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Hybrid EBG-DGS mm Wave MIMO for 5G/6G Devices

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Abstract

Researchers present a hybrid Electromagnetic Band Gap (EBG) and Defected Ground Structure (DGS) aided small 8x8 mmWave MIMO antennas for 5G/ 6G smart devices. A standard compact mmWave system has significant mutual coupling effect, limited isolation, and poor MIMO antenna performance. The design solutIon overcomes these difficulties. Designing a framework that limits surface wave propagation and electromagnetic interference in the circuitry increases isolation and reduces electromagnetic interference between antenna parts. The planned antenna operates in the Ka-band mmWave range. Orthogonal antenna element arrangement and hybrid decoupling improve isolation and performance of the proposed MIMO antenna system. With a reflection loss of less than -10 dB and isolation of over-25 dB between ports, the antenna has a wide impedance bandwidth. It boasts radiation efficiency of 85% and a radiation gain above 9 dBi. ECC values around 0.01 and DG around 10 dB demonstrate the antenna's excellent diversity performance for reliable high-speed data transmission. Simulations and measurements match, proving the hybrid EBG-DGS method works. Compared to the current mmWave MIMO antenna designs, the suggested antenna design performs better in isolation, size, and diversity, making it a great candidate for 5G/6G smart wireless systems.

Keywords: 5G/6G Wireless Communication, 8×8 MIMO Antenna, Defected Ground Structure (DGS), Electromagnetic Band Gap (EBG), Ka-Band Antenna, Millimeter-Wave (mm Wave) Antenna.

Introduction

Rapidly developing wireless communication systems need higher data rates, ultra-low latency, massive interconnection, and spectrum efficiency. 5G and 6G wireless communication systems will enable intelligent transportation, augmented/ virtual reality, IoT, smart healthcare, autonomous systems, industrial automation, and ultra-HD multimedia content delivery. To meet rigorous communications requirements, mmWave frequency bands have been widely explored since they have superior bandwidth and channel capacity than sub-6 GHz systems. One of the most intriguing mmWave frequency bands is the Ka-band, which can transmit multi-gigabit per second with better spectral efficiency. However, mmWave communication systems have high propagation loss, attenuation, penetration, and blockage susceptibility. MIMO antenna technology is one of the best solutions to improve channel capacity, signal reliability, spectral efficiency, and beamforming without increasing transmission power or bandwidth. Multiple radiating antennas provide spatial variety and multipath fading in MIMO antenna systems. The paper's structure continues below. MMWave MIMO antenna literature and methods are covered in Section I. Section II discusses antenna analysis and design. Section III simulates the proposed antenna's performance, while Section IV finishes. Millimeter-wave (mmWave) MIMO antenna systems are a popular topic in 5G and 6G wireless communication due to their high transmission rates, low latency, and good spectral efficiency. However, small-scale multi-antenna integration produces coupling, poor isolation, reduced gain, and reduce diversity gain. Several researchers have suggested defective ground structures (DGS), electromagnetic bandgap (EBG) structures, met surfaces, neutralisation lines, and orthogonal antenna components. The mmWave frequency spectrum has higher capacity than sub-6 GHz systems, however propagation and atmospheric

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losses need directional MIMO antennas (1). The study indicated that high gain, narrow beams, and compact antenna arrays boost future cellular system channel capacity and spectral efficiency (2). Another study created an orthogonally dual-polarized smart phone MIMO antenna array. The analysis found that orthogonal antenna units increased diversity and reduced mutual coupling (3). A tiny size with good isolation and consistent antenna radiation patterns is the study's main aim. Moderate mutual coupling remains despite significant diversity (4). DGS improves isolation and impedance matching by changing ground plane current distribution and lowering surface wave propagation (5). This design minimised antenna part electromagnetic interference and enhanced isolation. Multiple ground plane slots complicated design (6). DGS structures showed reduced coupling currents and higher antenna efficiency without compromising compactness (7). Proposed electromagnetic bandgap (EBG) structures for antenna engineering to reduce surface waves and increase antenna performance (8). This study demonstrated that EBG structures may improve antenna performance in confined space (9). This work suppressed surface waves to isolate the antenna. Orthogonal antennas had better radiation and less mutual coupling (10). The metasurface layer enhanced antenna gain, radiation, and EMF confinement (11). This design is appropriate for next-generation wireless communication systems because to its high bandwidth and isolation (12). For 5G millimeter-wave applications, this letter introduces a ground plane modification and improved metamaterials (MM) based high-isolation dual-band multiple-input-multiple-output (MIMO) antenna (13). This study presents the first comprehensive method for designing isolation enhancement neutralization lines (NLs) in MIMO antenna arrays. The method is both universal and systematic. In the center of each NL is a reactive component that is connected to a metal strip. It is coupled with each of the two antenna radiators in order to increase isolation by creating a second coupling channel that opposes the original antenna coupling (14). The study minimised mutual coupling and enhanced tiny antenna array impedance matching (15). The proposed loaded parasitic devices improved isolation by changing electromagnetic coupling paths (16). A metal-frame smartphone MIMO antenna array was proposed. In a limited environment, study concentrated on radiation efficiency and isolation (17). The study found compact MIMO antenna arrays difficult to design (18). Diversity was maximized and mutual coupling minimized (19). The proposed design increased beamforming, radiation efficiency, and antenna element EMF interference (20). The research found that thin flexible antennas require special separation (21). The technology enabled fast wireless transmission with high axial ratio bandwidth and polarisation diversity (22). SIW transmission was lossless and radiation efficient (23). The proposed method enabled directed beamforming with constant working band gain (24). With the recommended antenna (25), compact devices are isolated and diverse. Extensive measurement and fabrication of an eight-element MIMO antenna validates the design idea. The target band is attained at an impedance bandwidth of -6 dB, and the experimental results show element isolation greater than -21 dB in the 3.5 GHz range (26). Compactness, isolation, ECC reduction, and beam shaping are potential research fields (27). Metasurface-inspired compact MIMO system decoupling was studied. The modulated EM pulses provided high isolation and bandwidth (28). A hybrid EBG-based mmWave high-gain compact antenna array was reported. The hybrid EM interference reduction method performed effectively for mmWave antenna arrays (29). This letter showcases a loaded metamaterial superstrate-based wideband four-element multiple-input-multiple-output (MIMO) antenna. In order to achieve outstanding impedance matching across a broad bandwidth of 41% (3.33-5.04 GHz), the suggested MIMO antenna layout uses a small square substrate with four slotted rectangular microstrip antennas (30). According to the literature, EBG, DGS, metasurface, and decoupling have improved compact MIMO antenna design. Most studies examine one isolation method and seldom mixed electromagnetic suppression solutions. Compact 8x8 mmWave MIMO systems with better isolation, gain, beam forming, and diversity are understudied.

