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RESEARCH ARTICLE

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Development of a Low-Profile MIMO Antenna with Mutual Coupling Reduction for 5G Millimeter-Wave Systems

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Abstract

This research presents a compact Dual-Band (DB) Multiple-Input Output (MIMO) antenna characterized by extensive capacity and elevated isolations. The concept includes alterations to the ground planes. It employs Metamaterials (MM) to facilitate DB functionality in the Millimeter-Wave (MMW) space for 5G systems, notably in the 27/39 GHz bandwidths. The suggested antenna retains its DB functionality notwithstanding its modest dimensions of 3.6 × 3.5 × 0.76mm (without the feeding lines). The antenna is constructed on a Rogers RT5880 substrate, measuring 0.76 mm in width, with a relative permeability 2.1. The MIMO system consists of two symmetric radiating components in close range, yielding Mutual Coupling (MC) intensities of -22 dB and -14 dB at 27 and 39 GHz. Alterations to the ground width are implemented to improve isolation in the higher-frequency band, while the incorporation of MM significantly diminishes couplings in the lower-harmonic band. The integration of MM results in an increased capacity from 3.7 to 4.7 GHz in the shorter band (25-29.5 GHz) and 3.7 to 4.3 GHz in the upper band (37.7-41.9 GHz). The suggested system can function inside the 27/39 GHz bands with a compact layout, providing enough isolation, an envelope factor under 0.0002, and a notable diversity factor above 8.72 dB. These characteristics underscore the appropriateness of 5G MMW mobile connectivity.

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Introduction

Significant advancements in Wireless Communication Networks (WCN) have occurred recently, especially with their extensive capacity and elevated data speeds.[1] The advancement of 5G technology is driven primarily by the necessity to accommodate many consumers with exceptional data rates.[9] To mitigate the issues of congested 5G mobile frequencies during the implementation of 5G systems, the utilization of Millimeter-Wave (MMW) has been proposed.[2] The idea of deploying 5G models utilizing the MMW spectrum seeks to circumvent the issue of overcrowded cellular channels.[10] In the 5G bandwidth, networks have been allocated several bands of frequencies, like 27, 39, 62, and 72 GHz, which are now under active research and are expected to achieve commercial viability shortly.[3] The upcoming 5G networks are expected to satisfy the escalating demands for high data rates, dependability, and lower energy consumption for millions of linked gadgets, unlocking the full promise of new technologies such as smart cities, augmented reality, and autonomous vehicles.[17] Investigators encounter numerous obstacles while building antennas for MMW frequencies. Two primary design concerns are emphasized in the practical application of printed antennas: capacity enhancement and size minimization. Enhancing capacity and minimizing physical dimensions are essential in designing printed antennas.[12] New Radio Frequency (RF) designs necessitate that antenna components possess distinct characteristics, including a compact and low-profile layout, the ability to support dual or different operational bands, cost-efficiency, a small planar framework, and reduced dimensions.[4,13]

Alongside the specified effort, other dual-band (DB) antennas (DBA)for MMW purposes are the subject of rigorous research for deploying 5G communication systems.[11] These bands have demonstrated notable improvements and substantial enhancements relative to past versions of transmission systems.[16] Improving transmission reliability in the high-frequency region poses a difficulty that can be addressed using different methods, such as Multiple-Inputs Multiple-Outputs (MIMO).[5] MIMO is widely recognized as a crucial facilitator for 5G WCN, since it improves data speed, boosts spectral efficiency, and enhances capacity use.[15]

MIMO can substantially enhance the efficiency and reliability of MMW communications inside 5G networks.[18] This enhancement can be realized by incorporating a minimal gap between the emitting parts, ensuring sound isolations, and reducing correlations among the DBA. The restricted distance between antennas in MMW systems can lead to considerable coupling. This coupling adversely affects the efficiency of the MIMO network [14]. Several recent articles have examined the creation of 5G MIMO DBA functioning at MMW frequencies (27/39GHz) without employing any decoupling methods. Therefore, the MIMO mainly demonstrates Mutual Coupling (MC) due to its configuration. Coupling occurs at both frequency ranges of -21 dB. The DB MIMO setup exhibits an isolation of 24 dB. The DB MIMO system demonstrates enhanced isolation of 25 dB.

