IJMOT

INTERNATIONAL JOURNAL OF MICROWAVE AND OPTICAL TECHNOLOGY,
VOL.20, NO.3, MAY 2025

Compact Four Port MIMO High Gain HMSIW Slot Antenna for Sub-6 GHz Applications

V Shiva Prasad Nayak* and Manjunathachari K

Dept. of EECE, GITAM (Deemed to be) University, Hyderabad
E-mail: svadthya@gitam.edu*, mkamsali@gitam.edu

***Abstract*- A high-gain and compact size 2 × 2 multi-input multi-output (MIMO) antenna with a half-mode substrate integrated waveguide (SIW) antenna is introduced in this paper for sub-6GHz 5G applications. The material used to develop the structure is FR-4 substrate, which has a dielectric constant of 4.3 and a thickness of 1.6mm. The HMSIW antenna is designed for size miniaturization and further enhancing the substrate for improving gain, and extended to a 4-port MIMO antenna. The CST software is used to create the antenna, extract the simulation results, and fabricate the antenna. The antenna is measured and validated using a Vector network analyzer (VNA) and an anechoic chamber. The proposed work achieves superior performance with high gain (>11.2 dBi), ultra-low ECC (<0.00001), high diversity gain (>9.96 dB), and over 90% radiation efficiency, making it significantly better than previously reported designs for Sub-6 GHz 5G applications.**

***Index Terms*- Extended substrate (ES), Half-mode substrate integrated waveguide (HMSIW), Multi input multi output (MIMO), Substrate integrated waveguide (SIW), Sub-6 GHz.**

I. INTRODUCTION

The use of device-to-device technology, data-driven wireless communication applications, and industrial revolution 4.0 has resulted in a rapid growth of 5G wireless communication technology in recent days. Nowadays, 5G has good transmission capacity and provides good connectivity to multiple devices with relatively less power. This enables advanced applications like virtual reality, smart cities, and driverless vehicles. This will benefit from advanced communication techniques such as 5G to modernize the Internet of Things [1-4]. The operating bands are 3.8 to 4.3 GHz in the US, 4.4 to 4.9 GHz in Japan, and 4.8 to 5.9 GHz in China, which fall under sub-6 6GHz bands. The Federal Communications Commission (FCC) also allotted many bands like 24GHz, 28GHz, 37GHz, 39GHz, 47GHz, 60GHz, and 79GHz [5-6]. These freely licensed frequency bands are widely accessible and popular due to their high throughput, low latency, low power consumption, and cost efficiency. Their performance makes them ideal for electromagnetic testing, medical and radar imaging, and surveillance systems.

The Substrate Integrated Waveguide (SIW) is a planar transmission line from the Substrate Integrated Circuits (SIC) family, designed for high-frequency operation. It is formed by embedding two rows of metallic vias in a dielectric substrate, which connect the top and bottom metal planes. This versatile System on Substrate (SoS) technology implements compact antennas, filters, and other passive or active components.
The uniqueness lies in its specific use of a Half-Mode Substrate Integrated Waveguide (HMSIW) loaded with two optimized slots. This novel combination overcomes the common trade-off by enhancing gain, reducing size, and boosting efficiency. It exhibits exceptional MIMO performance that is crucial for modern systems. The antenna's remarkable versatility across 5G, Wi-Fi 5/6, and C-band satellite is a key differentiator from more specialized designs. This allows a single, compact antenna to serve multiple advanced applications effectively. Its strength is achieving these multi-faceted improvements in one integrated package.

The paper discussed the 2 x 2 MIMO loaded with HMSIW operating under the sub 6-GHz 5G application. Section II discusses the process of converting HMSIW with the extension of the substrate and MIMO antenna analysis, parameters, and design. Results, such as S-parameters, VSWR, DG, MEG, and ECC, are discussed in Section III, and the

conclusion, followed by references, is discussed in further sections.

II. MIMO ANTENA ANALYSIS, PARAMETERS AND DESIGN

The most critical parameter of SIW is holes, their diameter and spacing of vias are represented in Eq. (1) and the standard equation of SIW width is in Eq. (2) [7].

$$d \le \frac{\lambda_g}{5} \quad \text{and} \quad s \le 2d \tag{1}$$

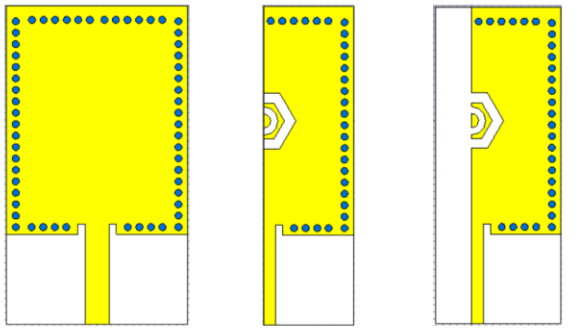
$$a_R = a_S - \frac{d^2}{0.95s} \tag{2}$$