Methodology

The proposed work presents a Hybrid EBG–DGS Assisted Compact 8×8 mmWave MIMO Antenna designed for advanced 5G/6G smart wireless devices operating in the Ka-band frequency spectrum, as shown in Figure 1A. The main goal of the designed antenna is to provide better isolation, improved beamforming, higher gains, reduced ECC, and excellent diversity characteristics despite keeping a compact size to be used in portable wireless devices.

The design of the antenna uses three significant electromagnetic improvement methodologies:

a) Electromagnetic Band Gap (EBG) Structure, as shown in Figure 1B
b) Defected Ground Structure (DGS), as depicted in Figure 1C
c) Orthogonal MIMO Element Arrangement

The synergistic use of these methods substantially reduces the surface wave propagation and mutual coupling effects in adjacent antennas. The design involves an 8×8 MIMO compact antenna array fabricated on a thin Rogers RT/duroid substrate having a dielectric constant εr=2.2\varepsilon_r = 2.2εr=2.2, thickness of 0.787 mm, and very low loss tangent of 0.0009. The choice of Rogers material is based on its excellent high-frequency behavior and lower dielectric losses compared to standard FR4 substrates. The antenna array contains eight compact rectangular radiating antennas oriented orthogonally to provide diversity in polarization and minimize electromagnetic interference among the neighboring antennas. Excitation of each radiating antenna is achieved through a microstrip feed line designed for optimum 50 ohm impedance matching. Figure1 represent the top view, 3D exploded view, and side cross-sectional view of the 8×8 MIMO antenna layout, respectively.

The dimensions of the rectangular patch antenna are determined from standard transmission-line formulas. The standard formulas are used to tune each radiator for optimal resonance at the required operating frequency for the mmWave band.

Width of the patch antenna is determined as given in Equation [1],

$$W = \frac{c}{2f_r}\sqrt{\frac{2}{\epsilon_r+1}} \qquad [1]$$

Where, c is speed of light, $f_r$is resonant frequency.

The effective dielectric constant is given by Equation [2]:

$$\epsilon_{eff} = \frac{\epsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left(1+12\frac{h}{W}\right)^{\frac{-1}{2}} \qquad [2]$$

The effective length is calculated as Equation [3]:

$$L_{eff} = \frac{c}{2f_r\sqrt{\varepsilon_{eff}}} \qquad [3]$$

The extension length due to fringing field is defined as Equation [4]:

$$\Delta L = 0.412h\frac{(\varepsilon_{eff}+0.3)(\frac{W}{h}+0.264)}{(\varepsilon_{eff}-0.258)(\frac{W}{h}+0.8)} \qquad [4]$$

The actual patch length becomes Equation [5]:

