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Machine Learning Assisted Design and Optimization of a Dual-Port SIW Antenna with LP-to-CP Conversion for sub-6 GHz 5G Communication System

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Abstract: In this paper, a machine learning assisted dual-port substrate integrated waveguide (SIW) antenna with linear to circular polarization (LP-to-CP) conversion is proposed for sub-6 GHz 5G communication systems. The proposed design couples the SIW cavity with the polarization converting structure for the conversion of linearly polarized waves to circularly polarized radiation with dual-port MIMO operation. The optimization of the critical antenna parameters is performed using the Artificial Neural Network (ANN) and Random Forest (RF) algorithms, and the design process is accelerated by using data from simulation. The optimized antenna shows an impedance bandwidth of 4.7-5.25 GHz covering the sub-6 GHz 5G spectrum and a 3-dB axial-ratio bandwidth of 4.9-5.18 GHz. A peak gain of 9.5 dBi is achieved over the operating band. The combination of SIW technology, LP-to-CP conversion, dual-port operation, and ML-assisted optimization provides a compact high-gain solution for polarization-robust sub-6 GHz 5G wireless communication applications.

Keywords: MIMO Antenna, Circular Polarization, SIW Antenna, Machine Learning

I. Introduction

The need for high-speed and reliable wireless communication has prompted the development of multiple-input-multiple-output (MIMO) antennas. MIMO technology uses multiple antenna elements to increase the channel capacity, data rate and link reliability. But the close proximity of elements causes strong mutual coupling, which degrades the performance of MIMO. To suppress coupling, many techniques have been studied, such as neutralization lines, superstrates, electromagnetic band-gap structures, and diversity schemes [1-4]. The circularly polarized (CP) antennas can reduce the polarization mismatch and improve the reliability of communication, which make the CP-MIMO antennas attractive for the modern wireless systems [5].

SIW technology has the advantages of low loss, high power handling capability, electromagnetic shielding and compactness [6]. The antenna size can be further reduced by

fractional-mode SIW configurations such as half-mode, quarter-mode, and eighth-mode resonators [7-8]. However, wide impedance bandwidth, wide axial-ratio (AR) bandwidth, and high port isolation are difficult to be realized at the same time for CP SIW-MIMO antennas [9–11].

The computational complexity of electromagnetic (EM) simulations is increasing, especially for antenna optimization in the high-frequency and THz regimes. Machine learning (ML) has been adopted as an efficient surrogate modelling technique. ML algorithms can learn the relationship between the antenna geometrical parameters and the performance characteristics from the datasets generated by simulation, thus decreasing the repeated full-wave simulations. Previous studies [12–15] have used support vector machines, artificial neural networks (ANN), K-nearest neighbours, XGBoost, random forest, and other ML techniques for antenna modelling and optimization at microwave frequencies.

In an effort to address the above challenges, this work proposes a machine-learning-assisted dual-port SIW antenna with LP-to-CP conversion for sub-6 GHz 5G applications. The proposed antenna combines the SIW technology and the polarization converting structure to realize the circularly polarized radiation and keep the dual-port MIMO operation. To minimize the reliance on repeated full-wave simulations, Artificial Neural Network (ANN) and Random Forest (RF) algorithms are employed to optimize the key geometrical parameters from the data obtained by the simulations. The optimized antenna shows an impedance bandwidth of 4.7-5.25 GHz, 3-dB axial-ratio bandwidth of 4.9-5.18 GHz and a peak gain of 9.5 dBi, which demonstrates its suitability for polarization-robust sub-6 GHz 5G communication systems.

II. Antenna Layout

The dual-port SIW-MIMO antenna is designed on FR4 substrate of 1.6 mm thickness, 4.4 relative permittivity and 0.02 loss tangent. The overall antenna has a compact rectangular area of $40 \times 80 \text{ mm}^2$. The proposed antenna comprises a SIW cavity with periodic metallic vias, a circular-ring defect, and rectangular slot. A metasurface is suspended over the dual port for converting linear waves into circular field. For metasurface design, FR4 substrate is utilised. The overall antenna design is shown in Fig.1 with its dimensions is mentioned in the caption of Fig. 1