The above equation not adding the ratio of diameter (d) to a waveguide width (a_R), will lead to small error values and the more proper equation is

$$a_{siw} = a_R + 1.08 \times \frac{d^2}{s} - 0.1 \times \frac{d^2}{a_{siw}} \tag{3}$$

The slot antenna is suitable for wireless applications due to its small size, low weight, and easy fabrication compared to other antennas like horns, arrays, etc. This antenna will be implemented in SIW technology as SIW slot antennas and move to cavity-backed antennas due to improved bandwidth, smaller size, and moderate gain [7-8]. A new scheme, named Half-Mode Substrate Integrated Waveguide HSMI)has been proposed for size miniaturization. It can be cut into half vertically or horizontally, representing half-mode SIW, and can operate in half-guided wave modes [4],[9],[13].

Fig.1 shows the design evaluation of the proposed design and the material used as FR-4 with a dielectric constant of 4.3. Fig.1a is the SIW cavity-backed antenna fed by a microstrip transmission line with an impedance of 50 ohms. A Half Mode SIW-shaped antenna is introduced and loaded with two slots for size reductions. The first is half hexagonal and the second is a half-circle, as shown in Fig. 1 b. Fig. 1c shows HMSIW with the extended substrate to enrich the efficiency and gain of the antenna.



(a) SIW (b) HMSIW (c) HMSIW with extended substrate

Fig.1. Proposed design

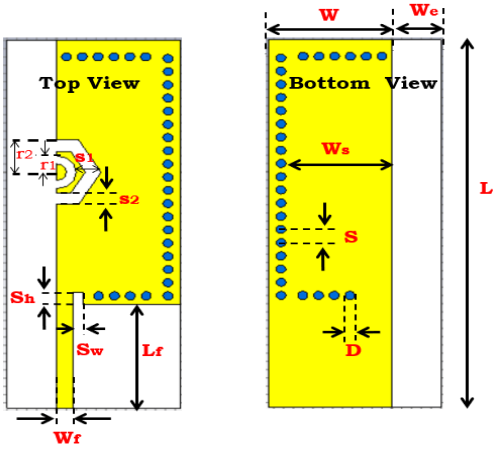


Fig.2. Parameter representation HM-SIW

Table 1. Optimized parameters

Parameters	Dimension (mm)	Parameters	Dimension (mm)
W	12.5	W_f	1.65
L	42.25	r1/r2	4.5/2
L_f	12.25	s1	1
Ws / We	11.25/5	s2	0.5
D / S	1/1.6	S_w / S_h	1.4/1

Fig.2 represents the parametric representation of the HM-SIW antenna, and slots are introduced in the middle of the SIW structure. The left side figure represents the parameters used in the slot design, and the right side indicates the outer parameter

representation. The CST studio suite is used for evaluating the antenna's performance in terms of S_{11}, gain, surface current, VSWR, and far-field pattern. Table 1 presents the parameters used in this design.

The proposed equivalent circuit models the HMSIW structure using via inductors and coupling capacitors, as represented in Fig.3. The configuration of SIW vias will affect the value of inductance, which is noted as Lvias.

The combination of capacitance (Cc) and inductance (Lc) will establish the planar transmission line. The inner slot is designed by lumped elements (R1, L1, C1), and the lumped elements (R2, C2, L2) are chosen to create the outer half hexagonal slot.

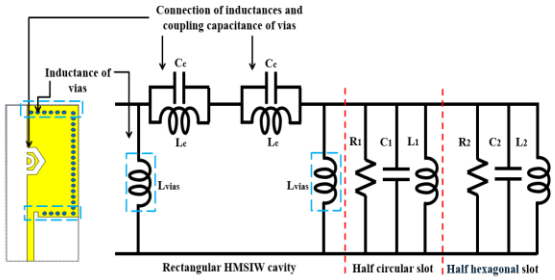


Fig.3. Antenna equivalent circuit

The growth of technology is rapidly increasing due to the provision of services to multiple users. A single antenna is not used, and sthe multiple input multiple output (MIMO) technology is the foundation of the future higher generation communication systems like 4G, 5G, and 6 G. Recently, 5G technology has been launched worldwide to provide the enormous data rates with low latency and has ample capacity in real time to exchange the information between the users [10-12]. Researchers are designing compact MIMO antennas to keep system sizes small to meet high demand and support multiple applications. Therefore, the amalgamation of MIMO technology with multiband functionality gives a prominent solution to this limitation of MIMO antennas. Multiband technologies can be achieved through microstrip feed-based MIMO antennas, which are also suitable for communication system operations due to ease of integration [13-16].