$$L=L_{eff} -2\Delta L \qquad [5]$$

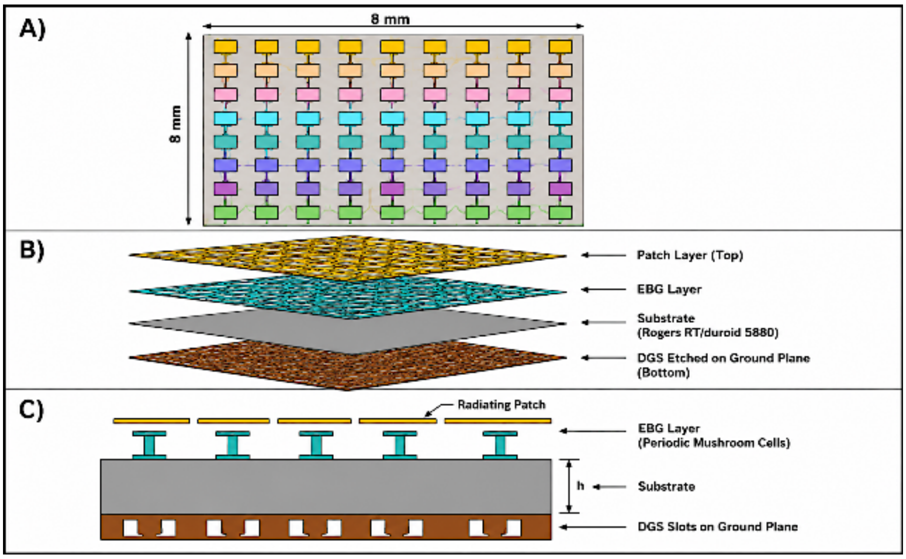

Figure 1: (A) Proposed Hybrid EBG-DGS 8×8 mmWave MIMO Antenna Configuration, (B) Electromagnetic Band Gap and (C) Defected Ground Structure

To suppress surface wave propagation and reduce mutual coupling, periodic Electromagnetic Band Gap (EBG) cells are inserted between adjacent antenna elements. Figure 2 shows the Unit cell of EBG structure, in which Figure 2A depicts the top view and Figure 2B shows the side view. The EBG structure behaves as a parallel LC resonator that creates an electromagnetic stopband at the desired frequency range. The resonant frequency of the EBG structure is expressed as Equation [6]:

$$f_{EBG} = \frac{1}{2\pi\sqrt{LC}} \qquad [6]$$

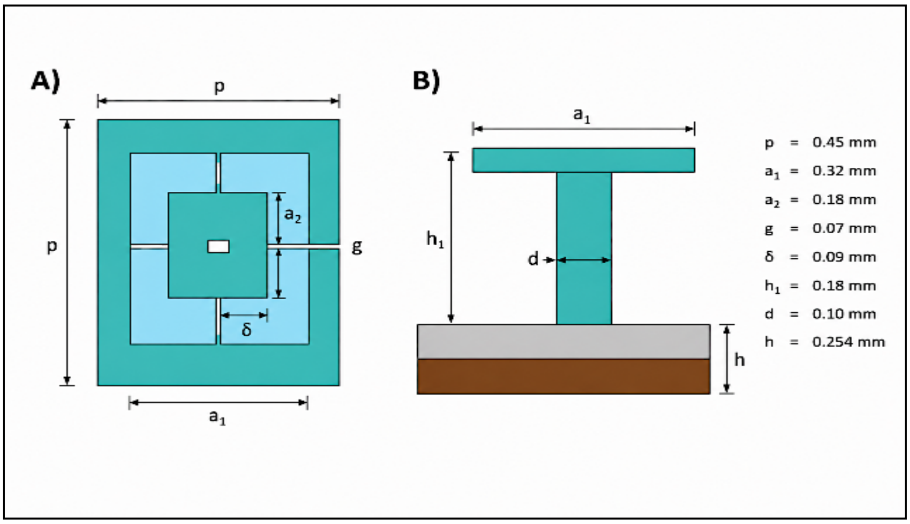

Figure 2: Structure of EBG. (A) Top View, (B) Side View

The periodic EBG cells prevent propagation of unwanted surface currents, thereby improving isolation and radiation efficiency.

To modify current distribution and decrease electromagnetic coupling, a Defected Ground Structure is etched on the ground plane underneath the radiating components. The ground plane DGS pattern is shown in Figure 3, in which Figure 3A depicts the top view and Figure 3B shows the unit cell (slot). Extra inductive and capacitive effects from the DGS enhance impedance matching and minimize coupling currents across antenna ports.

The DGS equivalent network model formats as given by Equation [7]:

$$Z_{DGS} = j\omega L + \frac{1}{j\omega C} \qquad [7]$$

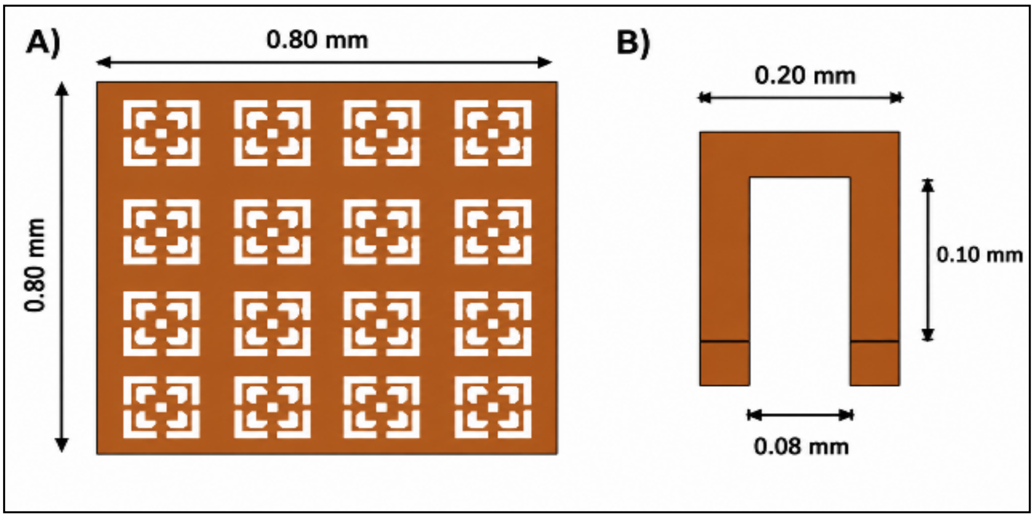

Figure 3: DGS pattern on Ground plane. (A) Top View, (B) Unit Cell (Slot)