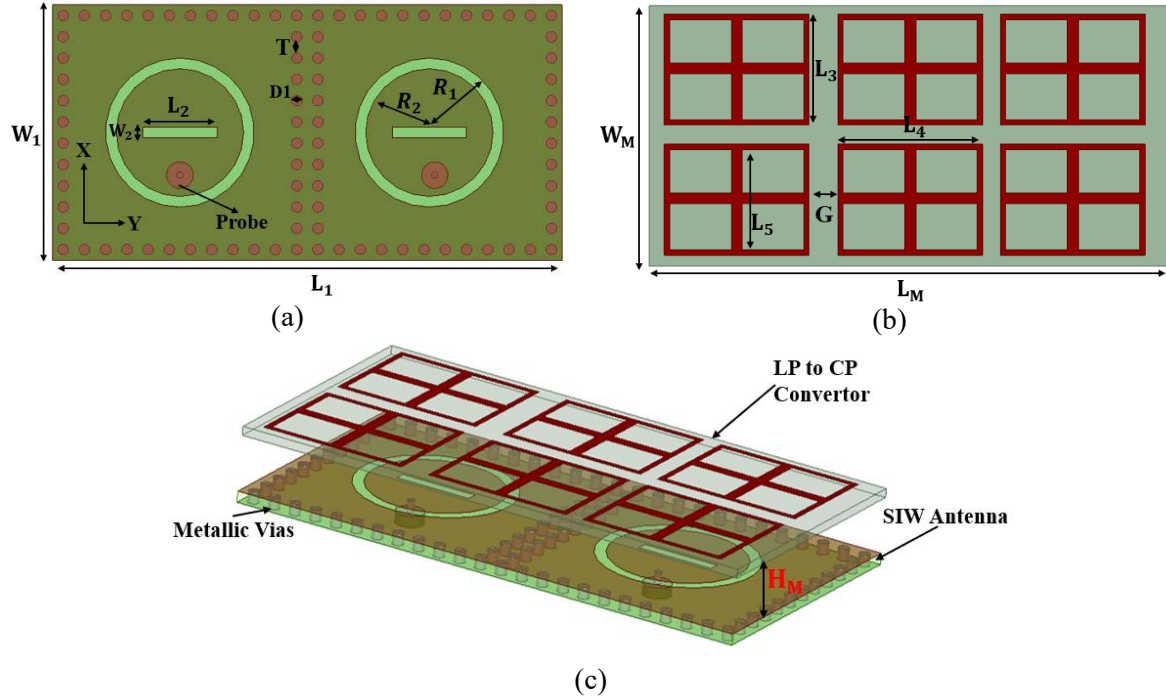


Fig. 1 Two-port SIW Antenna Layout (a) SIW Antenna (b) LP to CP Converter (c) 3D view of final radiator; $W_1=40.0$; $L_1=80.0$; $H_M=7.0$; $L_2=14.0$; $L_3=20.5$; $L_4=26.7$; $L_5=$; $W_2=2.0$; $T=0.5$; $D1=1.0$; $R_1=14.0$; $R_2=12.0$; $G=4.0$; $W_M=40.0$; $L_M=80.0$ (all dimensions are in mm)

III. Antenna Analysis

The proposed antenna configuration is modelled, simulated and optimized by using Ansys HFSS software. The design process was carried out systematically and iteratively, with the antenna parameters being progressively adjusted to attain the desired electromagnetic performance. Each design stage was evaluated by means of full-wave electromagnetic simulations before passing to the next optimization stage. Fig. 2 shows the evolution of the $|S_{11}|$ at the different steps of antenna design. In the first configuration, which is a probe-fed rectangular slot, without metallic vias, a weak resonance is obtained at 5.0 GHz. The resonance is significantly strengthened by introducing metallic vias. Next, the ring defect is incorporated in the via-loaded configuration resulting in improvement in impedance bandwidth. The SIW configuration offers high electromagnetic confinement and low radiation leakage, which may impose an intrinsic limitation on the impedance bandwidth. The employment of properly designed slots and resonant perturbations introduces additional resonances and improves impedance matching, thus leading to an overall bandwidth enhancement.

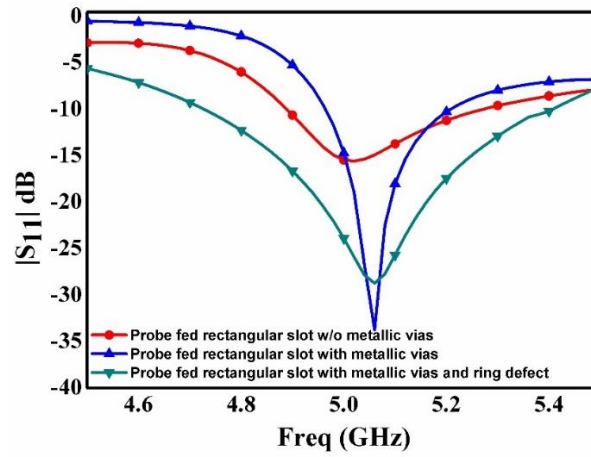


Fig.2 Evolution of $|S_{11}|$ at the different steps of antenna design

Fig. 3 shows the S-parameters of single and dual port antenna. The similar $|S_{11}|$ responses for single and dual port configurations indicate that the impedance variation is small after adding the second port. The $|S_{12}|$ in the operating band is below -25 dB, which shows the good port isolation. The low mutual coupling is attributed to the SIW via walls, which can suppress lateral electromagnetic leakage and confine the near-field energy in the individual cavities, thus improving the MIMO performance.