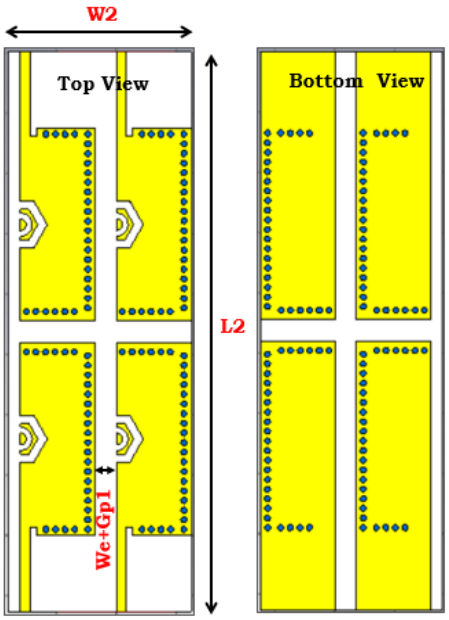


Fig.4. 2 x 2 MIMO antenna

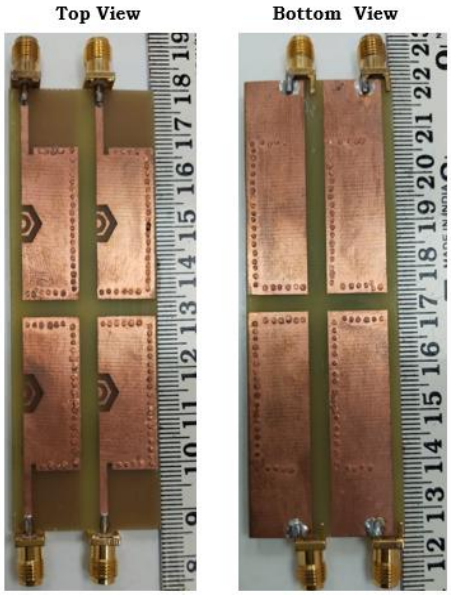


Fig.5. Fabricated prototype

The two 1x2 element MIMO configuration is amalgamated horizontally to get a 2 × 2 element MIMO antenna design, as shown in Fig.4, where the right-side diagram belongs to the bottom view and the left side to the top view. The value Gp1 indicates the separation of two column antenna and the slit between the antennas is enough to prevent significant

coupling that can otherwise degrade the radiation characteristics of the array antenna and dimensions are 91mm x 30.5mm x 1.6mm.



Fig.6. Measurement of proposed designs using VNA and anechoic chamber

The photolytic process is used to fabricate the 2x2 MIMO antenna; the material used in this design is FR-4 substrate with a dielectric constant of 4.3. The pictorial view of the top and bottom views of the fabricated prototype is shown in Fig. 5. Fig. 6 shows the measured photographs of the antenna, where the left side indicates the VNA Setup and the right side indicates the anechoic chamber.

III. RESULTS AND DISCUSSION

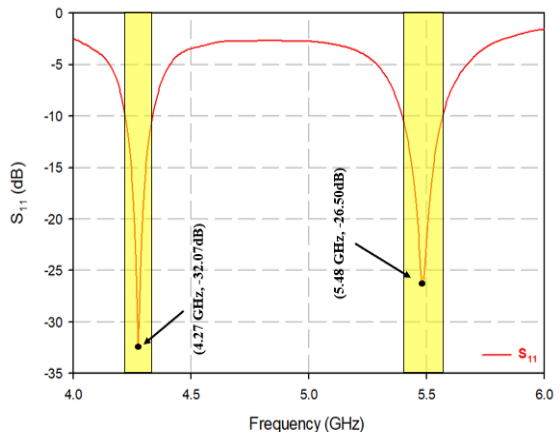
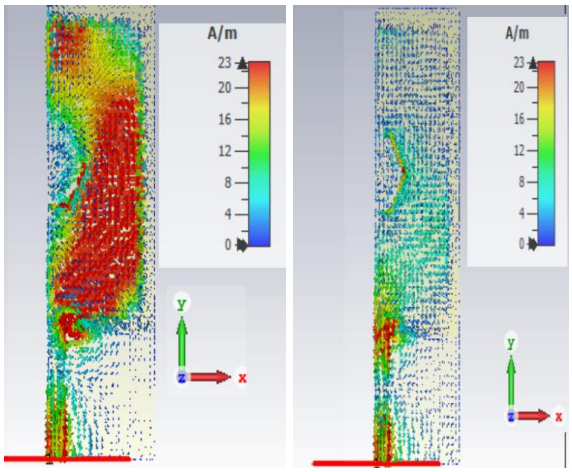


Fig.7. Reflection coefficient

Fig. 7 represents the S_{11} of the proposed design over the frequency range 4 to 6 GHz and is operated at two frequencies, i.e., 4.27 GHz and 5.48 GHz. The operating bandwidth of the proposed design is 120 MHz at 4.27 GHz resonant frequency (4.22 GHz to 4.34 GHz), 180 MHz at 5.48 GHz resonant frequency (5.39 to 5.57 GHz), with a -10dB baseline and well suited to operate in sub-6GHz applications.



