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SIW Cavity Assisted Improved Gain Four Port MIMO Antenna with Meta Absorber for 5G mmWave Applications

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ABSTRACT: The Substrate Integrated Waveguide (SIW) cavity is one of the cavity-supported slot antennas that use substrate SIW technology and 5G application. The proposed model antenna operates at 26 GHz–46 GHz frequency range. The proposed model resonates at 33.84 GHz and 40.28 GHz frequency range. The use of substrate-integrated waveguide (SIW) cavity offers low cost, easy implementation, high gain, and self-consistent electrical shielding. Existing dipole and monopole antennas have some limitations, such as a lack of potential ability, low capability, and high mutual coupling. The modified semicircle-shaped rectangular patch is intended on a Rogers RT6002 substrate with the dimension of 26 mm × 26 mm × 0.762 mm and dielectric constant of 2.94. To increase the gain of the antenna, a SIW cavity is placed on top of the patch. A Meta Absorber is added on the left and right sides of the patch to reduce electromagnetic interference, provide excellent absorptivity, and improve antenna performance. A coplanar waveguide (CPW) feed line offers high-speed data rates and low latency in a 5G mmWave application. The suggested model obtains enhanced simulated and fabricated performances related to traditional antenna models. The suggested model antenna obtains enhanced simulated and fabricated performance compared to traditional antenna models. The fractional bandwidth of the proposed antenna achieves a fractional bandwidth of 59%.

1. INTRODUCTION

The fifth generation of communication systems employs multiple bands and multiple-input and multiple-output (MIMO) technology to enable faster data speeds and increased channel capacity [1]. The diversity polarization is characterized using compact and planar CP-MIMO patch antennas [2]. Orthogonal polarization technique is employed to combine several antennas in a small space while maintaining acceptable separation as well as performance. The fundamental downside of MIMO antennas is their limited bandwidth. Many strategies have been employed to increase operational bandwidth and multi-band antenna design, including defected ground structure (DGS), metamaterial, slot, and fractal-based approaches. DGS appears in the shape of Minkowski fractals in a 4-port antenna; the design patch process begins with classical patch design [3, 4]. The MIMO antenna performs well; hence, no bending study is performed. Roger's substrate supports sub-1 GHz, WiFi-6, and sub-6 GHz 5G (NR) bands and may be configured as a shared radiator 4-port antenna [5]. MIMO antennas require a high bandwidth role to operate concurrently. To limit atmospheric reduction and absorption, significant gain at mm-wave frequencies is necessary, as well as a compact structure to house the MIMO system. There are numerous issues connected with MIMO antenna design; closely packed antenna design decreases mutual coupling and increases isolation, hence improving antenna performance [6].

The spatial statistical models of wireless channels derived the frequency band at 28 GHz and 73 GHz. The practical assessment this model provides is a small cell operating at mm-wave [7, 8]. A SIW antenna has been developed which covers a frequency range (FR) of 57 to 71 GHz for mm-wave 5G and is suitable for short-range presentations [9]. For wireless applications, a condensed four-element antenna functions in the frequency bands of 2 GHz and 10.6 GHz, as well as a compact four-port orthogonally polarized slotted MIMO antenna for WiMAX [10]. The multi-slot decoupling approach is utilized for dual-band MIMO antennas, while the multiport structure improves isolation among MIMO antennas. The 30–300 GHz mm-wave band is projected to provide a high rate of data transmission to meet the necessities of 5G applications [11–15].

Wong et al. [16] introduced Quasi-TM$_{1/2,1/2}$ mode for 5G MIMO Access-Point Application. The antenna was designed with the dimension of $42\,\text{mm} \times 42\,\text{mm} (0.58\lambda \times 0.58\lambda\, at\, 4.15$ GHz$)$ and positioned 10 mm above a ground plane. The single-patch antenna achieved four isolated radiation modes in 3.3–5.0 GHz range, each with return loss better than -10 dB, indicating good impedance matching, port isolation greater than 15 dB, antenna efficacy exceeding 80%, as well as envelope correlation constants below 0.03. Tadesse et al. [17] introduced a planar Four-port MIMO antenna for $28/38$ GHz millimeter-wave 5G submissions with a compact design. Here, a microstrip feed line was used in the antenna model, which operated at the FR of 28 GHz and 38 GHz bands. The MIMO antenna was assembled on a Rogers RT5880 substrate, measuring $14\,\text{mm} \times 14\,\text{mm}$ with a thickness of 0.8 mm and a comparative permittivity of 2.2. However,

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it was discovered that the performance was low in antenna diversity. Tamminaina and Manikonda [18] suggested an electromagnetic gap for 5G communications. A small MIMO antenna with four ports as well as a G slot was employed to enable 5G connectivity. The recommended MIMO antenna performed admirably, with an envelope correlation coefficient (ECC) of less than 0.0002 and a diversity gain (DG) ranging from 3.3 to 3.7 GHz.