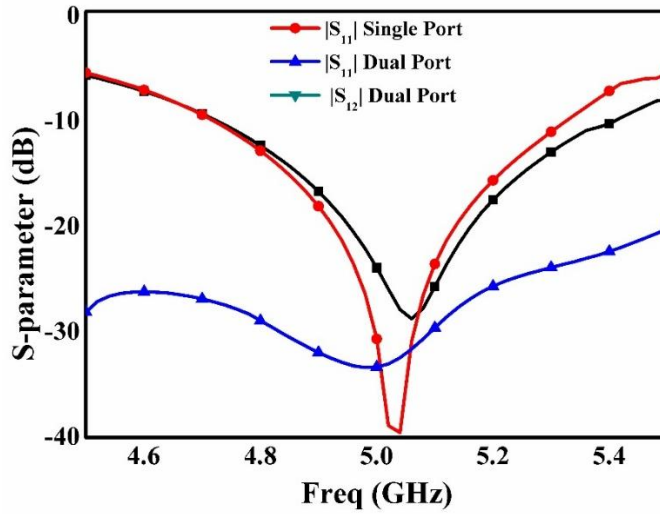


Fig. 3 S-parameters of single and dual port antenna

Fig. 4 compares the broadsided gain of the antenna without and with SIW concept. The antenna gain without SIW is relatively low and varies between about 2.0 and 3.0 dBi. In contrast, the gain is significantly enhanced by employing the SIW structure, from 8.9 to 9.7 dBi in the operating band. The gain improvement can be explained by the field-confinement and low-loss guiding features of the SIW structures, which causes a reduction of unwanted electromagnetic leakage and an improvement of the concentration of the radiated energy in the desired direction. The SIW cavity also helps to reduce the surface-wave losses which leads to more efficient radiation.

A periodic metasurface (MS) is integrated on top of the radiating elements to improve the overall performance of the proposed two-port antenna. The MS is a periodic structure composed of identical unit cells, which changes the interaction and propagation of the electromagnetic waves in the antenna environment. The effective permeability/permittivity parameters of the MS in relation to the frequency are presented in Fig. 5. Results show that the effective permeability remains positive while the effective permittivity takes negative values in the desired operating band. The combination of material properties confirms the single-negative (SNG) behaviour of the proposed MS [16].

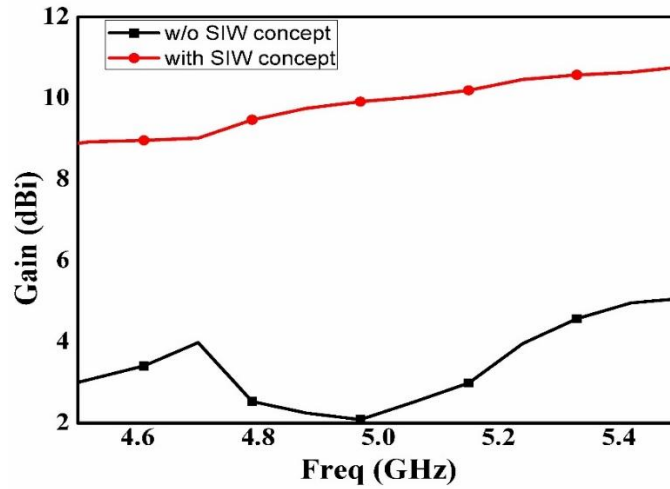


Fig. 4 Broadside gain of the antenna without and with SIW concept

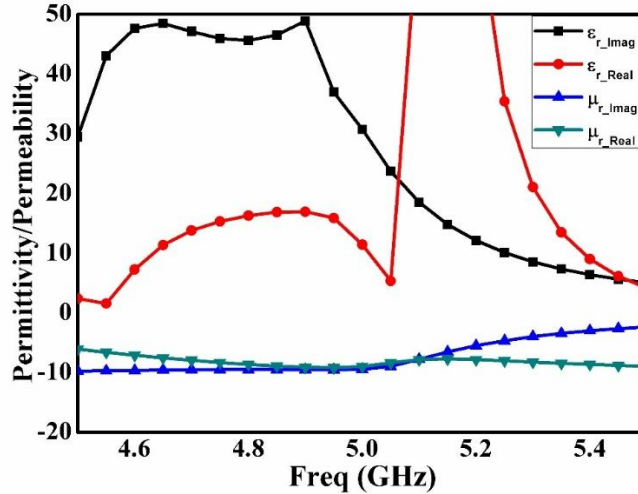


Fig. 5 Effective permittivity/permeability curve for unit cell

SNG MS is placed over the proposed antenna to enhance its EM performance. Fig. 6 shows S-parameters before and after MS integration. The $|S_{11}|$ response is nearly unaffected and the inter-port isolation is greatly improved exceeding 40dB over the operating band. The enhanced isolation is a consequence of the SNG properties of the MS that suppress surface-wave coupling between the closely packed silicon dielectric resonators. Thus, the mutual coupling is reduced which enhances the performance of MIMO [16]. Fig. 7 shows a comparison between

the axial-ratio (AR) response of the proposed radiator with and without MS. The addition of the MS significantly changes the polarization characteristics and results in CP radiation in the 4.91–5.09 GHz. This behaviour is realized by proposed unit-cells. The MS converts the incident linearly polarized field into two orthogonal components with nearly equal amplitude and phase difference of about 90° , thus fulfilling the fundamental requirement for the generation of CP radiation [17].