The swift progress in WCN has led to a growing demand for MIMO DBA with superior isolations to meet the needs of 5 G. The investigator examined the performance of a 5G MIMO single and DB antennae and analyzed many decoupled approaches to alleviate coupled issues. These antennas offer a variety of benefits, including compact size, wideband performance, frequency adaptability, significant gain, circularly polarization, and multiple-band capability. Studies have demonstrated considerable curiosity in using synthetic materials called Metamaterials (MM).[6] These materials possess remarkable electrical properties and have multiple uses, including antennae, microwave gadgets, cloaking technologies, and superlenses in microscopes. Several studies have investigated the application of MMs in MIMO antennas to reduce the MC and boost performance. The author presents an MM-based antenna called the Dielectric Resonance Antenna (DRA), which is 25 × 45 × 1.8 mm. The DBA attains a separation of roughly 29 dB at 28 GHz and exhibits diversity metrics of Diversification Gain (DG) (8.7) and Envelope Correlated Coefficient (ECC) (0.04).[22]

A separate study employed a vertical layout of MM unit cells (UC) to diminish coupling at 39 GHz, yielding enhanced gains of roughly 6.3 dB and 5.7 dB at 27 and 39 GHz. This antenna, equipped with a single-band MM, operates at a frequency of 6 GHz, reaching a gain of 7.6 dB and a separation of 14.2 dB. MIMO unit cells utilize periodic configurations to improve transmission efficiency, enabling optimal communication effectiveness at the resonance frequency region. It is enhanced by employing two or more progressively interconnected repeated surfaces. An MM-based antenna measuring 26 x 15 × 5.4 mm is described. The antenna functions at 42 GHz, attaining an enhanced separation of 33 dB, with diversity metrics of DG (8.7) and ECC (0.2). The paper presents a DB MM-inspired antenna, achieving a gain of 5.3 dB at 27 GHz and 5.4 dB at 39 GHz, alongside increased separation in the MIMO setup.

This work introduces a novel method to tackle the issues of 5G communications with a DB MIMO antenna device with wideband functionality, operating at 27 GHz and 39 GHz. Among the above-stated research, a few studies address coupling mitigation in DB MIMO systems, particularly inside the MMW spectrum. The DBA shows two antennas positioned closely on a Rogers substrate [7]. An MM is incorporated between the system parts to improve the efficiency of the DBA network.[21] This combination yields a broad frequency response with enhanced gain. Moreover, the incorporation of MMs aids the suggested design in diminishing coupling and improving isolation among the antennas within the specified frequency range.[20] The remarkable amalgamation of wide-band protection, DB functionality, augmented gain, and superior isolation achieved with MMs in this MIMO DBA design underscores its capacity to transform higher-speed wireless connectivity in the 5G epoch.[19] The Ansys High-Frequency Structural Simulation (HFSS) is utilized for testing0.[8]

Design and optimization of antennas

This research examines a specific component of the suggested model associated with the constructed model. The findings regarding (S11), frequency versus gains, irradiation effectiveness, and irradiation distribution are analyzed by analyzing the predictions from HFSS software with the measured outcomes. The proposed single-component design outcomes are juxtaposed with existing research.

Fig. 1 illustrates the structural design of the proposed DB antennae functioning throughout the Industrial, Scientific, and Medical (ISM) and Wireless Local Area Network (WLAN) frequency ranges. The suggested DBA has a coplanar wave-guide feeding line integrated across multiple stubs. Multiple stubs are employed to achieve an extensive and suitable resonant frequency. The intended project is constructed using RT/Duroid 5880, featuring a thickness of 0.8mm and a related permeability of 2.1. HFSS was employed as an electromagnetic simulation to evaluate the structure of the proposed antennas. A physical antenna was then built to verify the simulation results.

Methodology of Design

The results of the intended study are achieved by finishing multiple model stages. For 2.6 GHz ISM programs, a circle-structured patch with a radius of 5mm is fabricated in the initial step, with values derivable from the formula presented. The antenna exhibits a reflected ratio of -12 dB and functions at 2.6 GHz. A rectangle-shaped stub is incorporated to mitigate mismatched and enhance capacity. This stage enhances the refractive factor at 2.7 GHz from -12 dB to -17 dB, creating a band in 5.7 GHz. In the final stage, a rectangle-shaped stub with a dimension of 12 mm is added to the top of the radiators. This construction phase yields DB antennae at 2.5 and 5.7 GHz, providing 2.4-2.8 GHz capacity and 5.7-6.9 GHz. The antenna exhibits a wideband performance across each frequency band. A T-structured stub is incorporated on the top of the current stub-loading patched radiators to achieve the desired frequency ranges. The final shape is achieved, shifting the antennae resistance towards a lower frequency range. The antennae now functions in two frequency groups: 2.3 GHz and 5.6 GHz.

