

DESIGN AND ANALYSIS OF MIMO FOR 28 GHz 5G APPLICATION

Yerrakonda Yamuna¹, Nagari Naveen Kumar²

¹PG Scholar, Department of ECE, J.N.T.U.A. College of Engineering (Autonomous), Ananthapuramu., Andhra Pradesh, India

²Assistant Professor, Department of ECE, J.N.T.U.A. College of Engineering (Autonomous), Ananthapuramu, Andhra Pradesh, India

¹yamunayerrakonda@gmail.com, ²naveenecejntua@gmail.com

Abstract— In this paper, microstrip patch antennas were designed at a center frequency of 28 GHz, and their performance parameters were analyzed using a single feeding technique and one substrate material. The antennas were designed using inset feed on a low-loss RT/Duroid substrate with a dielectric constant of 2.2, while maintaining a constant substrate size of 5.75 mm × 4 mm × 0.254 mm. The performance variations of the antennas in terms of return loss (S11), voltage standing wave ratio (VSWR), gain, directivity, bandwidth, and impedance were analyzed using the CST simulator. At 28 GHz, the return-loss values obtained for the inset-fed single-element MIMO, 2-port MIMO and 4-port MIMO antennas were -35.13 dB, -33.81 dB, and -24.9989 dB, respectively, for the RT/Duroid substrate. The results indicate that better impedance matching was achieved using the inset feed, with VSWR values of 1.0306, 1.048 and 1.15, respectively, while maintaining equal substrate and ground-plane dimensions. The gains of the antennas were found to be 6.55 dBi, 8.16 dBi, and 8.39 dBi, respectively. The study reveals that the use of the low-loss RT/Duroid substrate improves the directivity and gain of the antennas, while reducing the bandwidth compared with designs using the FR4 substrate.

Keywords— Multi-Input Multi-Output (MIMO), 28 GHz, CST, Rogers RT/Duroid 5880.

I. INTRODUCTION

Rapid technological advancements have paved the way for high data rates, low latency, and enhanced network capacity through 5G technology. Microstrip patch antennas (MSPAs) play a significant role in 5G communications due to their compact structure, lightweight nature, ease of fabrication, and suitability for real-world communication requirements. Several researchers have developed MSPAs for 5G applications using different techniques, including substrate variations, different feeding methods, the introduction of slits and slots, and stacking of patches or substrates, to achieve improved performance in terms of gain, bandwidth, radiation efficiency, VSWR, and other antenna parameters. Combining different techniques has become significant in achieving the desired antenna performance. Therefore, this work focuses on the design and analysis of MIMO microstrip patch antennas at 28 GHz using the inset-feed technique on a low-loss RT/Duroid substrate, while maintaining constant length and width dimensions for the ground plane and substrate.

The basic structure of an MSPA consists of a dielectric substrate placed between two metallic layers. The upper metallic layer acts as the radiating patch, while the lower metallic layer serves as the ground plane. The substrate is made of dielectric material, whereas the radiating patch and ground plane are conductive materials. The radiating patch can be designed in various shapes, such as rectangular, triangular, circular, pentagonal, and hexagonal configurations. Among these, the rectangular patch is most commonly used

because of its simple geometry and ease of design. Various performance-enhancement techniques, such as different feeding techniques, Defected Ground Structures (DGS), slots, and slits, are commonly employed with rectangular patches to improve antenna characteristics. The primary function of an antenna is to efficiently transmit or receive electromagnetic waves at the desired operating frequencies.

In the 5G communication scenario, particularly in the sub-6 GHz frequency band, microstrip patch antennas are widely applicable because of their inherent characteristics and advantages. Compared with millimeter-wave frequencies, the sub-6 GHz band provides a better balance between network capacity and coverage, enabling longer-distance transmission and improved penetration through obstacles such as buildings and other large structures. Consequently, sub-6 GHz 5G communication can provide reliable connectivity and high data rates while supporting communication for multiple users. The main challenge in designing microstrip patch antennas for 5G applications is to achieve improved performance with reduced size and cost while satisfying the requirements of modern communication devices. Parameters such as wide bandwidth and high gain are particularly important for applications including Wi-Fi modules, Internet of Things (IoT) devices, and smartphones. One of the major challenges faced by researchers in MSPA design is the interdependence of antenna performance parameters, where an improvement in one parameter may adversely affect another. Therefore, achieving an optimized balance among the different performance parameters of an MSPA remains a challenging task.