Cheh Lin et al. [19] developed a triple band SIW with a dielectric resonator antenna (DRA) for 4G and 5G presentations. To generate many resonance frequencies, a U-cut form was employed. The antenna achieved excellent bandwidths up to 19.50% with 4.9 dBi gain and 81.0% efficacy at 1.8 GHz, 6.58% with 4.4 dBi gain, as well as 72.7% proficiency at 2.6 GHz, and 8.21% with 6.7 dBi gain and 73.5% efficacy at 3.7 GHz. However, it was discovered that the channel capacity was low in this model. Girjashankar and Upadhyaya [20] developed SIW for dual-band quad-elements. SIW in TM_{10} mode was utilized to simulate numerous ways in the dielectric resonator to accomplish many resonances. The MIMO antenna had a 9.9 dB PG and a minimum radiation efficacy of 96%. However, it was seen that there was low bandwidth. Jha et al. [21] introduced a common radiator for Sub-1 GHz, Sub-6 GHz 5G NR, and Wi-Fi 6 submissions. Furthermore, it exhibited a bandwidth of -10 dB among 0.7–1.01 GHz, 2.6–3.18 GHz, 5.3–6.06 GHz, as well as 6.7–6.94 GHz. However, this strategy was extremely computationally intricate.

Shah et al. [22] utilized substrate integrated waveguides for 5G. The suggested configuration mixes a dual linear polarized three-port difference antenna, an SIW common-mode power combiner, and a 180° phase shifter at 28 GHz. With a restricted gain of 6.95 dBi for Tx mode and 3.42 dBi for Rx mode, the suggested strategy attains a self-interference cancelation (SiC) of more than 36 dB across a 177 MHz bandwidth. However, it was determined that the model exhibited poor performance. Khalid et al. [23] introduced a 4-port MIMO array for 5G mmWave band submissions. The suggested antenna operated in the 25.5–29.6 GHz frequency band, which is associated with the imminent mmWave 5G applications. Sharma et al. [24] designed a condensed four-port MIMO optimized for mmWave 5G as well as navigation services. The suggested antenna operates at 27.76–28.15 GHz, 32.02–32.46 GHz, and 37.39–38.586 GHz frequencies.

1.1. Motivation

In existing research works, various MIMO antennas, such as two ports and four ports, have been developed for 5G mmWave applications. Existing antenna design technologies such as quasi-TM1/2,1/2 [16], planar Four-port MIMO antenna [17], electromagnetic band gap [18], triple band substrate integrated waveguide [19], and dual-band quad elements [20] have been developed and studied extensively for 5G applications. The existing antenna resonated at single frequencies and was not able to operate at more than one frequency. Especially the existing models have reported SIW based antenna and QMSIW antenna, which suffered from limitations such as single band operation and low gain. In addition to that, signal transmission, diversity performances, and communication speed were reduced, and a very limited number of parameters were analyzed, low reliability, data rate requirements, high power consumption, high signal fading, atmosphere absorption, and high path loss. The novelty of the proposed design lies in the integration of a full circular SIW cavity, CPW feed lines, and meta-absorber metamaterials forming a compact four port MIMO antenna, which operates efficiently in dual mmWave frequency bands. This configuration significantly enhances gain, reduces mutual coupling, and improves MIMO performances. The strategic use of meta-absorbers further suppresses unwanted reflections and improves signal clarity, which establishes the proposed design as a high performances, dual band antenna for future 5G and 6G applications.

- To design a four-port MIMO antenna for 5G mmWave applications with SIW cavity and coplanar waveguide feeding technique.
- To enhance the gain between the antennas, a meta-absorber metamaterial is used in the antenna design.
- To attain dual or multi-band frequencies, a CPW feed line is used for the antenna elements.

The rest of the paper is organized as follows. Section 2 explains the literature survey of the recent research model. Section 3 depicts the strategy analysis of antenna topology. Section 4 explains the simulation and experimental analysis of the suggested antenna model, and Section 5 provides the final conclusion of the paper.

2. PROPOSED ANTENNA TOPOLOGY

Multiple antenna models were designed to develop mmWave application, which had some issues like poor reliability, gain value, and efficacy. Initially, the antenna was designed with four rectangular patches with modified semicircular shapes on a Rogers RT6002 substrate. The proposed antenna was constructed on a low-profile Rogers RT6002 substrate with a dielectric persistent of 2.94 and loss tangent (tanδ) of 0.0012. The expected antenna design is realized in High Frequency Structure Simulator (HFSS), and performance is carried out in terms of return loss, gain, radiation outline, etc. MIMO technology will be considered for improving communication capacity and quality, suppressing multipath effects, and improving data transmission efficacy. The spectrum of millimeter and centimeter waves is particularly targeted for 5G applications.

A circle-shaped SIW cavity is designed with the top layer of the patch. SIW cavities are utilized to achieve high dependability, minimal power loss, and efficient energy radiation, all of which help to improve antenna gain performance. Figure 1 depicts the proposed antenna design, including top and bottom perspectives. A dual band hexagonal coplanar microstrip antenna with tooth-based metamaterial is recommended.