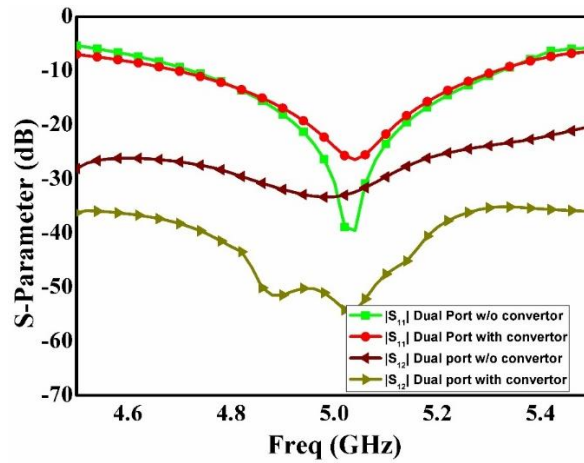


Fig. 6 S-parameter curve with and without polarization convertor/MS

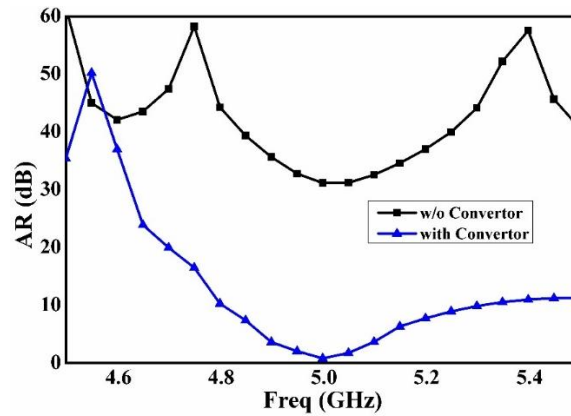


Fig. 7 AR curve with and without polarization convertor/MS

Fig. 8 depicts the effect of MS height (H_M) on the axial-ratio response of the proposed antenna. As ' H_M ' increases from 5.0 to 7.0 mm, the AR around the resonant frequency is greatly decreased. The lowest AR is achieved for $H_M = 7.0$ mm, with a value of approximately 1 dB at around 5.0 GHz. This behaviour is attributed to variation of the electromagnetic coupling and the phase balance between the orthogonal field components due to the MS spacing variation.

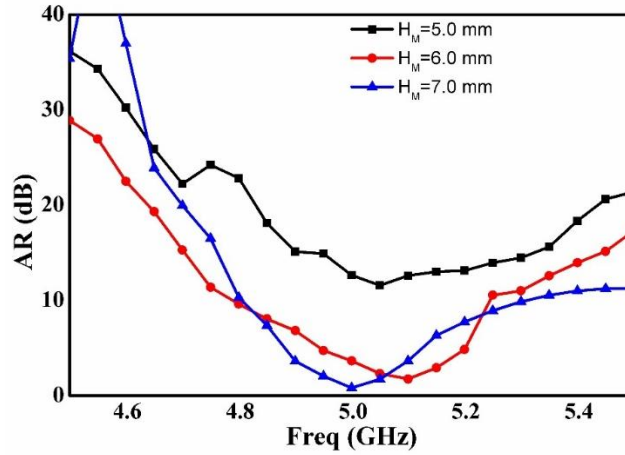


Fig. 8 AR curve with variation in ' H_M '

IV. $|S_{11}|$ Prediction using ML

The proposed radiator's reflection coefficient ($|S_{11}|$) is estimated using two supervised machine learning (ML) algorithms, namely Artificial Neural Network (ANN) and Random Forest (RF). For this purpose, a comprehensive dataset is generated based on full-wave EM simulations in the HFSS environment. The geometrical parameters of the radiator are varied systematically in the predefined ranges. Specifically, the parameters ' R_1 ', ' R_2 ', ' W_2 ', ' L_2 ' and ' H_M ' are varied in the range 9.0-16.0 mm, 9.0-16.0 mm, 0.5-3.5 mm, 12.0-17.0 mm and 5.0-9.0 mm respectively with a step interval of 0.1 mm. The frequency range 4.5-5.5 GHz and 201 frequency sampling points are used for each geometrical configuration in the calculation of EM response.