(a) 4.27GHz (b) 5.48GHz

Fig.8. Surface current

The surface current of the antenna is shown in Fig. 8, where Fig. 8a and 8b portray the surface current of the antenna operated at 4.27 GHz and 5.48 GHz, respectively. In both frequencies, current flow is high at the feed point and higher at the outer circle's edge in Fig. 8a, i.e., 4.27GHz resonant frequency.

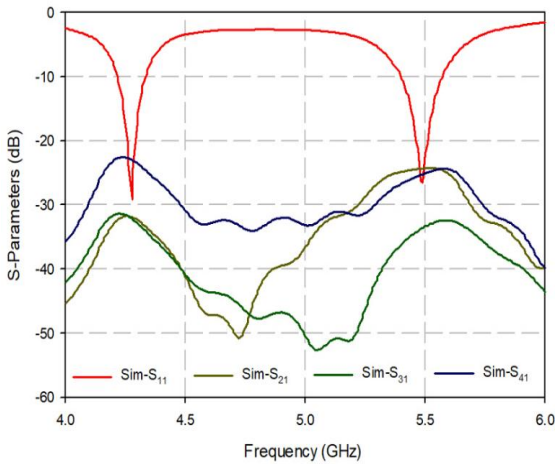


Fig.9. S-Parameters of 2 x 2 MIMO antenna

According to the symmetry configuration, the S

result is $S_{11} = S_{22} = S_{33} = S_{44}$, $S_{12} = S_{21} = S_{23} = S_{32}$, $S_{14} = S_{41} = S_{43} = S_{34}$ and $S_{13} = S_{24} = S_{31} = S_{42}$. For simplicity, the results of the S_{11}, S_{21}, S_{31}, and S_{41} are described in Fig. 9.

The S_{21}, S_{31}, S_{41} values are -32dB, -31.5dB, -23.2dB at 4.27 GHz resonant frequency, and -24.5dB, -33dB, -25dB at 5.48 GHz resonant frequency, and also show isolation between ports < -20dB over the operating band [10].

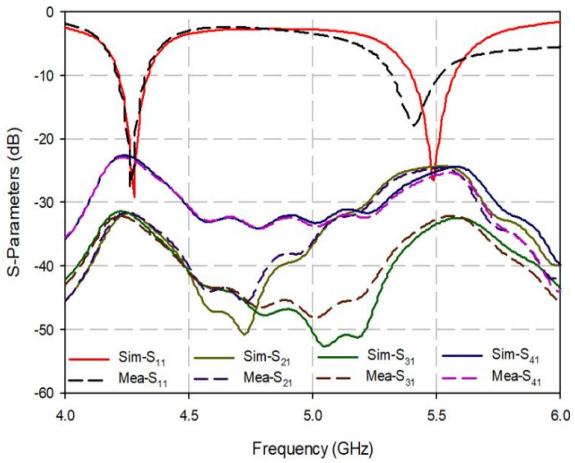


Fig.10. S- Parameters validation

Fig. 10 represents the S-parameter validation of a 2 x 2 MIMO antenna. The notation "Sim" used in the figure is simulation results, and "Mea" used in the figure is measured results. The comparison of S_{11} in terms of simulation and measured results over the frequency range 4 to 6 GHz, as observed in compromised results. There is a slight deviation at the second resonant frequency due to a little deviation that occurred while etching and filling the copper in the antenna. The measured antenna resonates at 4.28GHz (operating bandwidth 120 MHz), 5.4GHz (Operating bandwidth is 180MHz), and their S_{11} values are -27dB, -18 dB. The simulation measured S_{21} value is -32dB, -31.2 dB at 4.27 GHz frequency, and -24.5 dB, -24.22 dB at 5.48 GHz resonant frequency. The simulation measured S31 value is -31.5dB, -32 dB at 4.27 GHz frequency, and -33 dB, -32.72 dB at 5.48 GHz resonant frequency. The simulation measured S_{41} value is -23.2 dB, -23.4 dB at 4.27 GHz frequency, and -25 dB, -25.22 dB at 5.48 GHz resonant frequency. From the S parameter results, it is stated that a 2 x 2 MIMO antenna has isolation between the ports, with a value of less than <- 20 dB.