A CPW feed line has been placed at the bottom of the modified rectangular patch. This achieves dual-band operation between the resonating frequencies, which is widely employed in millimeter-wave applications. The CPW feed lines have been employed to increase the radiation design of the suggested

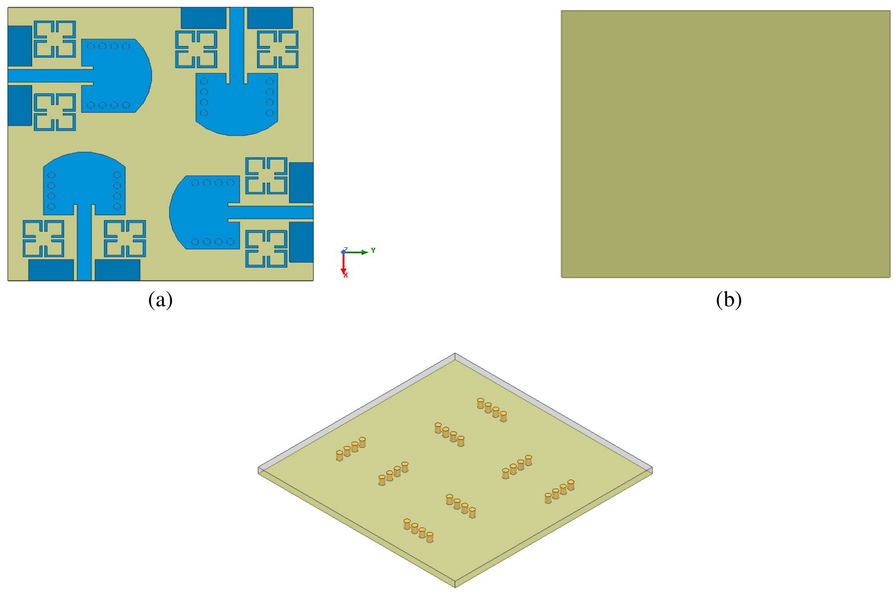


FIGURE 1. Design of the proposed antenna. (a) Front view. (b) Back view. (c) SIW design.

model. A meta-absorber is added to the left and right sides of the modified rectangular patch to increase the suggested model's antenna gain.

The miniaturization in the proposed four-port MIMO antenna design is primarily achieved through the implementation of an SIW cavity and a CPW feed structure combined with a modified semi-circular patch geometry. The SIW cavity, integrated within the compact Rogers RT6002 substrate, allows waveguide-like performance in a planar form, effectively reducing the antenna profile while maintaining high gain and low loss. The CPW feeding technique eliminates the need for a bulky ground plane, enabling tight integration of multiple ports within a small footprint. Additionally, the use of metamaterial-based meta-absorbers enhances the electromagnetic response, allowing compact element spacing without performance degradation, thereby minimizing the overall antenna size while preserving key MIMO characteristics such as low mutual coupling and high isolation. This integrated design approach enables dual-band operation and optimized spatial utilization, ensuring compactness suitable for dense 5G mmWave system deployments.

SIW Design in the Proposed Antenna

In the proposed antenna design, a Substrate Integrated Waveguide (SIW) cavity is embedded directly above the radiating patch within the top metal layer of the Rogers RT6002 substrate. To clarify its presence, Figure 1(c) has been added to explicitly illustrate the circular SIW cavity structure, which is formed by placing rows of metalized via holes that emulate the sidewalls of a traditional waveguide. The SIW cavity acts as a resonant structure that enhances the antenna's radiation efficiency and gain by confining the electromagnetic fields and reducing leakage. It also helps improve impedance matching and reduce surface wave losses, which are critical for millimeter-wave MIMO systems. This integrated cavity plays a vital role in achieving the reported dual-band response and high gain characteristics. Its inclusion ensures miniaturization without compromising performance.

2.1. Step by Step Design

The step by step design for the recommended four-port MIMO antenna is shown in Figure 2.

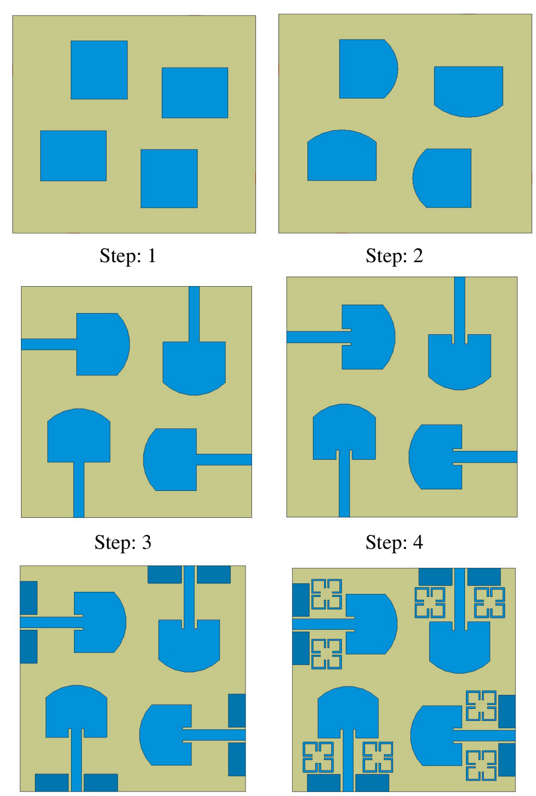
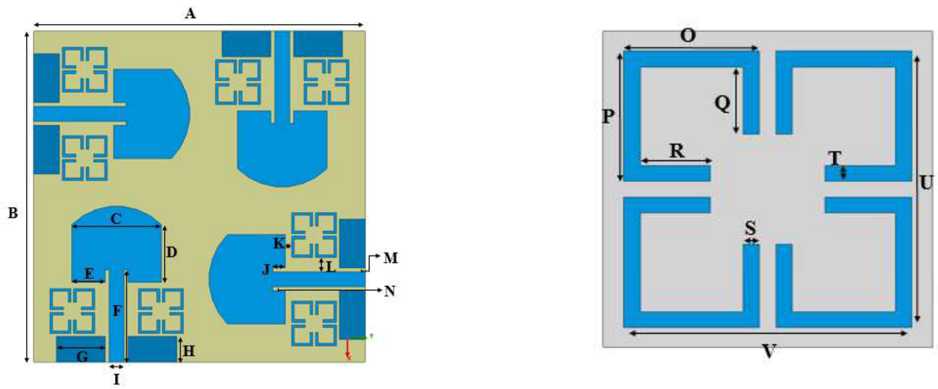


