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Research Article

MetaSlot-MIMO: A Compact Dual-Band Four-Port MIMO Antenna with Metamaterial-Inspired Decoupling Structure for 5G Millimeter-Wave Applications at 28/38 GHz

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Abstract

With fifth-generation (5G) millimeter-wave (mmWave) networks being deployed rapidly, multi-antenna systems are needed that are small, highly isolated, and able to support massive MIMO configurations in the standardized bands at 38 GHz (n260) and 28 GHz (n257/n261). Current dual-band MIMO antenna designs must trade miniaturization against isolation between elements, radiation efficiency, and wideband impedance matching; the complex decoupling structures they often require add to fabrication cost and overall footprint. Proposed here is MetaSlot-MIMO, a small MIMO antenna system with four ports and two bands, whose ground plane carries an etched decoupling structure of a novel kind, a complementary split-ring resonator (CSRR) inspired by metamaterials. Built on a Rogers RT/Duroid 5880 substrate ($\varepsilon r = 2.2$, $\tan\delta = 0.0009$), the proposed antenna has a total footprint of $26 \times 26 \times 0.254$ mm³. Each radiating element is a modified rectangular microstrip patch to which an L-shaped parasitic strip is added, so that resonances at 28 and 38 GHz occur together. The CSRR decoupling structure suppresses surface-wave coupling between neighboring ports while leaving the radiation characteristics intact. Simulation and measurement confirm: return loss $|S11| < -15$ dB in both bands; port isolation $|S21| > 35$ dB at 28 GHz and > 38 dB at 38 GHz; peak realized gain of 8.7 dBi at 28 GHz and 10.4 dBi at 38 GHz; radiation efficiency above 91% in both bands; and impedance bandwidth of 2.4 GHz (26.8–29.2 GHz) and 3.1 GHz (36.5–39.6 GHz). The MIMO diversity metrics also confirm excellent performance at both operating frequencies: envelope correlation coefficient (ECC) < 0.003, diversity gain (DG) > 9.99 dB, channel capacity loss (CCL) < 0.08 bps/Hz, and a mean effective gain (MEG) ratio within 0.4 dB. A comparison against eight state-of-the-art designs from the open literature validates the proposed design, which outperforms them in isolation, gain, and compactness.

Keywords: MIMO antenna; 5G millimeter-wave; Dual-band antenna; Microstrip patch; Complementary split-ring resonator; Decoupling structure; Envelope correlation coefficient; Channel capacity loss; 28 GHz; 38 GHz

1. Introduction

Since the worldwide rollout of New Radio (NR) networks of the fifth generation (5G) began, the need for small, high-performing antenna systems working in the millimeter-wave (mmWave) spectrum has reached unprecedented levels. For 5G NR mmWave operation, the band from 24.25 to 52.6 GHz has been set aside by the 3rd Generation Partnership Project (3GPP) and the International Telecommunication Union (ITU); of its sub-bands, 38 GHz (n260) and 28 GHz (n257, n261) have become the most widely licensed and commercially deployed [1], [2]. Each carrier at these frequencies can use contiguous bandwidth of up to 800 MHz, and carrier aggregation allows peak downlink rates beyond 20 Gbps, ten times what sub-6 GHz 5G NR offers [3].

MIMO (multiple-input multiple-output) technology underpins 5G mmWave performance, using spatial multiplexing and diversity to come close to the theoretical limits of channel capacity [4]. When mmWave MIMO systems are compact, however, antenna elements sit physically close together, and the resulting strong mutual coupling lowers port isolation, radiation efficiency, and diversity gain. Dual-band systems compound the difficulty; across two frequency bands lying about 10 GHz apart, the antenna has to deliver matched impedance, steady radiation patterns, and low mutual coupling all at once [5].

In the literature, isolation has been improved through Defected Ground Structures (DGS) [6], Electromagnetic Band-Gap (EBG) structures [7], neutralization lines [8], and decoupling based on metamaterials [9]. Complementary split-ring resonators (CSRRs) inspired by metamaterials [10] stand out among these options; their bandstop response at resonance is strong, they need no change to the radiating elements because they can be etched straight into the ground plane, and their dimensions shrink to sub-millimeter size at mmWave frequencies. Yet no earlier study has shown dual-band CSRR decoupling working at 28 and 38 GHz together inside a four-port MIMO footprint similar to the compact device form factor specified by ITU-T.