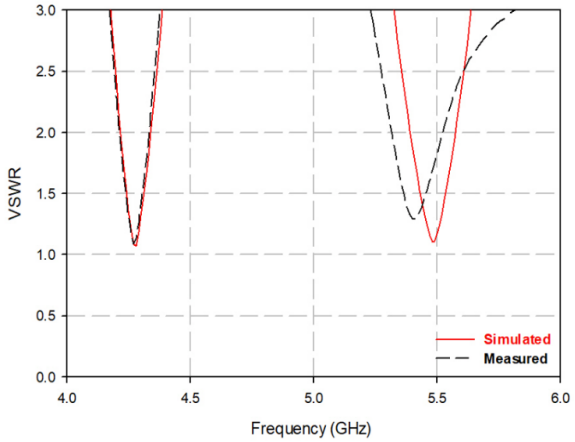


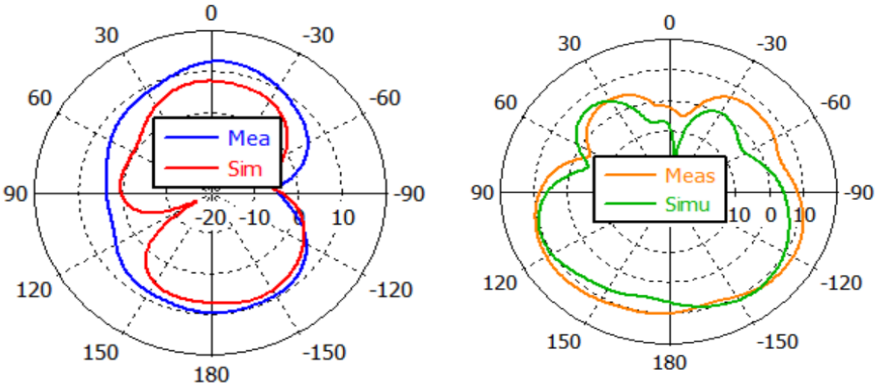
Fig.11. Voltage standing wave ratio

Fig. 11 compares the simulation and measured results over the 4 to 6 GHz frequency range. These results match the S_{11} = -10dB reference line. The simulation VSWR results resonate two frequencies, 4.28GHz and 5.4GHz, and their values are 1.1 and 1.32, respectively.

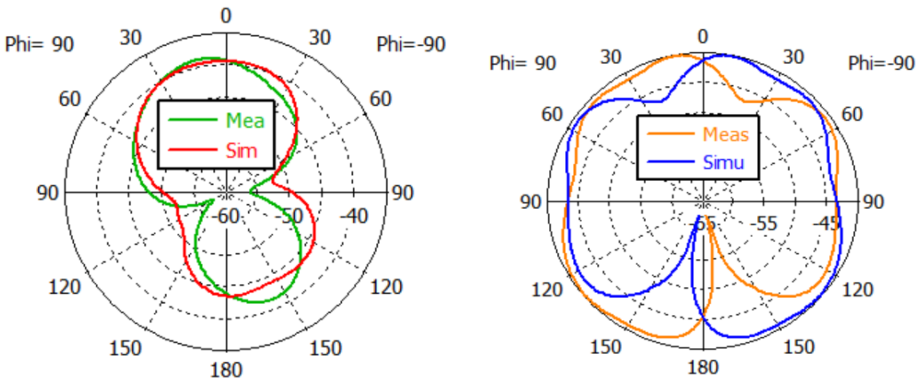
The measured VSWR resonates two frequencies, which are 4.28GHz and 5.5GHz; their values are 1.1 and 1.2. There is a slight deviation at the second resonant frequency due to a little deviation that occurred while etching and filling the copper in the antenna. Fig. 12 (a) describes the results of the e-field of two frequencies, 4.27 GHz and 5.48 GHz, respectively. Fig. 12 (b) illustrates the results of the h-field of two frequencies, 4.27 GHz and 5.48 GHz, respectively. The acceptable agreement between the simulation and the measured results. It is observed that radiation is bidirectional and optimistic for wireless applications.

The radiation and total efficiency obtained for the antenna design are recorded in Fig. 13, and the red line indicates transmission efficiency. In contrast, the blue line indicates the radiation efficiency of the antenna. The radiation, total efficiencies are 86.1%, 84.1% at a 4.27 GHz resonant frequency, and 91.6%, 87.2% at a 5.48 GHz resonant frequency, respectively. The Gain in dBi over

frequency is represented in Fig. 14 for simulated and measured results. The simulated gain values are 11.1dBi, 11.3dBi, 12.6 dBi, 12.4 dBi at frequencies 4.2 GHz, 4.3 GHz, 5.48 GHz, 5.6 GHz respectively, and their measured values are 11.02dBi, 11.27dBi, 12.62dBi, 12.45dBi over the frequencies 4.2 GHz, 4.3 GHz, 5.48 GHz, 5.6 GHz respectively. Table 2 compares proposed antennas with existing literature, and the chosen antenna is a 4-port MIMO antenna. The parameters to be discussed are size, operating bands, Number of elements, Gain in dBi, Bandwidth (MHz), VSWR, efficiency, ECC, and DG. Concerning MIMO parameters like ECG & DG, the proposed MIMO antenna has better ECG value (<0.000001) and DG (<9.965) in the entire operating band compared with existing literature. With respect antenna results, the proposed antenna has more gain that is more than 11 dBi, less size, operated in two frequencies, more accuracy interms of VSWR, high efficiency comparing with the existing literature reported in the table and also observed moderate bandwidth comparing with the literature [14], [18].