FIGURE 2. Performance analysis of step by step design.



(a) (b)

FIGURE 3. Geometric design of the proposed antenna. (a) Proposed antenna. (b) Meta Absorber.

2.2. Geometric Measurements of the Suggested Antenna Design

Figure 3 depicts the geometry of the suggested antenna. Table 1 shows the specifications for the recommended antenna design.

TABLE 1. Dimension of antenna design.

Parameters	Values (mm)
A	26
B	26
C	7
D	4.57
E	2.6
F	7.25
G	3.84
H	2
I	1.2
J	1
K	0.5
L	1.13
M	0.3
N	0.3
O	1.65
P	1.65
Q	0.85
R	0.85
S	0.2
T	0.2
U	3.5
V	3.5

Meta-absorbers are metamaterials that enhance electromagnetic wave absorption. The meta-absorbers are put on the left and right edges of the patch, which increases antenna performance, lowers the specific absorption rate (SAR), and improves 5G communication. Figure 4 illustrates how the proposed model antenna compares the return loss with and without meta absorption.

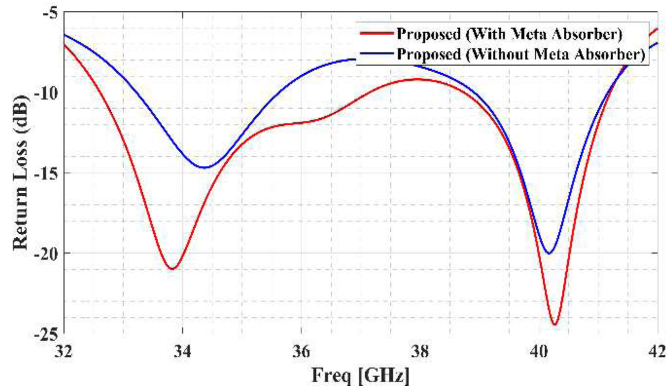


FIGURE 4. Parametric analysis of return loss with meta-absorber and without meta-absorber.

In this analysis, the red color curve represents the meta-absorber, and the blue color curve represents without meta-absorber. The proposed model antenna used with metamaterial absorber (MMA) signal quality can be significantly improved by absorbing unwanted reflections and reducing interference. The suggested model antenna, with a meta-absorber, obtains return loss of better than -20 dB and -25 dB, and without a meta-absorber, return loss is approximately -15 dB and -20 dB. The suggested model with a meta-absorber attained a better return loss value.

3. RESULT AND DISCUSSION

This part simulates and fabricates the suggested antenna design with various restrictions such as return loss, mutual coupling, gain, radiation pattern, voltage standing wave ratio (VSWR), surface current, and parameter analysis employing the SIW cavity.

3.1. Simulation Analysis

The proposed antenna model evaluates various parametric models using the HFSS tool. The return loss analysis of the proposed model is shown in Figure 5.

The return loss has been defined as the quantity of a wave replicated by an impedance discontinuity in the transmission standard. The suggested antenna model has obtained return loss

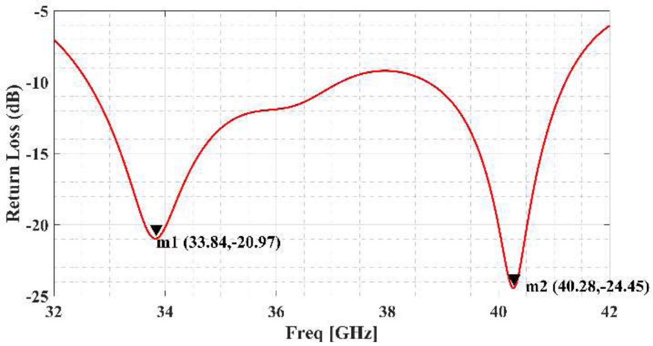


FIGURE 5. Performance analysis of return loss.

values of −20 dB and −24.45 dB at the resonating frequencies of 33.84 GHz and 40.28 GHz, respectively. The standard values of return loss have to obtain fewer than −15 dB, which means that the antenna has better performance. The optional model obtains a better return loss, which results in higher power gain and determines a better antenna performance level. Figure 6 shows the suggested model antenna performance evaluation of gain analysis for the proposed antenna.

