathan, "An Ultra-Compact 28 GHz Arc-Shaped Millimeter-Wave Antenna for 5G Application", *Micromachines*, Vol. 14, No. 1, pp. 1-10, 2022.

[28] R.K. Singh and K. Mamta, "A Compact Novel Quad Patch High Gain Triple Band Microstrip Antenna for 5G/6G mm Wave Applications", *Journal of Scientific Research*, Vol. 16, No. 1, pp. 187-199, 2024.

[29] B. Mishra, R.K. Verma, N. Yashwanth and R.K. Singh, "A Review on Microstrip Patch Antenna Parameters of Different Geometry and Bandwidth Enhancement Techniques", *International Journal of Microwave and Wireless Technologies*, Vol. 14, No. 5, pp. 652-673, 2022.

[30] M.M. Patel, "A Review on Comparative Analysis of VSWR Effect on Microstrip Patch Antenna: Analysis based on Various Feeding Techniques", *International Journal for Scientific Research and Development*, Vol. 3, No. 1, pp. 30-34, 2015.

[31] S. Singh and J. Kumar, "A Review Paper on Rectangular Microstrip Patch Antenna", *National Conference on Industry 4.0 (NCI-4.0)*, pp. 127-133, 2020.

[32] M.E. Munir, S.H. Kiani, H.S. Savci, M. Marey, J. Khan, H. Mostafa and N.O. Parchin, "A Four Element mm-Wave MIMO Antenna System with Wide-Band and High Isolation Characteristics for 5G Applications", *Micromachines*, Vol. 14, No. 4, pp. 1-7, 2023.

[33] T. Islam, F.N. Alsunaydih, F. Alsaleem and K. Alhassoon, "Analyzing the Performance of Millimeter Wave MIMO Antenna under Different Orientation of Unit Element", *Micromachines*, Vol. 14, No. 11, pp. 1-9, 2023.

[34] S.R. Agilesh, B.T. Madhav, A. Gangadhar and S.S. Chintalapati, "Design of Dual Band Substrate Integrated Waveguide (SIW) Antenna with Modified Slot for Ka-Band Applications", *Engineering, Technology and Applied Science Research*, Vol. 14, No. 4, pp. 14923-14928, 2024.

[35] R.N. Tiwari, D. Sharma, P. Singh and P. Kumar, "A Flexible Dual-Band 4×4 MIMO Antenna for 5G mm-Wave 28/38 GHz Wearable Applications", *Scientific Reports*, Vol. 14, No. 1, pp. 1-15, 2024.

[36] G. Kalyani, T.V. Likitha and A. Elisamma, "A Compact Dual-Band 28/38 GHz Two-Port MIMO Antenna for 5G mm-Wave Applications", *International Journal for Multidisciplinary Research*, Vol. 6, No. 2, pp. 1-10, 2024.

[37] F. Kiouach, M. El Ghzaoui, S. Varakumari, R. El Alami and S. Das, "A Low-Profile Wideband Two Ports MIMO Antenna Working at 38 GHz for mm-Wave 5G Applications", *Journal of Nano and Electronic Physics*, Vol. 15, No. 1, pp. 1-5, 2023.