(a)



(b)

Fig.12. Radiation Pattern (a) E-field: Right 4.27 GHz, left 5.48 GHz (b) H-field: Right 4.27 GHz, left 5.48 GHz

Table 2. Comparison of the proposed work with similar literature

Ref.	No. of Elements	Antenna size [mm^3]	Operating frequency (GHz)	Gain in (dBi)	Bandwidth (MHz)	VSWR	Efficiency (%)	ECC	DG (dB)
[14]	4	110 x 110 x 1.6	4.4	5	550	-	-	<0.004	-
[15]	4	89 x 86 x 1.6	2.4/ 5.8	2-4	72,175	-	-	<0.05	9.95
[16]	4	50 x 50 x 12.5	4.5/5.5	5	220	-	-	< 0.1	10
[17]	4	310 x 240 x 1.6	5.5	6.6	50	1.3	85-90	<0.005	10
[18]	4	80 x 80 x 1.6	4.8	3	400	-	60	0.1	10
Proposed work	4	91 x 31.5 x 1.6	4.27/ 5.48	11.2-12.6	120, 180	1.1, 1.32	86-92	<0.000001	9.97

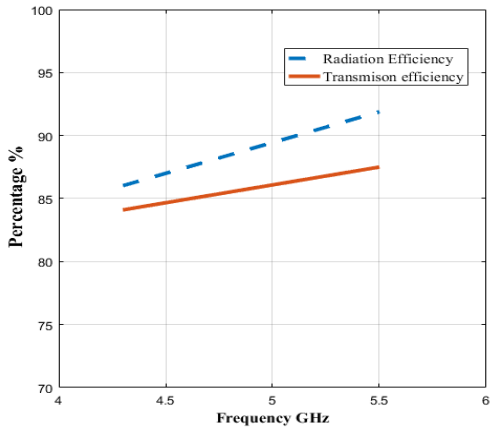


Fig.13. Efficiencies of the antenna

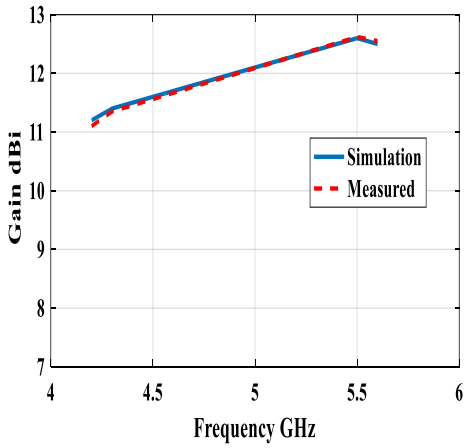


Fig.14. Gain in dB

The ECC and DG parameters are generally preferred values to validate the MIMO antenna, and their result is discussed in the preceding sections

A. Envelope Correlation Coefficient (ECC)

The quantity of similarity between the antenna ports concerning radiated signals is noted as ECC. It computes the similarity or correlation of the signal envelopes, other than the magnitude or phase of the signals themselves. The ideal value of the ECC should be zero, but in a practical situation, the tolerable value of ECC is below 0.5. The ECC's 2 x 2 MIMO array magnitude is shown in Fig. 15 and is observed as less than 0.0001 for all operating frequency bands.

ECC value is [11-12].

$$\mathrm{ECC} = \frac{|S_{11}^{*}S_{12} + S_{22}S_{21}^{*}|^2}{(1-|S_{12}|^2-|S_{22}|^2)\,(1-|S_{12}|^2-|S_{22}|^2)} \quad (4)$$

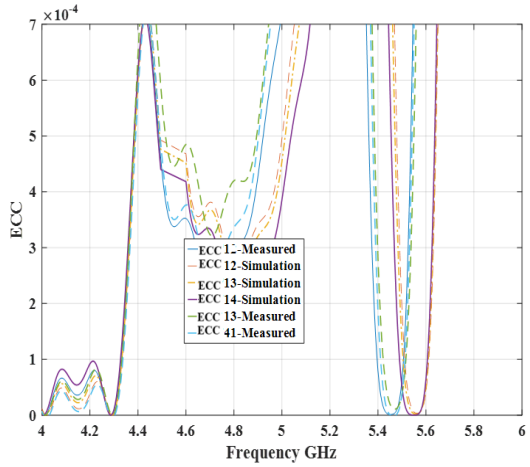


Fig.15. ECC of proposed 2 x 2 Antenna

B. Diversity Gain (DG)

DG is another essential feature used to evaluate MIMO performance and is expressed in terms of ECC, as represented in Eq. (5) [10]. If the DG is 10 dB, the SNR or BER will increase tenfold, equated to a single-antenna system. Fig. 16 represents the comparison of simulation, measured 2 × 2 MIMO antenna, and has a DG value of more than 9.9962 dB at 4.27 GHz resonant frequency and 9.975 dB at 5.48 GHz operating frequency. The proposed antenna has been proven effective in combating fading, with less system performance. The DG and ECC are correlated with an inversely proportional relation, indicating that decreasing ECC will increase the value of diversity gain [11-12].