Furthermore, the compact structure of microstrip patch antennas makes them suitable for integration into base stations, mobile phones, and various 5G-enabled devices. Recent advancements in fabrication techniques and material sciences have also enabled the development of conformal, flexible, and semi-flexible microstrip patch antennas. Radiation efficiency is another important parameter for microstrip patch antennas used in 28 GHz 5G applications. High radiation efficiency indicates that a greater proportion of the input power is effectively radiated, which is essential for maintaining adequate signal strength and reliable communication.

The paper is organized into six sections. Section 1 presents the need for microstrip patch antennas in 5G 28 GHz applications and discusses their characteristic features. Section 2 provides a review of the relevant literature. Section 3 describes the proposed antenna design methodology along with the corresponding mathematical equations. Section 4 discusses the simulation results and performance characteristics of the proposed antennas. Section 5 presents the conclusions drawn from the study, while Section 6 outlines the future scope of the work.

II. LITERATURE REVIEW

A microstrip patch antenna with a flag-shaped structure was designed using an RT/Duroid substrate with a dielectric constant (ϵ_r) of 2.2 and operating at a resonant frequency of 2.4 GHz [1]. A Defected Ground Structure (DGS) and rectangular slots were incorporated to achieve wider bandwidth and reduce the resonant frequency. The ground plane was designed in an L-shaped configuration, while a slit was introduced into the radiating patch. The implemented antenna achieved a bandwidth of 200 MHz and a high radiation efficiency of 92%.

An omnidirectional dual-band circular patch antenna was proposed in [2]. The radiating patch consists of a circular structure with a star-shaped slot at its center, enabling dual-band operation at 2.45 GHz and 5.2 GHz. A truncated arc and partial ground-plane structures were incorporated to improve the bandwidth and reflection coefficient. The antenna achieved gains of 2.5 dBi and 4.63 dBi, with corresponding radiation efficiencies of 98.5% and 95%, respectively. Owing to its semi-flexible nature, the proposed antenna was found to be suitable for Wireless Body Area Network (WBAN) applications.

An inset-fed microstrip patch antenna operating at 3.5 GHz was designed on an RT/Duroid 5880 substrate with a dielectric constant of 2.2 [3]. The proposed antenna exhibited a good radiation efficiency of 89.56% and a reflection coefficient of -13.772 dB. In [4], a circular-shaped patch antenna operating at 3.2 GHz was designed using a T-shaped feed that acts as a stepped-impedance structure for harmonic suppression. Two arms were incorporated parallel to the T-shaped feeding structure. The proposed antenna achieved a gain of 7.5 dBi along with improved bandwidth. Its compact size, harmonic suppression capability, null radiation in the out-of-band region, and wider bandwidth indicate its potential for integrated wireless communication applications.

A circularly polarized patch antenna was designed using slots and coupled strips to enhance the 3-dB Axial Ratio Beamwidth (ARBW) [5]. The measured S11 results showed good agreement with the simulated results, with values below -10 dB over the frequency range of 2.36 GHz to 2.48 GHz. The simulated and measured ARBW values were 241° and 244° , respectively. The proposed antenna was found to be suitable for wireless applications operating at high-elevation angles.

A tri-polarized microstrip patch antenna operating at 2.65 GHz was proposed in [6]. Left-Hand Circular Polarization (LHCP) was achieved by incorporating slots and exciting a set of radiative modes on a single patch. Shorting vias were employed to mitigate or suppress unwanted modes occurring at the edges of the patch. Similarly, Right-Hand Circular Polarization (RHCP) and linear polarization were achieved using slots and shorting vias on quarter- and half-patch configurations, respectively. Finally, all the individual patches were fabricated as a single structure while maintaining an isolation greater than 20 dB.