This HFSS simulation data gives about 114569 data samples which are used to develop and validate the ML models. The whole data set is randomly split into training and testing sets, where 80% of the samples are used for training and 20% for testing. The input features are the selected geometrical parameters and the operating frequency, while the corresponding electromagnetic response, especially ($|S_{11}|$), is taken as the prediction target. The developed ANN and RF models are trained to find the nonlinear relation between dimensions of the radiator and its simulated EM characteristics. Then the trained models are able to produce fast predictions, without the need of a separate full-wave simulation for each geometrical configuration. The predictive capability of both ML models is evaluated using three widely used statistical measures, namely Mean Absolute Error (MAE), Mean Squared Error (MSE) and coefficient of determination (R^2). MAE measures the mean of absolute deviation between predicted value and reference value. MSE is the average of squared deviations and therefore it magnifies large prediction errors. The R^2 score describes how much of the variability of the

target variable is explained by the model. A value close to 1.0 indicates that the model is a good fit to the HFSS generated results [14].

The predictive performance of developed machine learning algorithms is evaluated by comparing respective error and goodness-of-fit metrics. Table-1 shows a comparative evaluation of the ANN and Random Forest (RF) models on the selected performance indicators. The obtained results show that the prediction capability of both models is good in terms of reflection coefficient ($|S_{11}|$) with a prediction accuracy more than 75%. This validates the ability of data-driven models to provide a good estimate of the electromagnetic response of the proposed radiator. A comparative analysis also shows that the Random forest model has better predictive performance as compared to the ANN model. Specifically, the RF model shows lower prediction errors and a better agreement with the results from HFSS for $|S_{11}|$ prediction.

Table-1 Comparative assessment of ANN and Random Forest models for $|S_{11}|$ prediction based on MAE, MSE, and R^2 metrics

ML Method	MAE	MSE	R^2
ANN	0.996	5.048	0.744
RF	0.886	4.667	0.891

The comparison between the real and ML-predicted $|S_{11}|$ responses for the ANN and RF models are shown in Fig. 9. As can be seen from the figure, the predicted curves agree well with reference values in the considered range of frequencies. The small difference between the simulated and predicted response indicates that both models have learned well the nonlinear mapping from the radiator parameters to its reflection characteristics. The close agreement further validates the capability of developed ML models in reproducing antenna response with satisfactory accuracy, thus reducing the need of repetitive full-wave EM simulations in the design and optimization process.

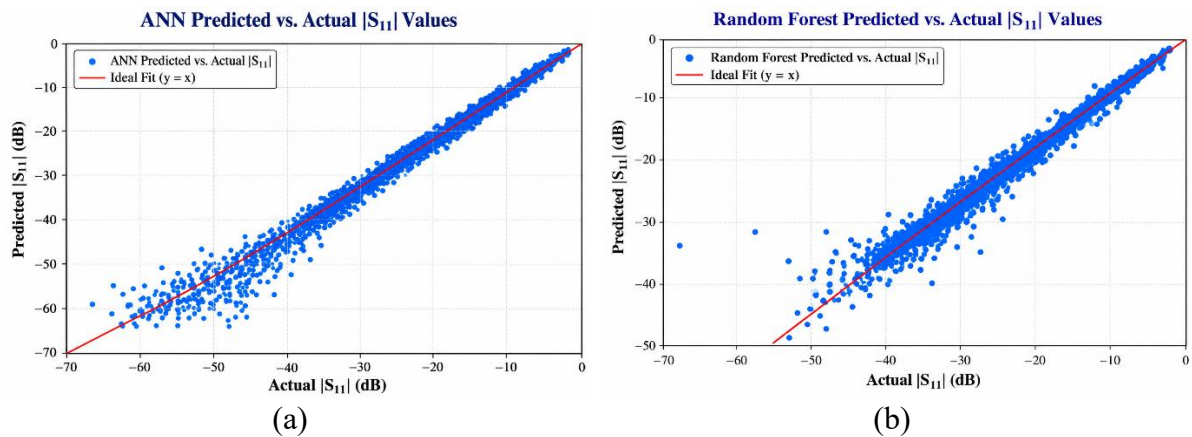


Fig. 9 Comparison of predicted and actual $|S_{11}|$ responses: (a) ANN and (b) RF

V. Measured Results

A prototype of the proposed antenna was fabricated to experimentally verify the simulated results as shown in Fig. 10. The manufactured antenna was characterized using the Keysight PNA-X N5247A vector network analyser. The measured S-parameters were then compared with the result of the HFSS simulation to evaluate the consistency between the numerical and experimental responses.