$$DG = 10\sqrt{1 - ECC} \tag{5}$$

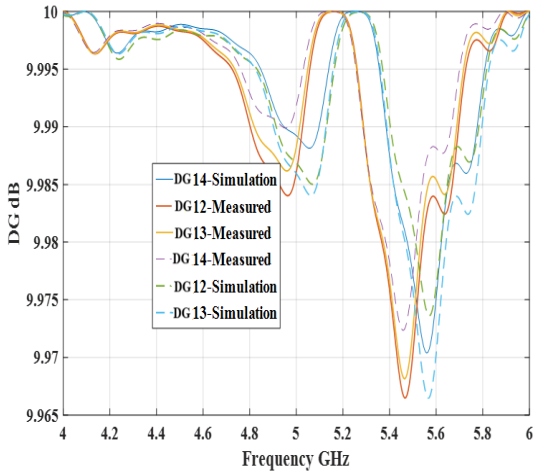


Fig.16. Diversity gain (DG)

C. Mean Effective Gain (MEG).

This measures the antenna's gain in a desired direction, ranging from −3 dB ≤ MEG ≤ −12 dB [16-18]. The formula used to find the MEG is in Eq. (6). Figure 17 represents the MEG between the ports and shows that it lies between -3.1 dB and -3.3 dB over the operating frequency band.

$$MEG_{\mathrm{i}} = 0.5\left(1 - |S_{\mathrm{ii}}|^2 - \left|S_{ij}\right|^2\right) \tag{6}$$

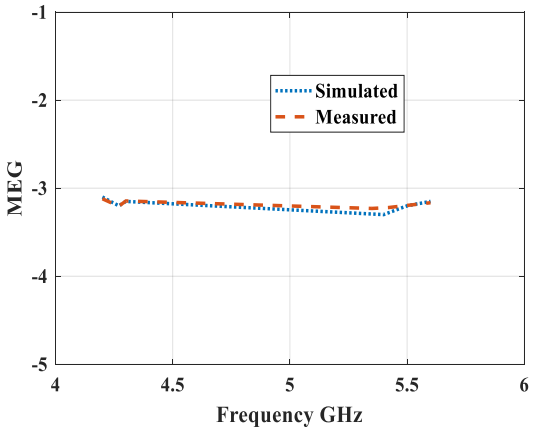


Fig.17. Mean effective gain (MEG)

IV. CONCLUSION

The half-mode SIW enhanced substrate with slot antenna for sub-6GHz 5G applications has been introduced. Further, invented to 2x 2 MIMO for better use of 5G applications as it resonates 4.27GHz, 5.48GHz, and is well suited for wireless applications. The impedance bandwidth of the 2 x 2 MIMO is 120 MHz at 4.27 GHz frequency, 220 MHz at 5.48 GHz frequency, and as sound isolation between the ports (1-2, 1-3, 1-4) that is less than -20dB at every operating frequency. As simulated, the 2 X 2 MIMO antenna has 91 x 31.5 x 1.6 mm^3 dimensions. The antenna was fabricated, measured, and validated. There is a slight deviation in the simulation and measured results due to small fluctuations during fabrication. The gain, radiation efficiency, and total efficiency values are 11.2 dB. 86.1%, 84.1% at 4.27 GHz resonant frequency, 12.5dB, 91.6%, 87.2% at 5.48 GHz resonant frequency. The ECC value is <0.000001, the MEG value is -3.1 dB to -3.3 dB, and the diversity gain DG is more than 9.965 dB, which shows that the MIMO antenna has maintained radiation between radiating elements.

REFERENCES

[1] D. Manoj, U. Shrivastava and V. K. Verma, “A Study on 5G Technology and Its Applications in Telecommunications”, *International Conference on Computational Performance Evaluation (ComPE)*, Vol. 22, pp. 365–371, June. 2021.

[2] Kumari, P., Das, S., “A Wideband Circularly Polarized SIW MIMO Antenna Based on Coupled QMSIW and

EMSIW Resonators for Sub-6 GHz 5G Applications," *IEEE Antennas and Propagation Letters*, Vol. 23, No. 10, pp. 2979–2984, Oct. 2024.