Microstrip patch antennas operating at 2.4 GHz with different configurations, including single-layer, double-layer substrate, diagonally slotted, and corner-slotted structures, were designed and analyzed in [7]. FR4 epoxy, with a substrate thickness of 1.5 mm and a dielectric constant of 4.4, was used for the antenna designs. The gains of the four configurations

varied from 0.16 dBi to 1.38 dBi, while the bandwidths ranged from 80 MHz to 120 MHz. The results demonstrated that the diagonally slotted microstrip patch antenna provided a better reflection coefficient compared with the other investigated configurations.

In [8], a microstrip patch antenna was designed using three different substrate materials with dielectric constants of 4.3 (FR4), 2.2 (RT/Duroid 5880), and 3 (TLC-30). The corresponding substrate thicknesses were 1.6 mm, 1.575 mm, and 1.58 mm, respectively. The results demonstrated that variations in the dielectric constant and substrate thickness significantly influence the antenna gain and bandwidth. Among the three substrates, TLC-30 provided better radiation efficiency compared with the other two materials.

A direct-fed microstrip patch antenna was implemented on an FR4 substrate with a dielectric constant of 4.4 and a thickness of 1 mm using the IE3D simulator [9]. An H-shaped metallic ground plane with two slots was employed in the design. An Ultra-Wideband (UWB) microstrip patch antenna was implemented on an FR4 substrate with a dielectric constant of 4.4 using CST Microwave Studio [10]. The initial antenna design resonated at 6.7 GHz. Modifications to the ground-plane geometry through the introduction of slots resulted in an improvement in bandwidth, extending it to 5.7 GHz. Owing to its wide bandwidth, the proposed antenna was capable of covering Wi-Fi, WiMAX, Bluetooth, and WLAN applications. A direct-fed microstrip patch antenna operating at 1.176 GHz was designed on an FR4 substrate with a dielectric constant of 2.33 using the IE3D simulator [11]. The antenna exhibited a bandwidth of 0.021 GHz and a gain of 6.3 dBi. The obtained return loss was -29.752 dB.

An inset-fed microstrip patch antenna operating at 2.4 GHz was designed using FR4 material with a dielectric constant of 4.4 [12]. The patch width was varied to obtain different bandwidth characteristics. A direct-fed microstrip patch antenna incorporating an H-shaped slot on the radiating patch was proposed using different substrate materials at an operating frequency of 2.4 GHz [13]. The analysis showed that the antenna designed using the FR4 substrate achieved a significant return loss of -23.68 dB. An inset-fed microstrip patch antenna operating at 3.5 GHz was designed using an RT/Duroid substrate with a dielectric constant of 4.3 and a thickness of 0.1 mm [14]. The antenna was simulated using ANSYS HFSS and achieved a return loss of -19.89 dB, a directivity of 6.7 dBi, a VSWR of 1.22, and a bandwidth of 128.9 MHz.

An inset-fed microstrip patch antenna with a T-shaped slot incorporated into the radiating patch and operating at 948 MHz was proposed in [15]. The antenna was designed for low-power applications and was therefore suitable for Unmanned Aerial Vehicle (UAV) communications. A Rogers RO4003C substrate with a dielectric constant of 3.55 was used for the design. The antenna achieved a return loss of -28.6 dB and a gain of 5.3 dBi. The study demonstrated that incorporating insets and slots improved the antenna gain from 2 dBi to 5.3 dBi.

A coaxial-fed stacked microstrip patch antenna was implemented on an FR4 dielectric substrate for GPS and Wi-Fi applications [16]. The upper and lower patches operated at 1.227 GHz and 2.4 GHz, respectively. The performance of the stacked patch antenna was compared with that of a

conventional single-patch antenna. The experimental results showed improved performance, with S11 values of −15 dB and −24.8 dB, VSWR values of 1.49 and 2, and a bandwidth of 50 MHz at 1.227 GHz and 2.4 GHz, respectively.

A direct-fed microstrip patch antenna operating at 4 GHz was designed by varying the substrate thickness and dielectric constant [17]. Three different substrates, namely RT/Duroid 5870 ($\epsilon_r = 2.33$), Neltec NY9320 ($\epsilon_r = 3.2$), and FR4 epoxy ($\epsilon_r = 4.4$), were considered. The results indicated that an increase in substrate thickness resulted in a decrease in gain and directivity, while the bandwidth increased. An inset-fed microstrip patch antenna was designed on an FR4 substrate with a dielectric constant of 4.3 and a thickness of 1.5 mm using CST Microwave Studio and operating at 2.25 GHz [18]. An inset-fed microstrip patch antenna operating at 3.5 GHz was designed on an FR4 substrate with a dielectric constant of 4.4 for sub-6 GHz 5G applications [19]. The study demonstrated that incorporating a T-shaped slot on the upper surface of the patch and employing a partial ground plane improved the antenna performance, particularly in terms of S11 and VSWR.