Figure 6, the proposed model antenna obtains maximum and minimum gains of 9.7 dB and 7.1 dB at 33.56 GHz and 40.28 GHz resonant frequency ranges. The gain combines an antenna's directivity and radiation efficacy.

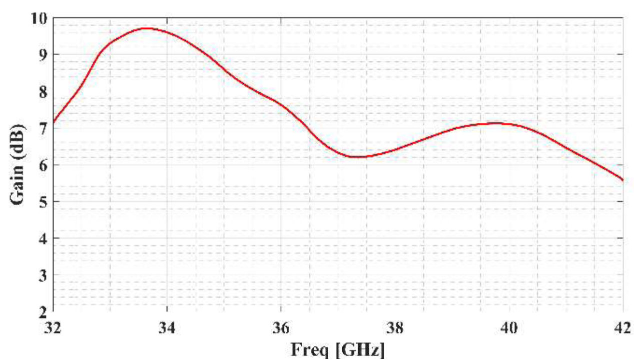


FIGURE 6. Gain analysis for the proposed antenna.

From this analysis, the proposed model antenna obtains radiation patterns in two frequency ranges, 33.56 GHz and 40.16 GHz, respectively. Figure 7(a) obtains a radiation pattern above 24 dB at 33.56 GHz frequency. In Figure 7(b), the proposed antenna design obtains a radiation pattern above 20 dB at the range of 40.16 GHz resonating frequency. The proposed model antenna achieves better radiation pattern value on the E-plane (Electric field) as well as the H-plane (Magnetic field). Figure 8 shows mutual coupling in the proposed model antenna. This research shows the mutual coupling characteristics of the proposed four port MIMO antenna. The coupling between the first port and the other three ports is observed to be better than −25 dB, indicating good isolation. Additionally, port-port isolation among the remaining port pairs is maintained above 50 dB. The optional four-port MIMO antenna provides a higher mutual coupling value, which improves reliability and performance while reducing impedance mismatch in wireless 5G communication. The external present dissemination of the suggested model antenna is depicted in Figure 9.

In this analysis, the recommended four-port MIMO distributes 50 Ω surface current on the antenna's first port. Different colors are used to associate both the electric and magnetic current surface values for the proposed model antenna. Blue color shows the low current intensity, and red color denotes the high current intensity.

3.2. Experimental Analysis

The recommended antenna is fabricated on a Rogers RT6002 substrate and simulated with the HFSS tool, which ensures the acquired outcomes. Figures 10(a)–10(d) show several fabricated samples of the proposed antenna model.

The performance analysis of the return loss, as well as the radiation outline for the recommended antenna model with simulated and restrained values, is presented in Figure 11.

In Figure 11(a), the suggested antenna obtains simulation evaluation in return loss of nearest −20 dB at 33.56 GHz and resonant frequency and nearest −25 dB at 40.16 GHz resonant frequency. The measured results closely align with the simulated data, confirming good agreement between simulation and fabrication. At 33.56 GHz and 40.16 GHz, the proposed four-port antenna has been shown to have a VSWR of less than 2 dB (Figure 11(b)). The measured result is almost equal to the simulated one. Figure 11(c) replicates and restrains the radiation pattern at two resonant FRs. The suggested antenna model obtains a radiation pattern above 20 dB on the E-plane and above 10 dB on the H-plane at 33.56 GHz. Similarly, the suggested antenna attains a radiation pattern of 30 dB on the E plane and above 20 dB on the H plane at 40.16 GHz.

3.3. Four-Port MIMO Analysis

In this research work, the recommended four-port MIMO antenna analyses the various restrictions such as total active reflection coefficient (TARC), ECC, mean effective gain (MEG), channel capacity loss (CCL), and DG. Figures 12(a)–12(b) show a performance analysis of TARC and ECC for the recommended antenna.

Figure 12(a) depicts the TARC of the suggested antenna. TARC has been tested employing three ports: TARC 12, 13, and 14. TARC describes the connection among total reflected power as well as total incident power toward the device's input, which is used to characterize the MIMO antenna array. The suggested model achieves a TARC of less than −60 dB near 40 GHz. Figure 12(b) shows a channel capacity loss (CCL) analysis for the proposed antenna with three CCL ports (12, 13, and 14). CCL describes the determined rate of information that can be transmitted over a communication channel without significant loss. A stable rate of CCL should be less than 0.4 bits/seconds/Hz for reliable communication. The suggested model antenna obtains a CCL of fewer than 0.03 bits/seconds/Hz. The suggested antenna attains higher TARC and CCL values than conventional antenna designs. TARC and CCL are the key metrics for evaluating MIMO antenna performances. TARC quantifies the overall re-