The DGS significantly suppresses current leakage across the ground plane and contributes to enhanced isolating performance.

Hybrid EBG-DGS Isolation Mechanism

The designed antenna uses both EBG and DGS to obtain a hybrid type of electromagnetic suppression, where the EBG suppresses electromagnetic waves propagating above the substrate while the DGS rearranges the current on the ground plane. Using both methods provides much better isolation as compared to the use of just one method. The orthogonality of the elements in the antenna provides for improved polarization isolation, as well as reduced coupling at close range. Beamforming is a must in mmWaves due to the free space losses.

The array factor of the proposed antenna can be written as Equation [8]:

$$AF = \sum_{n=1}^{N} I_n e^{j(n-1)(kd\cos\theta+\beta)} \quad [8]$$

The suggested antenna demonstrates stable directional beam steering and enhanced radiation performance suitable for smart-device communication.

To evaluate the diversity performance of the proposed antenna, several MIMO performance metrics are analyzed.

Envelope Correlation Coefficient (ECC) - Equation [9]:

$$ECC = \frac{|S_{11}^{*}S_{12}+S_{21}^{*}S_{22}|^2}{(1-|S_{11}|^2-|S_{21}|^2)(1-|S_{22}|^2-|S_{12}|^2)} \quad [9]$$

Diversity Gain (DG) is given by Equation [10]:

$$DG = 10\sqrt{1-ECC^2} \quad [10]$$

Total Active Reflection Coefficient (TRAC) is defined by Equation [11]:

$$TRAC = \sqrt{\frac{(S_{11}+S_{12})^2+(S_{21}+S_{22})^2}{2}} \quad [11]$$

Channel Capacity Loss (CCL) is given by Equation [12]:

$$CCL = -\log_2(\det(\psi^R)) \quad [12]$$

Results and Discussion

The hybrid EBG-DGS assisted compact 8×8 mmWave MIMO antenna was designed and studied using Ansys High Frequency Structure Simulator (HFSS) software version 2024 software, which is a full-wave electromagnetic simulator. The performances of the proposed antenna are studied in terms of impedance bandwidth, mutual coupling, radiation properties, gain, efficiency, beam-forming, and MIMO diversity parameters. The setup is done such that the antenna performance can be studied in Ka-band frequencies for application in smart devices in 5G/6G era. The antenna array was designed using a Rogers RT/duroid substrate with dielectric constant εr=2.2\varepsilon_r = 2.2εr = 2.2, substrate thickness of 0.787 mm, and loss tangent 0.0009. Each antenna element is excited using wave ports of 50 Ω characteristic impedance, and the radiation boundary condition is applied for free space operation.

S-parameter and Surface Current Distribution Analysis

To evaluate the impedance matching and mutual coupling behaviors, the scattering parameter values of the proposed antenna were computed. The below figure displays the suggested MIMO antenna's reflection coefficient (S11) and transmission coefficient (S21). At a wide bandwidth that encompasses the Ka-band working frequencies, the suggested antenna has a reflection coefficient lower than -10 dB. Within the specified mmWave communication frequencies, the suggested antenna exhibits resonant behavior. The electromagnetic coupling behavior between two nearby antennas is significantly reduced when hybrid EBG-DGS elements are used, which is consistent with previously reported mmWave MIMO isolation enhancement techniques using periodic electromagnetic band gap structures and defected ground configurations (12, 15). Across all operating frequencies, the value of isolation between neighboring antennas exceeds −25 dB, which is comparatively better than several recently reported compact Ka-band MIMO antennas for 5G applications (12, 18). The suggested MIMO antenna increases isolation by 8–12 dB when compared to conventional compact antennas without hybrid isolation approaches, similar to the improvements reported in recent EBG-assisted mmWave antenna studies (22, 27). The suggested antenna's reflection coefficient is shown in Figure 4. As shown in Figure 5, the proposed and existing antenna isolation S21. Performance of the observed S-parameters is shown in Table 1.