Parametric examination

A parametric evaluation of essential factors is conducted to examine the influence of each parameter on achieving wideband characteristics. The alteration in the |S11| parameter resulting from changes in the width of the bottom stub. It provides DB functionality throughout the 2-4 GHz and 4.7-6.3 GHz ranges at a specified length of 14 mm. The DBA's reflecting ratio is reduced to -17 dB, which influences connectivity, if the value is increased to 12mm. The effect on the reflecting coefficients and capacity becomes more evident if the stub width is reduced to 12mm. It provides a DB reflecting factor reaction with the previously indicated broad spectrum at the optimal value of 10mm. The DBA exhibits narrow-band characteristics and cannot function within the necessary frequency ranges if the stub width is maintained at 8 mm. The DBA operates at 3.5 GHz and 6.7 GHz, with capacities ranging from 2.8-3.6 GHz and 5.6-7.2 GHz, provided the measurement exceeds the optimal value of 12 mm.

Optimization for layout

A antennae featuring a circularly slit with a diameter of RO is initially developed. The dimensions of the proposed antennas are modified to get the intended results. The fundamental circular configuration is restructured using a regular stub to enhance capacity and resistance matching. The dimensions of stubs are optimized based on parametric analysis. Multiple stubs are situated at the upper section of the patches, with

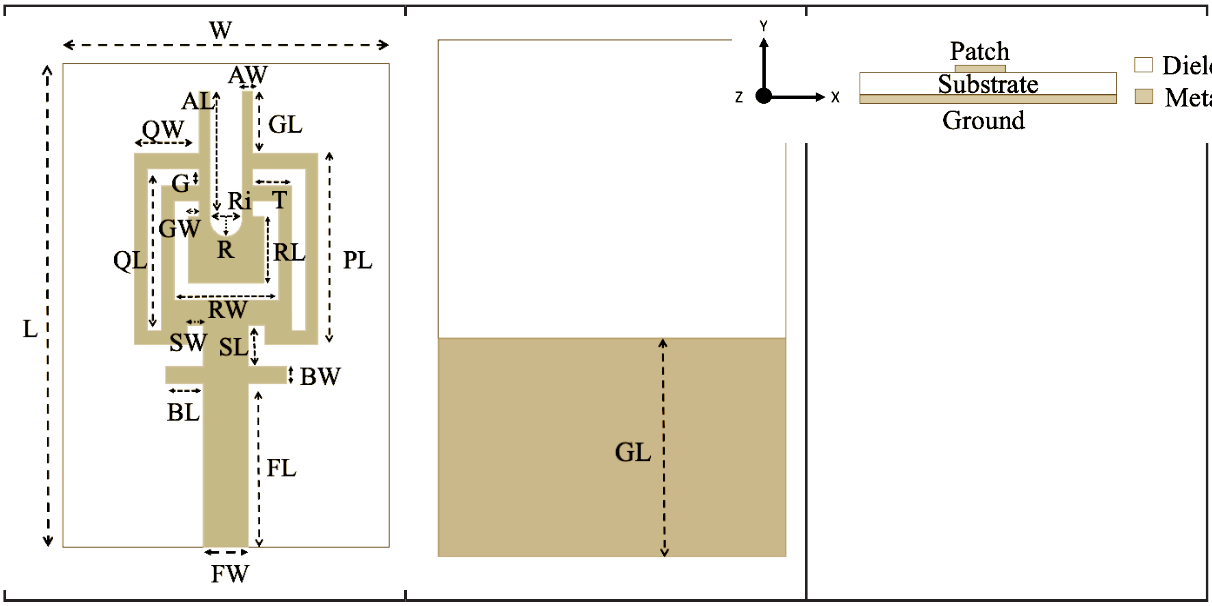

Fig. 1: Antennae design[8]

W2 and W4. The computation of both models' breadth and height achieves the optimal parameter values to maximize bandwidth. The variables W2, W4, and L3 are examined to attain optimal results regarding bandwidth. It is noteworthy that alternative artificial intelligence techniques are utilized for additional optimization.

Observations and findings of the DB antenna

Several essential variables are analyzed to evaluate the antenna's performance. To validate these designed outcomes, a hardware prototype of the intended DBA is constructed to analyse them and contrast with the simulations.

Scattering parameters

The results indicate that the functional impedance bandwidth ranges from 2.3 to 2.8 GHz and 5.4 to 5.8 GHz. At 2.6 and 5.7 GHz, the suggested operation yields a reflection ratio of -23 dB. The hardware evaluations and software results demonstrate significant resemblance, positioning the suggested system as optimal for future gadgets operating inside the ISM and WLAN spectrum. The direction of radiation is another essential aspect to assess when assessing an antenna's effectiveness. The proposed work demonstrates omnidirectional irradiation in the E-planes at 2.6 GHz and bidirectional irradiation in the H-plane. At 5.6 GHz, the E-planes remain identical to those at 2.7 GHz, exhibiting an omnidirectional characteristic; the H-plane design displays little distortion while preserving a bidirectional configuration. This distortion results from multi-stub loading and a shift into higher frequencies. The observed radiation patterns and predicted outcomes exhibit remarkable consistency. The correlation between actual and simulated results and radiation pattern evaluation renders the proposed antennas appropriate for WCN gadgets functioning at 2.7 GHz and 5.9 GHz.