A UWB microstrip patch antenna incorporating a staircase-shaped structure and a rectangular slot in the radiating patch was proposed in [20]. The introduction of the slot improved the antenna bandwidth, resulting in an operating frequency range of 3.1 GHz to 16.7 GHz. A rectangular microstrip patch antenna operating at 3.5 GHz was designed using an FR4 substrate with a dielectric constant of 4.4 and a thickness of 1.6 mm [21]. The antenna bandwidth was enhanced by increasing the substrate thickness. The designed antenna achieved a return loss of −43.52 dB, a bandwidth of 2.3 GHz, and a gain of 2.646 dBi.

From the reviewed literature, it is observed that most of the research has focused on improving one or more performance parameters of microstrip patch antennas, such as gain, VSWR, S11, bandwidth, multiband operation, and wideband characteristics. Various approaches have been investigated, including modifications to the patch geometry, such as triangular, flag-shaped, and circular configurations; the introduction of slots and slits in the radiating patch; Defected Ground Structures (DGS); different feeding techniques, including coaxial, aperture-coupled, and direct feeds; and the use of different substrate materials.

Recent research has increasingly focused on bandwidth and gain enhancement, as well as the integration of Machine Learning (ML) techniques and Multiple-Input Multiple-Output (MIMO) configurations, particularly for 5G-related applications. However, combining different design parameters and techniques while maintaining fixed physical dimensions remains an important area of investigation. Therefore, the proposed work focuses on improving the performance of microstrip patch antennas by employing the inset-feed technique on a low-loss RT/Duroid substrate while maintaining constant substrate and ground-plane length and width. Single-element, 2-port and 4-port MIMO antennas are designed and analyzed at an operating frequency of 28 GHz for 5G applications.

III. GEOMETRY OF THE MICROSTRIP RECTANGULAR ANTENNA USING INSET-LINE FEEDING TECHNIQUE

The proposed antennas are designed on a Rogers RT/Duroid 5880 substrate. The substrate and ground-plane size is kept constant at 5.75 mm × 4 mm × 0.254 mm for the single-element, 2-port and 4-port MIMO configurations. The patch width (W), effective permittivity (ϵ_{eff}), patch length (L) and the radiation impedance at the patch edge (Z_a) are obtained from the following standard design equations:

$$L = \frac{1}{2 f_r \sqrt{\epsilon_{eff}} \sqrt{\epsilon_0 \mu_0}} - 2 \Delta L \tag{1}$$

$$W = \frac{1}{2 f_r \sqrt{\epsilon_0 \mu_0}} \sqrt{\frac{2}{\epsilon_r + 1}} \tag{2}$$

Effective permittivity:

$$\epsilon_{eff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2 \sqrt{1 + \frac{12h}{w}}} \tag{3}$$

The radiation impedance of a patch at the edge:

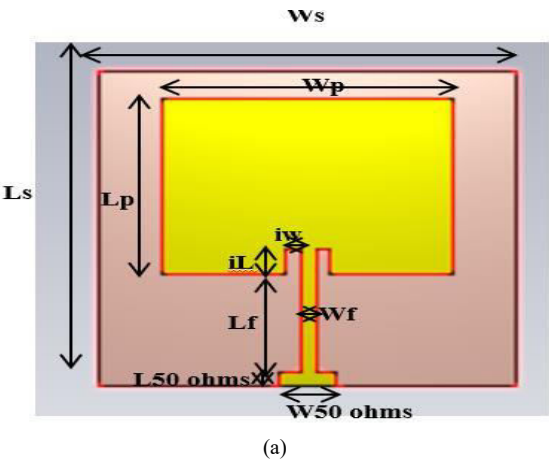
$$Z_a = 90 * (\epsilon_r^2)/(\epsilon_r - 1) * (L/W)^2 \tag{4}$$

where f_r is the resonant frequency, ϵ_r is the dielectric constant of the substrate, h is the substrate height, μ_0 and ϵ_0 are the permeability and permittivity of free space, and ΔL is the length extension caused by the fringing fields. The substrate parameters used in the proposed work are listed in Table I.