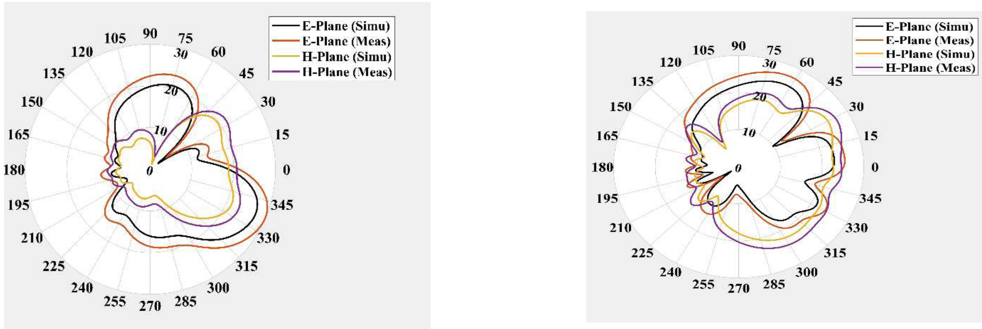


FIGURE 7. Performance analysis of radiation pattern. (a) 33.56 GHz. (b) 40.16 GHz.

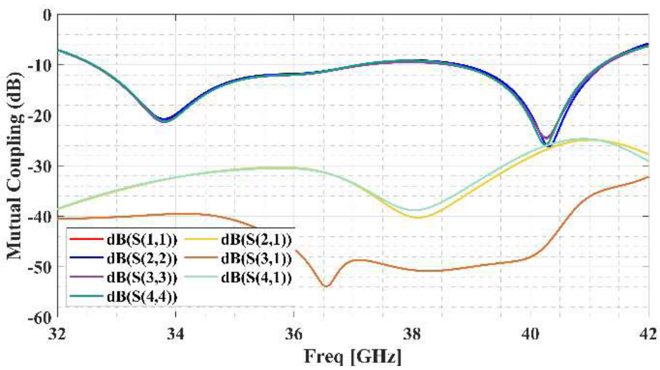


FIGURE 8. Mutual coupling in the proposed model antenna.

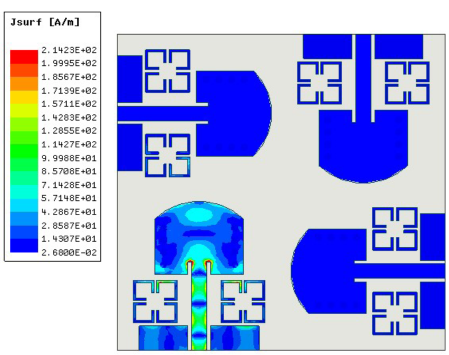


FIGURE 9. Surface current of proposed model antenna.

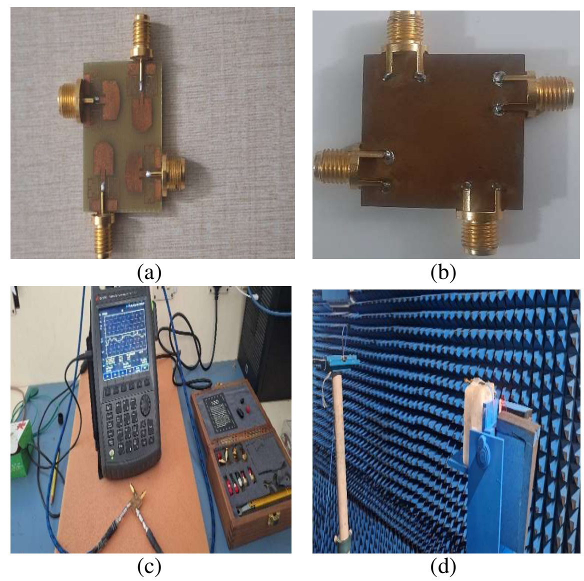


FIGURE 10. Sample fabricated images.