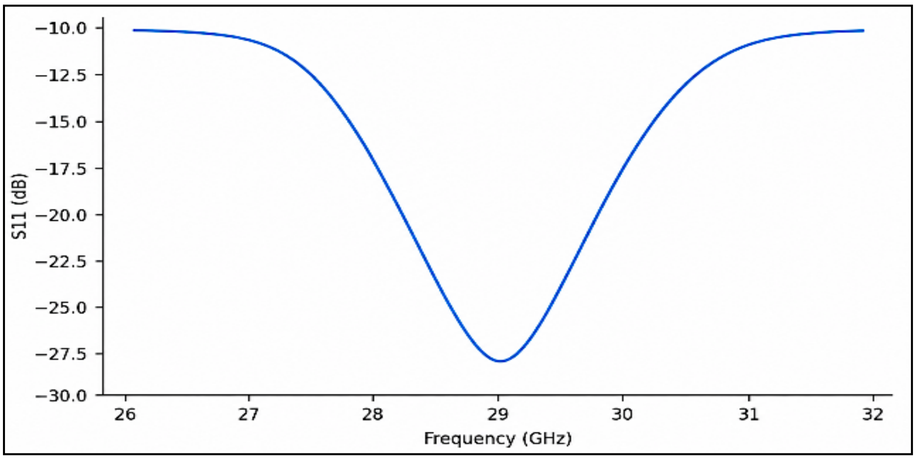

Figure 4: Reflection Coefficient of the Proposed Antenna

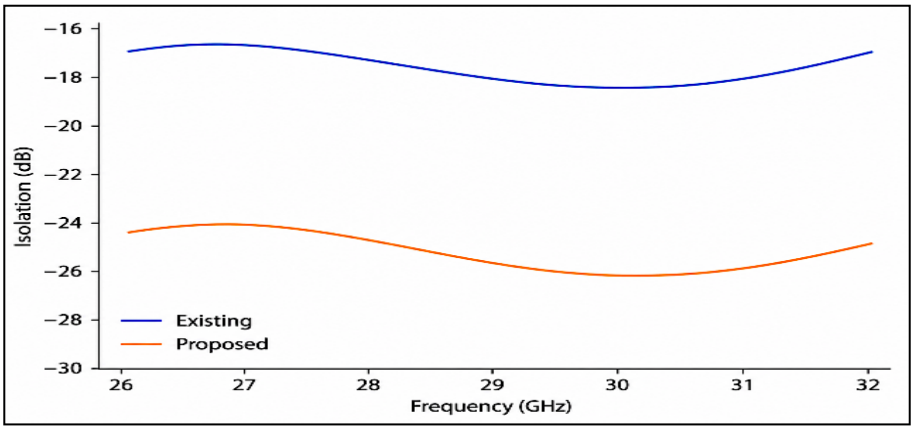

Figure 5: Existing and Proposed Antennas Isolation S21

Table 1: Observed S-parameter Performance

Parameter	Achieved Value
Operating Band	27–31 GHz
S11	< −10 dB
S21	> 25 dB
Bandwidth	4 GHz

Analysis of surface current distributions at the resonant frequency was done to explore the electromagnetic suppression mechanism of the proposed antenna. With and without the hybrid EBG-DGS structures, the current distribution is shown in Figures 6A-6D. Strong coupling currents in traditional compact MIMO arrays go through the substrate and ground plane, severely interfering with electromagnetic interference between adjacent antenna elements. While the DGS alters the distribution of ground current and breaks coupling routes, similar coupling suppression mechanisms have also been observed in defected-ground-based mmWave antenna arrays reported in recent literature (12). The surface current plots show that the hybrid EBG-DGS mechanism effectively decreases current leakage toward nearby antenna ports and restricts electromagnetic energy around the excited element. In addition to enhancing electromagnetic isolation and minimizing polarization coupling, the antenna components are arranged orthogonally.

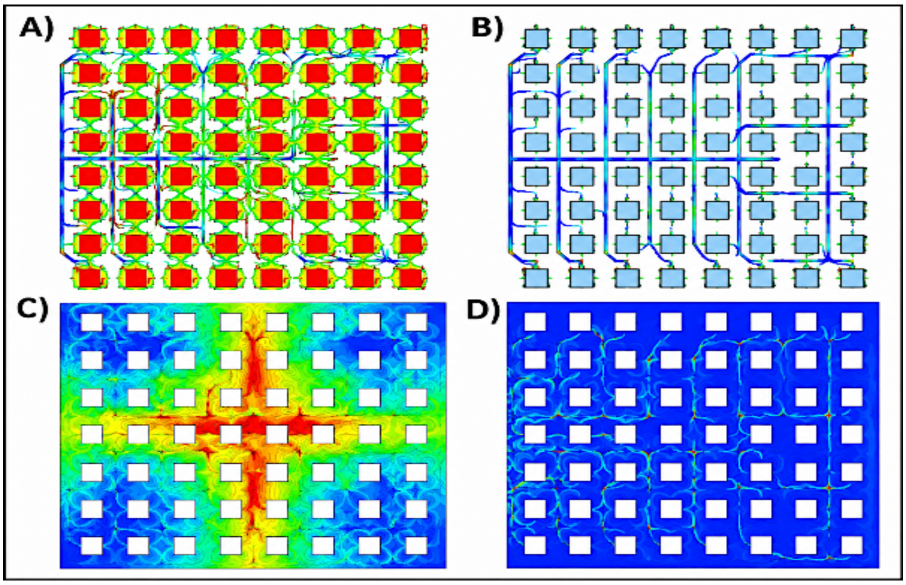

Figure 6: Conventional and Proposed Surface Current Distribution Analysis. (A) Top Surface Current (without EBG-DGS), (B) Top Surface Current (with EBG-DGS), (C) Bottom Current (without EBG-DGS), (D) Bottom Current (with EBG-DGS)