Substrate	Dielectric Constant (ϵ_r)	Height (mm)	Loss Tangent
Rogers RT/duroid 5880	2.2	0.254	0.0009

TABLE I. Various PARAMETERS USED IN THE PROPOSED WORK.

The inset feed is used to bring the 50 Ω feed point inside the patch: adjusting the inset depth places the feed at the location where the input impedance of the patch equals 50 Ω, which improves impedance matching. Fig. 1 shows the geometry of the proposed single-element, 2-port and 4-port MIMO antennas.



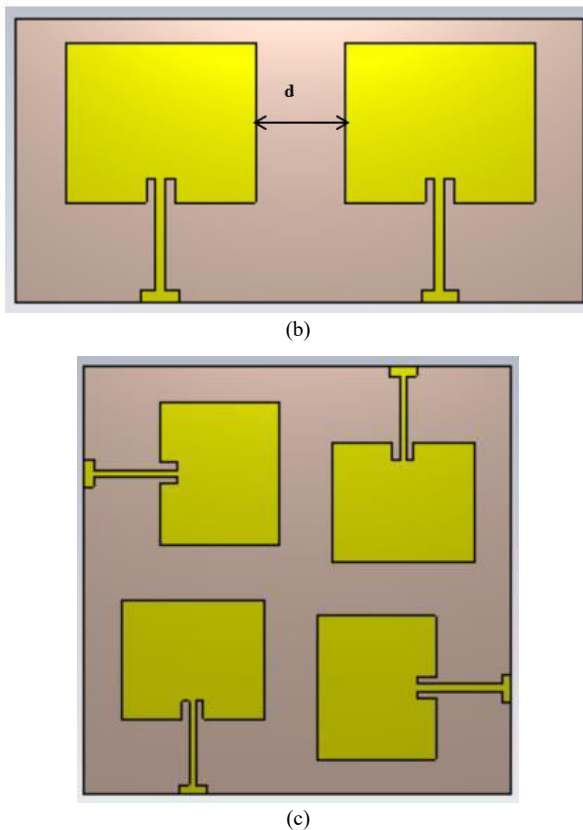


Fig. 1. Geometry of the proposed MIMO antenna: (a) single element, (b) 2-port MIMO, (c) 4-port MIMO.

IV. RESULTS AND DISCUSSION

The performance parameters of a single microstrip patch antenna, including return loss (S_{11}), VSWR, gain, bandwidth, radiation efficiency, radiation pattern, electric field (E-field), magnetic field (H-field), and surface current density (J_{surf}), were evaluated using the CST simulator. The parameters are defined as follows.

Return Loss (S_{11}): Return loss (S_{11}) represents the ratio of reflected power to incident power at the antenna input. For most antenna applications, an S_{11} value of -10 dB or lower is generally considered acceptable. At -10 dB, approximately 90% of the incident power is accepted by the antenna, while the remaining 10% is reflected.

VSWR: The Voltage Standing Wave Ratio (VSWR) indicates the degree of impedance matching between the antenna and its feed line. Its minimum value is 1, representing perfect impedance matching, whereas its maximum value approaches infinity. For antenna applications, a VSWR value below 2 is generally preferred.

Gain: Antenna gain describes the ability of an antenna to direct electromagnetic energy in a particular direction compared with an isotropic radiator. It is generally expressed in dBi.

Bandwidth: Bandwidth refers to the range of frequencies over which the antenna operates satisfactorily. In this analysis, it is defined as the frequency range within which S_{11} remains below -10 dB.