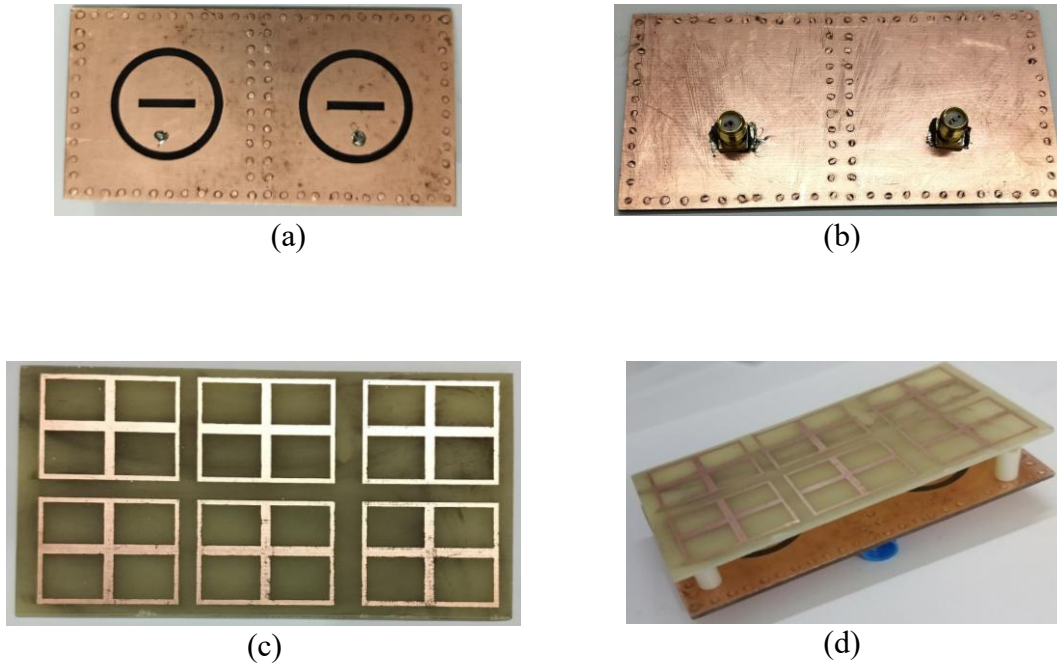


Fig. 10 Pictures of antenna prototype (a) Top view of SIW antenna (b) Bottom view of SIW Antenna (c) Polarization Converter/MS (d) 3D view of final radiator

The S-parameters of the proposed dual-port antenna obtained from HFSS simulation, measurement, and ML prediction are compared in Fig. 11. The measured $|S_{11}|$ response is in good agreement with the HFSS result in the considered frequency range. The ANN and RF predictions also capture the overall simulated behaviour of $|S_{11}|$ with low deviation, showing the potential of these methods to estimate the antenna impedance characteristics. Also, $|S_{12}|$ is less than -40 dB for most of the operating band indicating good port isolation. Differences between the measured and simulated responses can be ascribed to fabrication inaccuracies, slight differences in probe placement, material-property tolerances, and measurement uncertainties. The fabricated prototype is validated by the good agreement between the simulation and measurement.

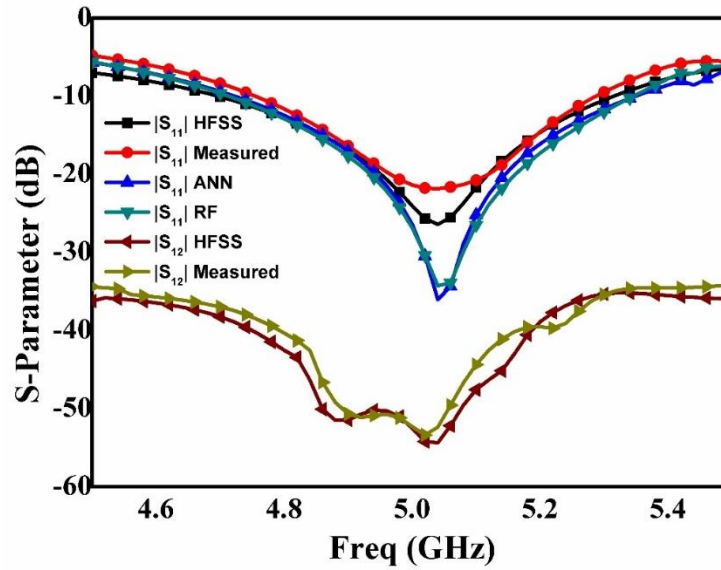


Fig. 11 Measured/Simulated/Predicted S-parameter curve

The circular-polarization characteristics of the fabricated antenna are evaluated using the measured axial-ratio (AR) response, as shown in Fig. 12. AR is experimentally measured using the dual-linear polarization measurement technique [18]. The measured results verify the CP operation from 4.9-5.18 GHz. Good agreement has been achieved between the simulated and measured responses. Small variations within the CP band can be attributed to practical fabrication and measurement tolerances. The broadside gain characteristics obtained by the two-antenna measurement method [19] are shown in Fig. 13. The proposed antenna has a measured gain of 9.5dBi. The observed directional broadside radiation is attributed to the concurrent excitation of two orthogonal cavity modes, providing the necessary field distribution for enhanced CP radiation and directional beam formation.