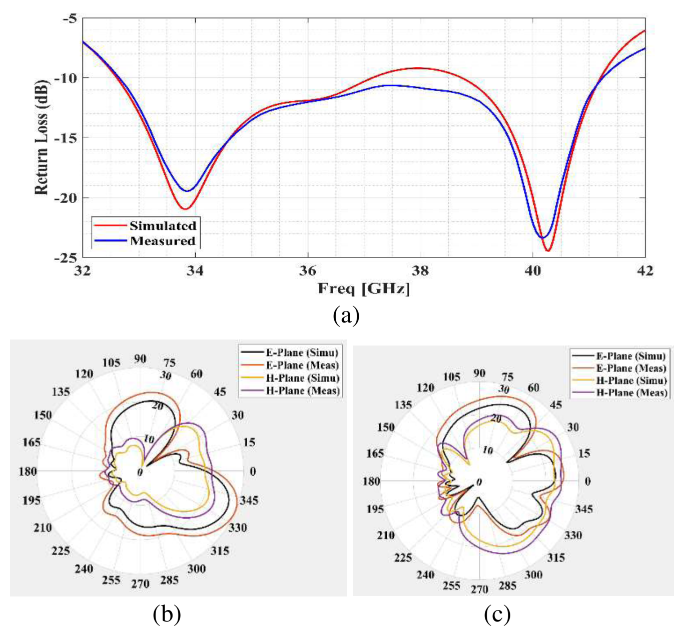
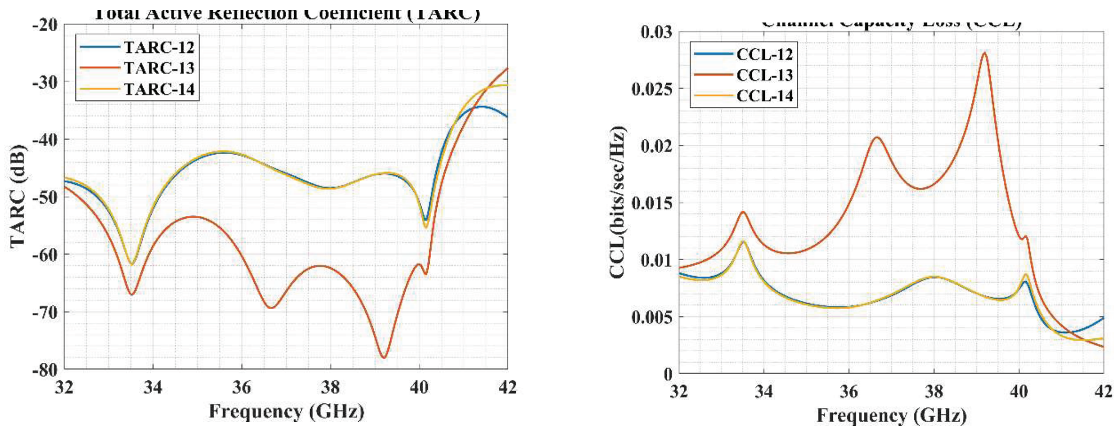


FIGURE 11. Performance analysis of (a) return loss, (b) radiation pattern at 33.56 GHz, (c) radiation pattern at 40.16 GHz.

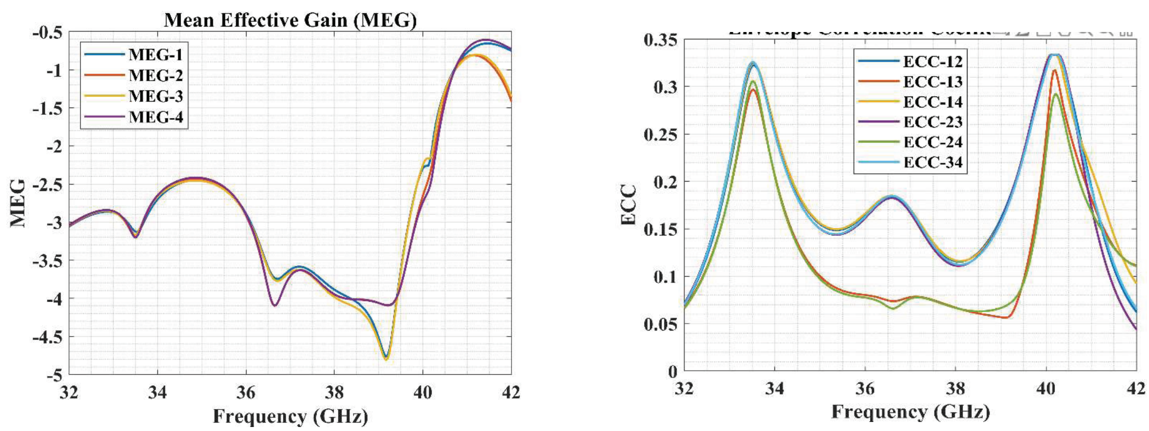
flected power from a MIMO subsystem under active excitation, which indicates an impedance matching and inter-port coupling. Lower TARC values signify better performances with minimal signal reflection. CCL measures the degradation in achievable data rate due to correlation and mutual coupling between antenna elements. CCL value below 0.4 bits/s/Hz indicates different channel utilization and reliable communication in MIMO systems. Figures 13(a)–13(b) illustrate the performance analysis of MEG and ECC.

Figure 13(a) signifies the mean effective gain (MEG) analysis of the suggested MIMO. The MEG of an antenna measures the interaction between the antenna and the channel in real propagation environments. The standard value of MEG is around -3 dB for MIMO antenna. The suggested analysis



(a) (b)

FIGURE 12. Performance analysis of MIMO. (a) TARC. (b) CCL.



(a) (b)

FIGURE 13. Performance analysis of (a) MEG (b) for MIMO antenna.

TABLE 2. Comparison of various existing and proposed model antennas.