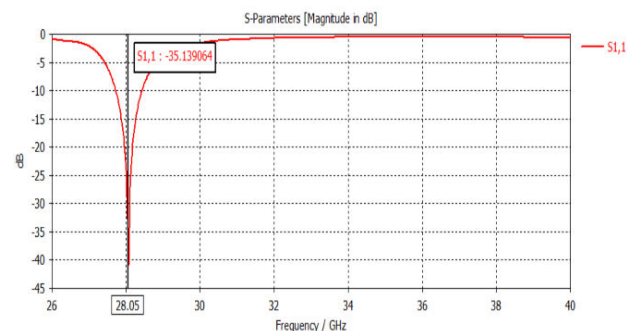
Radiation Efficiency: Radiation efficiency indicates the ability of an antenna to convert accepted input power into

radiated electromagnetic energy. It is defined as the ratio of radiated power to accepted input power.

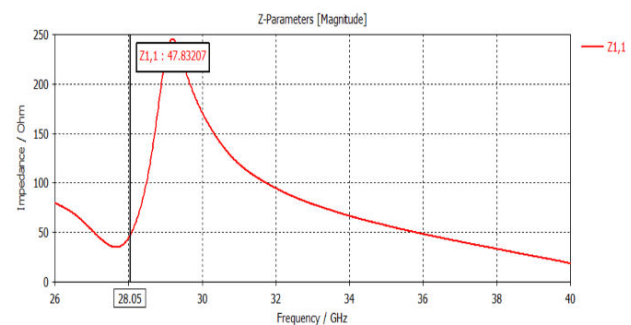
Radiation Pattern: The radiation pattern graphically illustrates the distribution of radiated electromagnetic energy in different directions.

E-field, H-field, and Surface Current Density (J_{surf}): The E-field and H-field represent the electric and magnetic field distributions around the antenna, respectively, while surface current density describes the current distribution per unit width on the antenna's conducting surface. These parameters help characterize the resonant behavior and electromagnetic radiation mechanism of the antenna.

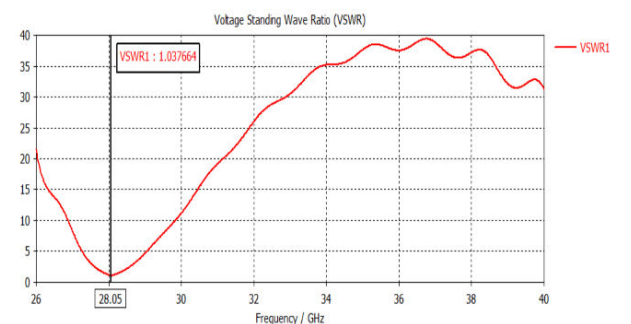
The MIMO antennas were designed using inset feed. As shown in Fig. 2, the inset-fed MIMO exhibited better impedance matching, with a return loss of -35.13 dB for the RT/Duroid substrate. These results indicate that adjusting the inset depth to position the feed point at the appropriate 50-ohm impedance location on the patch improves impedance matching. Antennas intended for practical applications generally require an S_{11} value of -10 dB or lower and a VSWR value below 2. In all the implementations, the S_{11} values were below -20 dB, while the VSWR values were close to the ideal value of 1, specifically remaining below 1.2. Compared with the designs reported in [3], [4], [12], and [16], the proposed microstrip patch antenna (MSPA) designs offer a more compact structure.