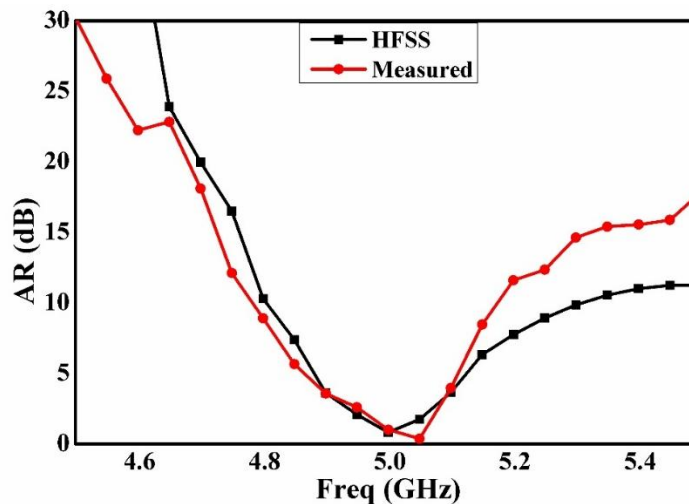


Fig. 12 Measured/Simulated axial ratio curve

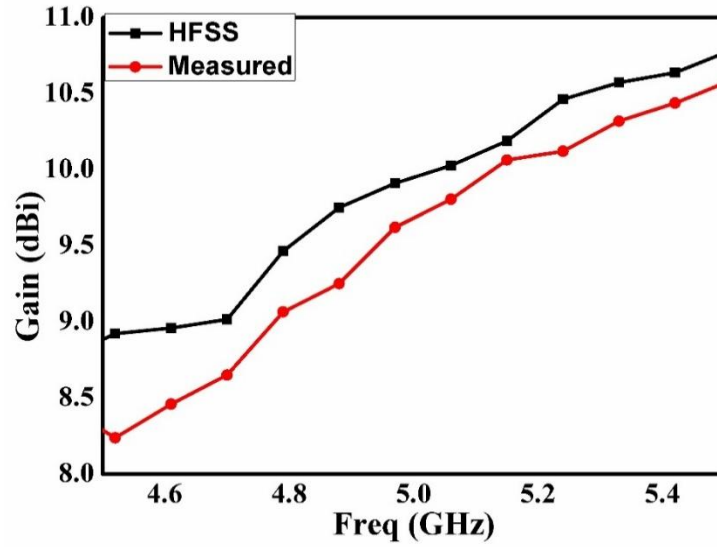


Fig. 13 Measured/Simulated broadsided gain curve

Simulated and measured radiation patterns of the proposed antenna at 5.0 GHz for both RHCP and LHCP components are shown in Fig. 14. A strong LHCP response is observed in the broadside direction, which confirms the desired polarization behaviour. The large separation between co- and cross-polarized fields shows a good rejection of the unwanted polarization component and a good purity in circular polarization. Furthermore, the close agreement between the simulated and measured radiation patterns provides an experimental verification of the radiation characteristics of the antenna.

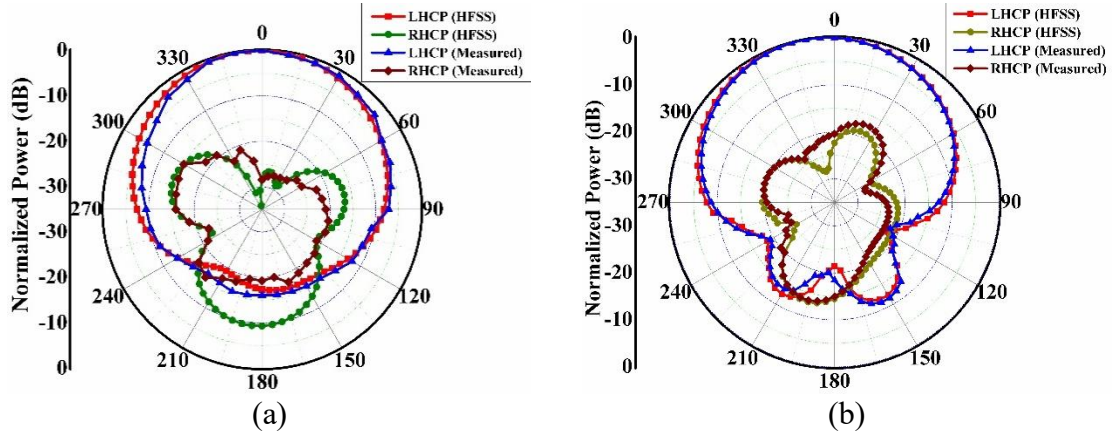


Fig. 14 Measured/Simulated LHCP/RHCP at 5.0 GHz (a) Terminal-1 (b) Terminal-2

Table-2 compares the proposed antenna with the recently reported CP-MIMO and CP slot antennas in terms of impedance bandwidth (IBW), axial-ratio bandwidth (ARBW), port isolation, normalized size and peak gain. The proposed dual-port SIW CP-MIMO antenna provides an IBW of 11.05% and an ARBW of 5.56% with approximately 40 dB isolation between the ports. Furthermore, it has a maximum gain of 9.5 dBi and a small normalized size of $0.094\lambda_0$. However, some of the reported designs have wider impedance or axial-ratio

bandwidth, but they usually have lower gain and/or different isolation and size characteristics. Therefore, the proposed design provides a good trade-off between bandwidth, circular-polarization performance, port isolation, compactness and gain. In particular, the proposed antenna has an isolation of about 30 dB and a gain of 9.5 dBi, which shows the suitability for compact CP-MIMO applications.