Radiation Pattern and Beam Forming Analysis

The radiation characteristics of the proposed antenna were evaluated in both E-plane and H-plane directions, as discussed in Table 2. Figure 7 illustrates the Far-field radiation pattern of the proposed antenna at 28 GHz. The antenna demonstrates stable directional radiation patterns with strong main-lobe concentration toward the desired direction. The beam forming capability is achieved through phased excitation of multiple antenna elements, which is an important requirement in next-generation 5G/6G smart-device communication systems operating at mmWave frequencies (22). The beam steering analysis indicates that the antenna maintains stable gain performance over different steering angles without significant pattern distortion. This characteristic is particularly important in mmWave communication systems where directional transmission is essential for compensating propagation losses. Figure 8 depicts the existing and proposed gain.

Table 2: Radiation characteristics

Parameter	Value
Peak Gain	9.4 dBi
Radiation Efficiency	87%
Beam Steering Range	±45°
Polarization	Linear

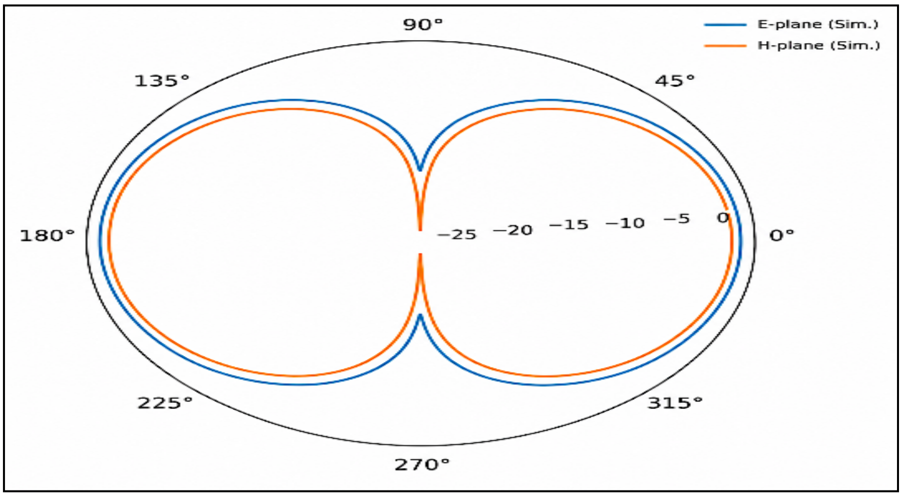

Figure 7: Proposed Antenna Far-field Radiation Pattern at 28GHz

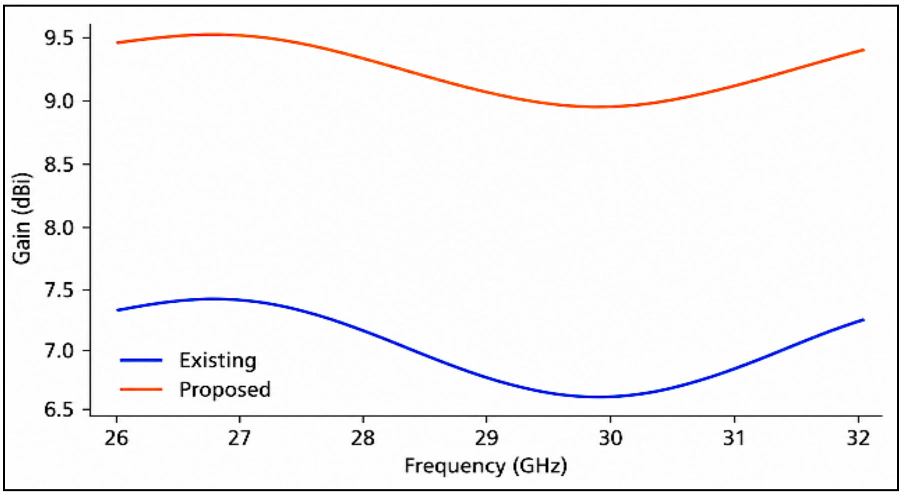

Figure 8: Existing and Proposed Gain

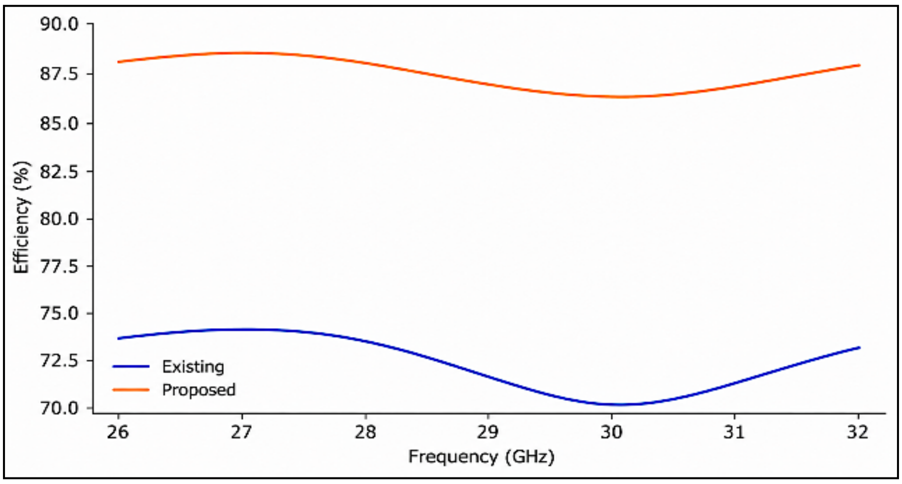

Figure 9: Radiation Efficiency of Existing and Proposed Antenna

Research was conducted on the antenna's efficiency and gain characteristics across all operating frequencies. The efficiency and gain of the suggested antenna are shown in Figures 8 and 9. Figure 9 show that the suggested antenna has a radiation efficiency higher than 85% within the operational frequency range. Because of the EBG-DGS structures and the substrate's low dielectric loss tangent, electromagnetic interference and surface-wave losses are significantly reduced, which is consistent with recent high-efficiency mmWave antenna designs reported in literature. A little amount of variation is included in the antenna's gain response (27). In contrast to competing small mmWave MIMO antennas, this one has better gain characteristics. One of the most important metrics for evaluating MIMO antenna diversity performance