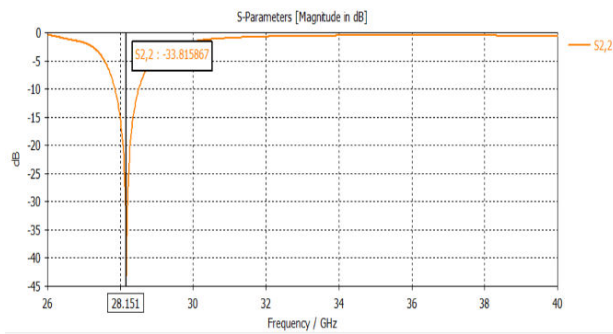
a) S_{11} vs Frequency



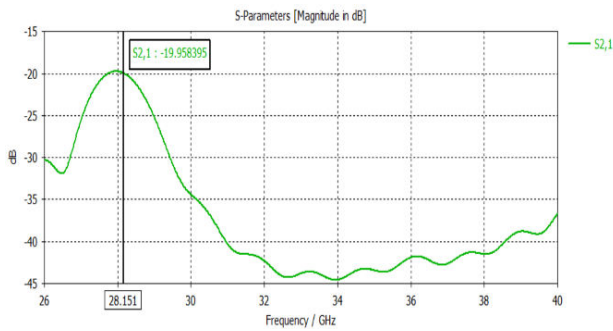
b) Impedance vs Frequency



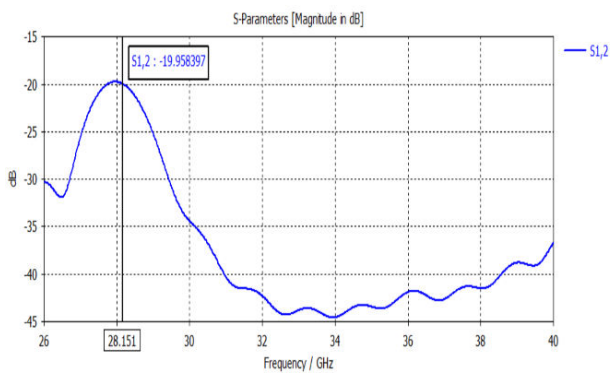
c) VSWR vs Frequency



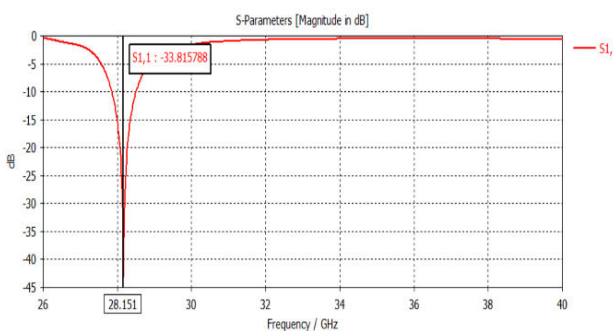
d) S11 vs Frequency



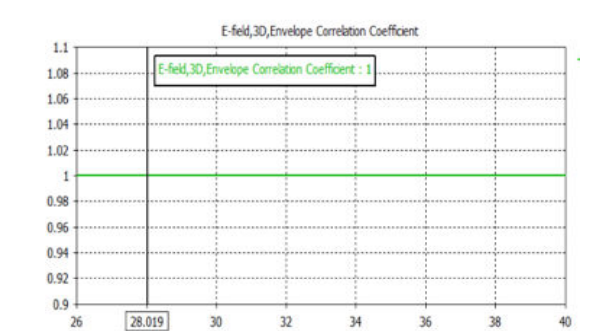
e) S12 vs Frequency



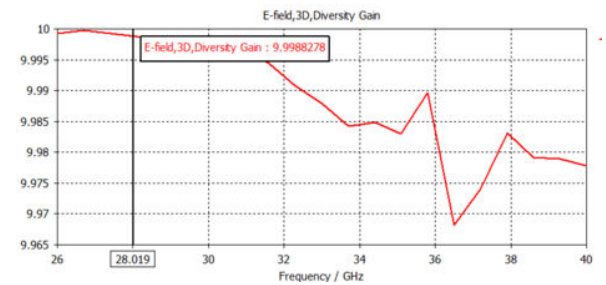
f) S22 vs Frequency



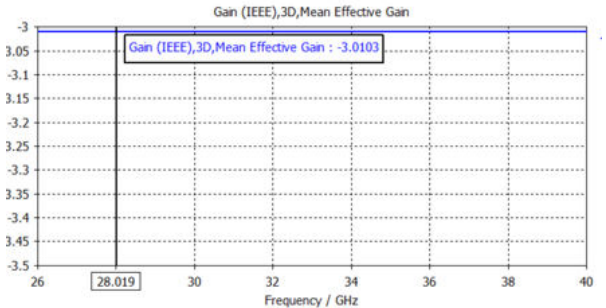
g) S21 vs Frequency



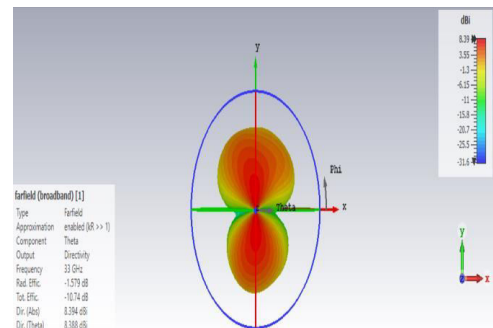
h) ECC



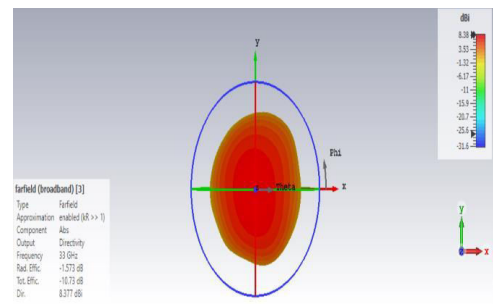
i) Diversity gain



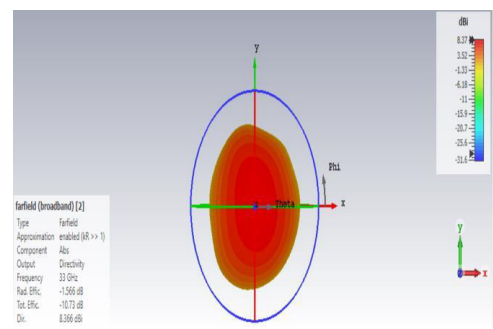
j) Mean effective gain



k) Directivity for MIMO



l) Directivity for 2-port MIMO



m) Directivity for 4-port MIMO

Fig. 2. Simulated results of the antennas designed on RT/Duroid substrate with inset feed. (a)–(c) S11, impedance and VSWR of the single-element MIMO; (d)–(g) S11, S12, S22 and S21 of the 2-port MIMO; (h)–(j) ECC, diversity gain and mean effective gain; (k)–(m) directivity of the single-element, 2-port and 4-port MIMO.

V. CONCLUSION

In this study, multiple-input multiple-output (MIMO) antennas were designed to operate at 28 GHz using the inset feed on an RT/Duroid substrate, while maintaining constant dimensions for the substrate and ground plane. The antenna structures were analyzed using the CST simulator. The results indicate that antennas designed using the low-loss RT/Duroid substrate exhibit higher gain although they offer a narrower bandwidth. The study also reveals that substrates with a higher dielectric constant are preferable for bandwidth-critical applications, whereas low-loss substrates are more suitable for applications requiring higher gain.