Reference	Antenna size	Band	Bandwidth	Substrate	Frequency (GHz)	Gain (dB)	Isolation
[16]	42 mm × 42 mm	Single	-	FR4	3 to 5	6.1	<15
[17]	14 mm × 14 mm	Dual	2 GHz	Rogers RT5880	38–44	8.0 6.1	<20
[18]	$48 \times 48 \times 1.6\,mm^3$	Single	400 MHz	FR4	3–4	3.2	<13
[21]	130 mm × 90 mm	Single	-	RT Duroid 5880	1–5.8	5.53	<20
[22]	48 mm × 80 mm	Single	0.49 GHz	RT Duroid 5880	26–29	6.95	-
[23]	30 mm × 35 mm	Single	2.8 GHz	Rogers R04350B	25.5–29.6	8.1	-
[24]	$31 \times 42\,mm^2$	Dual	2 GHz	Rogers RT Duroid 5880	26–40	7.06	<15
[25]	9 mm × 15.8 mm × 0.035 mm	Single	-	Rogers RT/Duroid5880.	25-35	8.2	<20
[26]	24 mm × 37 mm × 0.035 mm	Single	-	Rogers 5880	35.181–39.689	-	<14
[27]	20 mm × 15 mm × 1.575 mm	Single	-	Rogers 5880	3.5	6.94	-
[28]	26 mm × 20 mm × 0.5 mm	Single	144.1 MHz	F4	3–4	6.05	<16
[29]	23 mm × 18 mm × 0.254 mm	Dual	-	RO5880	26–40	3.8, 5.36	<20
[30]	32 mm × 32 mm × 1.6 mm	Dual	-	Rogers RT-5880	2.6–4.1 22.5–29.3	1.5 and 6.5	<20
Proposed	**26 mm × 26 mm × 0.762 mm**	Dual	**4.54 GHz 2.47 GHz**	**Rogers RT6002**	**26–44**	**9.7 and 7.1**	**<22**

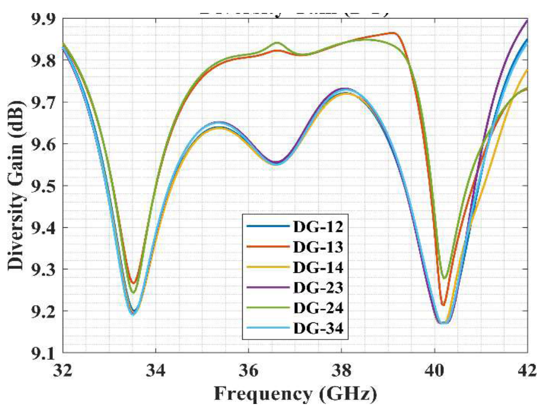


FIGURE 14. Performance analysis of diversity gain (DG).

obtains an MEG of −3 dB. Figure 13(b) signifies ECC for the suggested MIMO, which is measured in three different configurations: ECC-12, 13, and 14. A standard assessment of ECC is lower than 0.5 for the functioning frequency. The suggested antenna acquires an ECC of less than 0.5 at above 40 GHz. The recommended model antenna shows the best MEG and ECC values. Figure 14 illustrates the performance analysis of DG for the MIMO antenna.

The DG designates the number of copies in transmitting antennas and the number of receiving antenna signals. In this analysis, the DG is measured employing different ports such as DG-12, 13, 14, 23, 24, and 34. The suggested method obtains DG of the nearest 9.2 dB. The proposed antenna attains a better DG value, which improves the signal reliability and quality in MIMO antenna.

3.4. Discussion

In this recent analysis, the antenna model is obtained with low efficiency, poor gain, and complex patterns, and low flexibility and coverage. To overcome those existing issues more effectively, this research designs an SIW cavity assisted four-port MIMO antenna with a meta-absorber. Initially, the antenna is designed with a rectangular patch that modified the semicircular shape on a Rogers RT6002 substrate. To increase the gain, mete-absorber metamaterial is added to the bottom of the patch. For wireless communication, a circular SIW cavity is employed at the top of the patch, improving gain, bandwidth, and low profile. A CPW feed line is added to the left and right edges of the patch. Table 2 compares the performances of numerous prevailing antenna designs with the suggested model antenna.

From this analysis, the proposed model obtains better performances in terms of gain, bandwidth, and resonating frequency. In the proposed SIW cavity-assisted four-port MIMO antenna, bandwidth enhancement is achieved through the synergistic use of CPW feeding, modified semi-circular patch geometry, and SIW cavity loading. These elements contribute to the excitation of multiple resonant modes and improved impedance matching over a wider frequency span. For the proposed model, operating between 26 GHz and 46 GHz with resonance peaks at 33.84 GHz and 40.28 GHz, the fractional bandwidth (FBW) is approximately 59%, indicating a broad operational range suitable for 5G mmWave systems. The SIW cavity enables strong mode confinement and low radiation loss, while the meta-absorbers minimize unwanted reflections, maintaining stable radiation patterns across the band.

4. CONCLUSION

In this research work, a novel SIW cavity assists improved gain of four port MIMO antenna with meta-absorber for 5G mmWave applications. The antenna has been intended for the Rogers RT6002 substrate with a four-port modified rectangular patch. CWP feed line and meta-material have been added at the top and bottom of the modified rectangular patch. The proposed antenna is evaluated on various performances like return loss, VSWR, and surface current dissemination. The suggested antenna achieves a return loss of −20 dB and −24.45 dB and gains of 9.7 dB and 7.1 dB at 33.56 GHz and 40.16 GHz, respectively. The meta-absorber includes more potential advantages. However, it absorbs too much of the desired signal, significantly weakening the received signal. In future work, the proposed model antenna will be developed for 5G and 6G with a quarter-mode SIW cavity, which can achieve better performance and promising potential for future real-time applications. The fractional bandwidth of the proposed antenna is 57%.

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