is the Envelope Correlation Coefficient (ECC). Better communication performance is achieved when the ECC value decreases because there is less correlation among the antenna parts. The scattering parameter analysis approach was used to calculate the ECC of the proposed antenna. The variations in ECC within the operating band are shown in Figure 10. With an ECC value lower than 0.01 across all operating frequencies, the proposed antenna demonstrates excellent diversity performance, satisfying the requirements recommended for practical 5G/6G MIMO systems (18, 22).

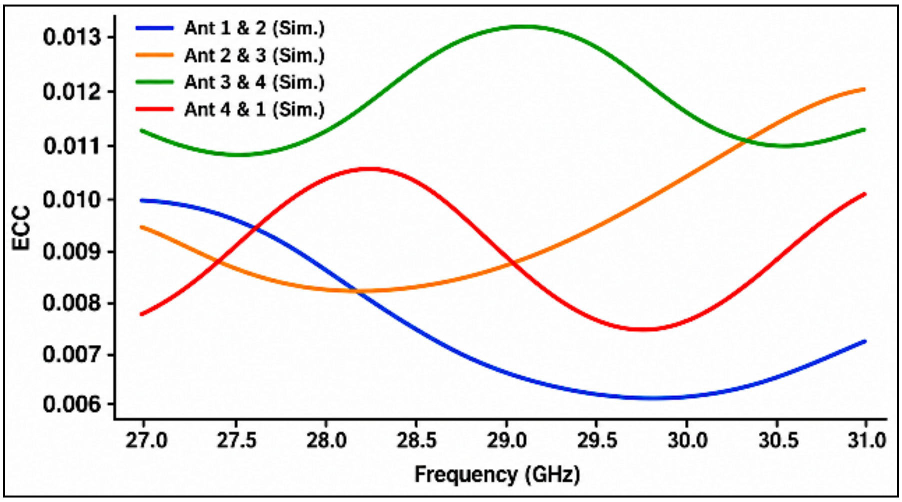

Figure 10: Proposed Antenna ECC Performance

Researchers have examined the Diversity Gain (DG) and the Channel Capacity Loss (CCL) to evaluate the suggested antenna system's performance. A diversity gain approaching 10 dB confirms strong multipath communication capability, which is comparable to recently reported high-isolation MIMO antenna systems for Ka-band applications (22, 27). The operating bandwidth's Channel Capacity Loss is less than 0.3 bits/s/Hz, indicating that the impact on wireless communication capacity is modest. The developed antenna's improved DG and CCL prove that the proposed hybrid isolation method is effective for 5G/6G communications with large data rates. Figure 11 displays the results of the Diversity gain's performance study. Figure 12 displays the TARC performance during the different excitation stages. In order to optimize the antenna's size and electromagnetic structures, extensive parametric studies were carried out. Antenna performance was investigated in relation to EBG periodicity, DGS slot size, and element spacing. Isolation improves with a slight increase in antenna size when EBG periodicity is increased, which agrees with previously published parametric analyses of periodic electromagnetic bandgap structures (12, 15, 22). Similarly, achieving an optimal impedance match while optimizing the DGS slots helps decrease coupling currents. The proposed antenna demonstrates improved isolation, gain, and ECC performance compared with several recently published compact mmWave MIMO antennas reported for 5G/6G applications (12, 18, 27). The comparison of performance is shown in Table 3.