The antennas designed on the RT/Duroid substrate achieved gains of 6.55 dBi, 8.16 dBi, and 8.39 dBi for the single-element, 2-port and 4-port MIMO configurations, respectively. The corresponding S11 values are -35.13 dB, -33.81 dB, and -24.9989 dB. Furthermore, the inset-fed antennas exhibited VSWR values of 1.0306, 1.048 and 1.15, respectively, indicating better impedance matching. These results demonstrate that the inset feeding technique is a suitable choice for achieving effective impedance matching

Table II compares the proposed work with several microstrip patch antennas reported in the literature. The proposed designs operate at 28 GHz with a very compact footprint of $5.75 \times 4 \times 0.254 \text{ mm}^3$ and provide gains of 6.55 dBi, 8.16 dBi and 8.39 dBi for the single-element, 2-port and 4-port configurations, respectively.

Technique used	Freq. (GHz)	Return Loss (dB)	Gain (dBi)	BW (GHz)	Rad. Eff. (%)	Size (mm ³)
Partial ground with rectangular slots [1]	2.48	-32.21	2.5	0.5	93	34×22×0.8
Circular patch with star slot [2]	2.45/5.2	-24/-21	2.5/4.63	1.396/2.02	98.5/95	47×30×0.787
Inset-fed MSPA [3]	3.5	-13.772	7.55	0.0236	89.56	100×100×0.077
Circular patch with T-shaped feeding [4]	2.55	<-10	7.5	0.26	-	62×60×6.1
Inset-fed MSPA [14]	3.5	-19.89	-	0.1289	-	50×50×0.1
Constant length and width of substrate and ground plane with inset feeds [This work]	28	-21.2316/ -32.1485/ -22.9989	6.55/ 8.16/ 8.39	0.74/ 0.687/ 0.635	-	5.75×4×0.254

TABLE II. COMPARISON OF VARIOUS WORKS WITH THE PROPOSED WORK ON ROGERS RT5880 (εr = 2.2).

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