Table-2 Performance Assessment of designed SIW MIMO with existing structures

Ref.	Antenna Technology	IBW (%)	ARBW (%)	Isolation (dB)	Size (λ_o^2)	Peak Gain (dBi)
[7]	EMSIW	10.5	3.4	11.6	0.006	5.74
[8]	CP MIMO	5.5	10.47	20	0.03	3.6
[9]	CP slot antenna	7.4	4	—	0.0015	3.6
[10]	CP slot antenna	7.9	4.1	—	0.0094	3.2
[11]	CP slot antenna	9.1	9.1	11.1	0.098	5.22
This Work	Dual-port SIW CP/MIMO	11.05	5.56	40	0.094	9.5

Fig. 15 shows the simulated and measured envelope correlation coefficient (ECC) and diversity gain (DG) of the proposed MIMO antenna. The ECC is still very low with values below 0.002 for simulation and measurement in general. Showing very low correlation between radiation characteristics of two ports. Meanwhile the DG is around 10 dB for the explored frequency range. The combination of very low ECC and DG approaching 10 dB indicates a high degree of port independence and good diversity performance. These properties are useful for the reduction of signal correlation and the reliability of MIMO wireless communication system [1].

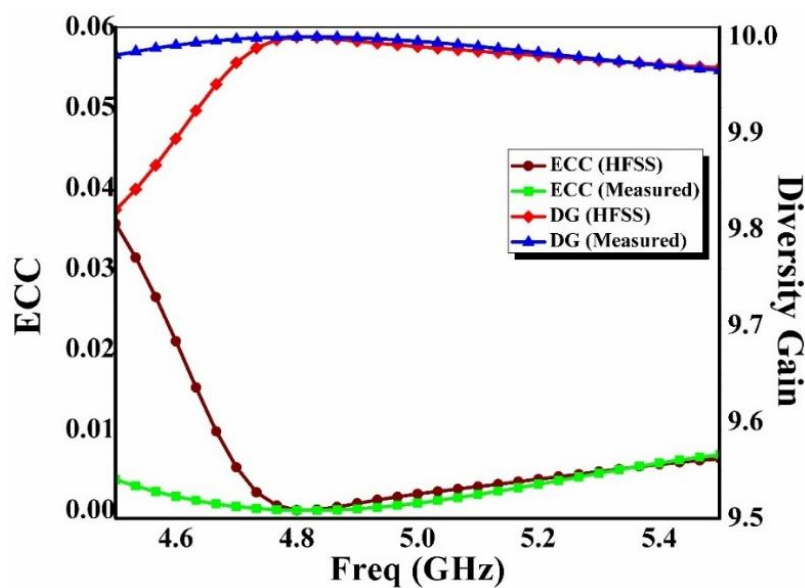


Fig. 15 Measured/Simulated ECC/DG Curve

VI. Conclusion

A dual-port SIW antenna with machine learning aided LP-to-CP conversion for sub-6 GHz 5G applications is proposed. The designed antenna has an impedance bandwidth of 4.7-5.25 GHz, a 3-dB axial-ratio bandwidth of 4.9-5.18 GHz, an isolation of about 40 dB and a peak gain of 9.5 dBi. The ANN and RF models predict the antenna response well, with RF being more accurate. Good MIMO performance is confirmed from the measured ECC of less than 0.002 and diversity gain of around 10 dB. Hence, the proposed design offers a compact combination of high gain, circular polarization, strong isolation and ML-assisted optimization for sub-6 GHz 5G communication systems.

Declarations

***Ethics approval and consent to participate: Not Applicable**

*** Consent for publication: I, Subodh Singh, give my consent for the publication of identifiable details, which can include photograph(s) and/or videos and/or figures and/or details within the text (“Material”) to be published in the above Journal and Article**

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* Authors' contributions: Conceptualization and Methodology [Subodh Singh]; Writing - revised draft preparation: [Amit Prakash]; Analysis and Investigation: [Subodh Singh]; Writing - original draft preparation and Supervision: [Amit Prakash]

* Disclosure of potential conflicts of interest: There are no potential conflicts of interest.

*** Research involving Human Participants and/or Animals: Not Applicable**

*** Acknowledgements: Not Applicable**

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