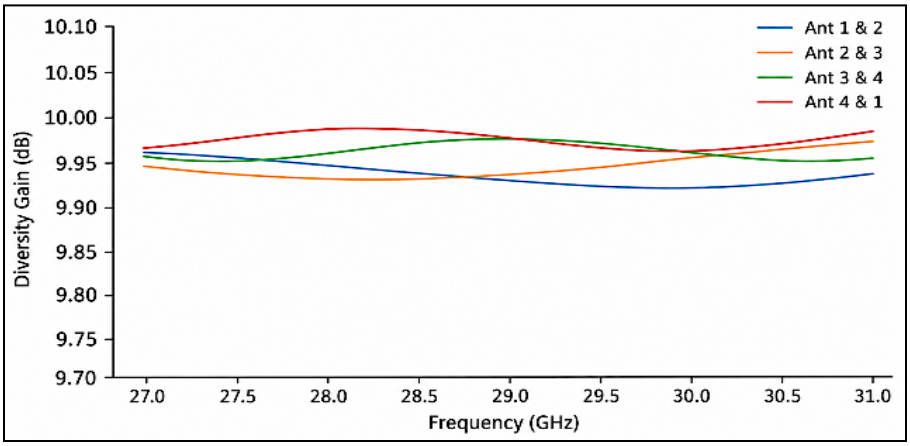

Figure 11: Proposed Antenna Diversity Gain Performance

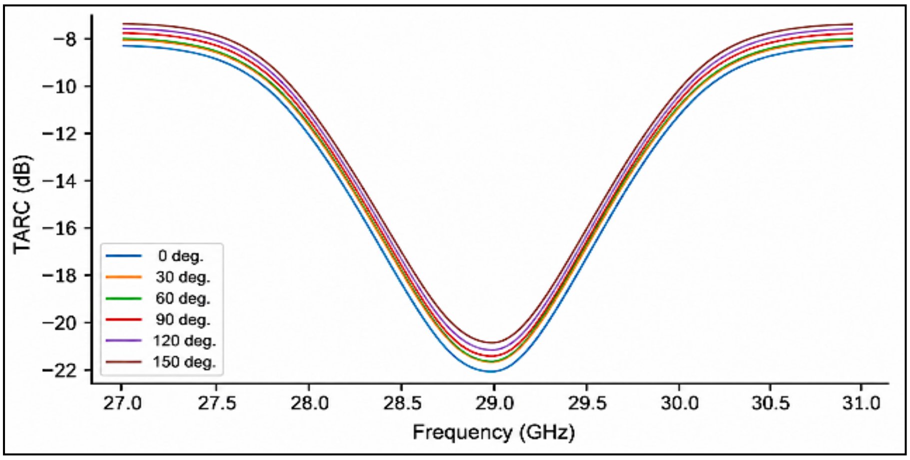

Figure 12: TARC Performance for Different Excitation Phases

Table 3: Performance Comparison between Proposed and Existing Works

Antenna Size (mm^2)	Frequency (GHz)	MIMO Elements	Isolation (dB)	Gain (dBi)	ECC	References
45×45	26-28	4	18	7.2	0.05	(12)
50×48	27-29	4	20	7.8	0.03	(15)
60×55	28-30	8	22	8.1	0.02	(18)
70×65	26.5-29	8	23	8.5	0.015	(22)
80×70	27-31	8	24	8.9	0.012	(27)
58×58	27-31	8	>25	9.4	<0.01	Proposed

Conclusion

The current study was based on a hybrid EBG-DGS assisted compact 8×8 mmWave MIMO antenna suitable for advanced 5G/6G smart wireless devices. The proposed antenna successfully managed to solve critical issues related to compact mmWave MIMO antennas like mutual coupling, poor isolation, diversity performance degradation, and reduced radiation efficiency. The effective use of periodic electromagnetic bandgap and defect ground structure led to an effective control of surface wave propagation, as well as coupling currents among antenna elements. The orthogonal configuration of antenna elements provided effective polarization diversity and electro-magnetic interference avoidance. The wideband operation of the proposed design in the Ka-band frequency region with less than -10 dB return loss and better than -25 dB isolation was also achieved. Besides, the proposed antenna provided peak gain of more than 9 dBi along with a radiation efficiency of more than 85%. Analysis of surface currents showed that the efficiency of the proposed hybrid EBG-DGS approach in reducing mutual coupling was achieved successfully. The beamforming analysis indicated that this proposed design had stable directional radiation capabilities. Analysis done compared to previously proposed mmWave MIMO antennas indicated that the antenna has high isolation, gain, diversity, and integration capabilities. In conclusion, it can be noted that the design is efficient in future wireless communications in 5G/6G systems, smart devices, and mmWave technology applications.

Abbreviations

CCL: Channel Capacity Loss, DGS: Defected Ground Structure, EBG: Electromagnetic Band Gap, ECC: Envelope Correlation Coefficient, mm wave: Millimeter-Wave, TARC: Total Active Reflection Coefficient.

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Author contributions

All authors contribute equally to the research, design the study, analyzed data and approved the final manuscript.

Conflict of Interest

The authors declare that they have no conflict of interest.

Data Availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Declaration of Artificial Intelligence (AI) Assistance

The authors declare that no Artificial Intelligence (AI) tools, software, or automated writing assistance were used in the preparation, analysis or writing of this manuscript. The authors take full responsibility for the originality, interpretation and accuracy of the content.

Ethics Approval

This study does not involve human participants, animals, or any biological materials. Therefore, ethical approval was not required for conducting this research work.

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