[3] I. Ishteyaq and K. Muzaffar "Multiple Input Multiple Output (MIMO) and Fifth Generation (5G): An Indispensable Technology for Sub-6 GHz and Millimeter Wave Future Generation Mobile Terminal Applications", *International Journal of Microwave and Wireless Technologies*, Vol. 11, pp. 1–17, Dec. 2021.

[4] B.J. Niu and J.H Tan, "Halfmode SIW Cavity Antenna for Tri-Band MIMO Applications", *Microwave and Optical Technology Letters*, pp. 1–5, Nov. 2019.

[5] N.M. Kumar and T. Shanmuganantham, "Broadband I-shaped SIW Slot Antenna for V-Band Applications", *Applied Computational Electromagnetic Society (ACES)*, Vol. 34, No. 11, pp.1719-1724, Nov. 2019.

[6] Meena, R.K., Avinash, D., Dabhade, M.K., Srivastava, K., Kanaujia, B.K., "Antenna Design for Fifth Generation (5G) Applications", *URSI Asia-Pacific Radio Science Conference (AP-RASC)*, pp. 1–4, March 2022.

[7] J. Hirokawa, and M. Ando, "Model Antenna of 76 GHz Post-Wall Waveguide Fed Parallel Plate Slot Arrays", *IEEE AP-S International Microwave Symposium Digest*, Vol. 1, pp. 146–149, June. 1999.

[8] M.N. Kumar and T. Shanmuganantham, "Broadband Substrate Integrated Waveguide Venus Shaped Slot Antenna for V-Band Applications", *Microwave and Optical Technology Letters*, Vol. 61, No. 10, pp. 2342–2347, Oct. 2019.

[9] B.J. Niu and Y.J. Cao, "Bandwidth-Enhanced Four-Antenna MIMO System Based on SIW Cavity," *Electronics Letters*, Vol. 56, No. 13, pp. 643–645, July 2020.

[10] Tirado-Méndez, J.A., Jardón-Aguilar, H., Rangel-Merino, A., Vásquez-Toledo, L.A., Gómez-Villanueva, R., "Four Ports Wideband Drop-Shaped Slot Antenna for MIMO Applications", *Journal of Electromagnetic Waves and Applications*, Vol. 34, No. 9, pp. 1159–1179, Sep. 2021.

[11] L. Malviya, and S. Chouhan, "Multi-Cut Four-Port Shared Radiator with Stepped Ground and Diversity Effects for WLAN Application", *International Journal of Microwave and Wireless Technologies*, Vol. 11, No. 10, pp. 1044–1053, Oct. 2022.

[12] I.N. Khalid, R. Hussain, M. Fawad, Y.Amin, and S.S. Mirjavadi,, "4-Port MIMO Antenna with Defected Ground Structure for 5G Millimeter Wave Applications", *Electronics*, Vol. 9, No. 1, pp. 71–72, Jan. 2020.

[13] V. S. P. Nayak and K. Manjunathachari, "Design and Analysis of Tri-band Quarter Mode SIW Antenna for Sub-6GHz, WLAN and WiFi Applications," *Proc. Int. Conf. Trends Material Sci. Inventive Mater. (ICTMIM)*, pp. 1–4, doi: 10.1109/ICTMIM65579.2025.10988196. May 12, 2025.

[14] J.A. Tirado-Méndez, H. Jardón-Aguilar, A. Rangel-Merino, L.A.Vásquez-Toledo, and R. Gómez-Villanueva, "Four Ports Wideband Drop-Shaped Slot Antenna for MIMO Applications", *Journal of Electromagnetic Waves and Applications*, Vol. 34, No. 9, pp. 1159–1179, Sep. 2020.

[15] A.Birwal, S.Singh, B.K Kanaujia, and S.Kumar "Low-Profile 2.4/5.8 GHz MIMO/Diversity Antenna for WLAN Applications", *Journal of Electromagnetic Waves and Applications*, Vol. 34, pp. 1283–1299, Oct. 2020.

[16] I. Din, M. Alibakhshikenari, B. S. Virdee, S. Ullah, and M. Akram, "High Performance Antenna System in MIMO Configuration for 5G Wireless Communication Over Sub-6 GHz Spectrum", *Radio Science*, Vol. 58, pp.1-22, Oct. 2023.

[17] J. Khan, S. Ullah, F.A.Tahir, F. Tubbal, and R. Raad "A Sub-6 GHz MIMO Antenna Array for 5G Wireless Terminals", *Electronics*, Vol. 10, April 2021.

[18] Ali, H., Ren, X.C., Bari, I., Bashir, M.A., Hashmi, A.M., Khan, M.A. and Anjum, M.R., "Four-Port MIMO Antenna System for 5G n79 Band RF Devices", *Electronics*, Vol. 11, pp. 35–36, Jan. 2021.