Gain versus frequency graph

The antenna provides a gain exceeding three dBi across the operating frequency between 2.2 and 2.6 GHz, achieving a 4dBi at 2.5GHz. Conversely, the DBA has a gain above 4.3 dBi.

Radiative efficiency

The result indicates that the DBA functions within 2.2-2.8 GHz and 5.2-5.8 GHz, with an effective radiation of over 91%. The antenna achieves an optimal radiation effectiveness of 97.2% at 2.7GHz and 93% at 5.9GHz. The overall effectiveness of the DBA exceeds 74%, which is satisfactory for everyday use. Future gadgets utilizing the ISM and WLAN spectrum of frequencies benefit from the proposed DBA-enhanced irradiation properties.

Comparison with literary works

The effectiveness comparison of the exhibited design with prior works is conducted regarding size, functional connectivity, resonant frequency, and gain. The proposed antenna exhibits substantial gain, a compact size, and operates across a broad bandwidth, all while featuring a simplified design.

Results

Analysing a MIMO efficacy requires assessing the correlating features among its ports. Critical metrics such as the ECC, DG, and Channel Capacity Loss (CCL) are meticulously examined to determine the observed MIMO network's effectiveness. A comprehensive study of these variables is provided below.

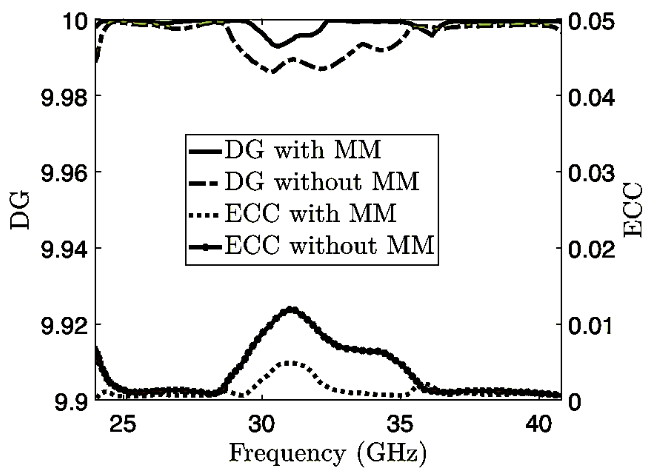

Fig. 2: DG and ECC analysis

Fig. 2 depicts the fluctuation of the ECC at the specified frequency of a suggested antenna structure, contrasting scenarios with and without the use of MMs. The measured figures indicate that the ECC at 29 and 39 GHz is less than 0.0002, signifying a substantial decrease relative to the typical limit of 0.5 used in WCN. Diversity in MIMO is attained by obtaining several sent indicators over different routes, facilitated by using many antennas inside the system. An elevated signal strength is achieved when the messages obtained at the source are independent, leading to enhanced reception of signals. The variety gain can be calculated by a reference that suggests a lower correlation value results in greater diversity gain. It demonstrates that both frequencies exhibit DG close to the typical value of 12 dB. The MIMO transmission variables have been computed and are presented in Table 1.

Table 1: MIMO communication variables

Frequency	Correlation	DG	Multiplexing effectiveness
2.5	0.3	10.2	94.23
5.3	0.08	9.5	97.29

Conclusions

A compact MIMO model including an MM array is introduced. This architecture facilitates operations in DB MMW spectrums while efficiently controlling lower MC. This DBA layout is designed to meet the requirements of sophisticated 5G communications networks. The suggested MIMO design attains a DB reaction at 27/39 GHz and comprises two contiguous radiating elements with a compact physical dimension of 3.6 × 3.5 × 0.76 mm. A meticulously engineered DB MM has been carefully placed between the two irradiating components of the MIMO to augment isolation without modifying the system's footprints. Integrating the MIMO DBA array and MM on the RT5880 lower-loss foundation guarantees outstanding efficiency in the MMW bandwidth. The MIMO system demonstrates outstanding diversity attributes, characterized by an extraordinarily low ECC, CLL, DG, and unidirectional irradiation distribution. The simulation findings align with the analysed outputs across every indicator of the entire structure. The suggested antenna design offers distinct advantages, making it suitable for 5G MMW WCNs.

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