The present paper introduces MetaSlot-MIMO, an antenna system with four MIMO ports designed to meet every challenge listed above. The main contributions are:

- An antenna element for compact four-port, dual-band MIMO use, formed from a rectangular microstrip patch modified with an L-shaped parasitic strip so that it resonates at 28 and 38 GHz at the same time, with each element occupying 6.5 × 5.8 mm² of Rogers RT/Duroid 5880.
- Characterization on a broad scale by both simulation and measurement, including S-parameters, radiation patterns, gain, and efficiency, as well as every MIMO diversity metric (ECC, DG, CCL, MEG, TARC, and channel capacity at SNR = 20 dB), with suppression of both electric and magnetic coupling modes.
- A systematic comparison against eight dual-band MIMO antenna designs for mmWave from recent publications, in which the proposed antenna proves superior in isolation, gain, and compactness.

The rest of the paper is arranged as described below. Related work is surveyed in Section 2. The antenna geometry and the design procedure are presented in Section 3. In Section 4, the CSRR decoupling structure is described. Fabrication and the measurement setup are detailed in Section 5. Results are presented and discussed in Section 6. The comparative analysis is given in Section 7. Section 8 concludes the paper.

2. Related Work

2.1 Dual-Band mmWave MIMO Antenna Designs

The literature reports a number of dual-band MIMO antennas for the 28/38 GHz bands. Iqbal et al. [11] built a two-element MIMO using DGS, with isolation > 20 dB and 6.6 dBi of gain; the design, however, stops at two ports, and neither CCL nor channel capacity is given. Tiwari et al. [12] showed a flexible 4×4 MIMO on Rogers 3003 with ECC < 0.001 and peak gains at 28 and 38 GHz of 4.15 dBi and 7.73 dBi, respectively, but the higher loss tangent of the flexible substrate caps radiation efficiency at 80.1–85.4%. Ali et al. [13] obtained good isolation (> 27 dB) and ECC < 10^{-4} with a compact four-port layout, though the gain they report does not go beyond 6.5 dBi. Using a 1×2 array as its element, the quad-port wideband MIMO of Hassan et al. [14] spans 24–40 GHz with 18.2 dBi of peak gain; its element, however, is too large (28 × 30 mm²) for compact handset integration. For their dual-port DRA-MIMO, Fathy et al. [15] report DG = 9.98 dB, ECC = 0.007, and CCL = 0.06 bps/Hz together with isolation improved by 27 dB, but assembly tolerances keep the DRA approach from PCB-level integration at mmWave frequencies.

2.2 Metamaterial-Based Decoupling Structures

Since the theoretical framework for negative permeability media was established by Pendry et al. [16], split-ring resonators (SRRs) and their complementary forms (CSRRs) have found wide use as bandstop filters and near-field couplers in microwave circuits. Within antenna arrays, CSRRs etched into the ground plane produce a stopband at their resonant frequency that blocks surface wave propagation between antenna ports [9]. CSRR-based isolation improvement was shown by Alibakhshikenari et al. [17] in a 2.4 GHz array, with isolation > 30 dB. At mmWave frequencies, applications are still few; the main difficulty is dimensional accuracy, since a CSRR resonant at 28 GHz needs ring dimensions on the order of 1–2 mm and hence fabrication tolerances below 100 μm, which standard PCB laser cutting can achieve. Our dual-band CSRR design deals with the difficulty through stacked concentric CSRRs whose inner (38 GHz) and outer (28 GHz) resonances are tuned independently and separated by a 0.1 mm dielectric gap.

2.3 MIMO Diversity Performance Metrics

Characterizing the diversity performance of a MIMO antenna in the standard way calls for several interdependent metrics. The correlation between the radiation patterns of antenna pairs is quantified by the Envelope Correlation Coefficient (ECC); values below 0.5 are generally considered acceptable, while values below 0.1 indicate excellent diversity [18]. Diversity Gain (DG) measures the improvement in SNR obtainable through diversity combining, with values near 10 dB representing near-ideal performance. The loss of achievable channel capacity caused by antenna correlation is quantified by Channel Capacity Loss (CCL); for practical MIMO systems, values below 0.4 bps/Hz are acceptable [19]. A system-level measure of active impedance matching under all simultaneous excitations is given by the Total Active Reflection Coefficient (TARC) [20]. Mean Effective Gain (MEG) describes the average gain in a realistic multipath environment; for balanced diversity, the MEG ratio between ports should lie within 3 dB [21].

3. Antenna Element Geometry and Design

3.1 Substrate and Element Design

The MetaSlot-MIMO system is built on Rogers RT/Duroid 5880, a laminate with low loss, whose relative permittivity is εr = 2.2 and loss tangent tanδ = 0.0009, with a substrate thickness of h = 0.254 mm and copper cladding of t = 17 μm (0.5 oz). Research on mmWave antennas commonly uses the substrate, which therefore gives a well-characterized basis for comparing results with published work [12], [13], [14]. The low dielectric constant of 2.2 limits how far the effective wavelength is elongated, which keeps the radiating elements compact while dielectric loss stays low between 28 and 38 GHz.

The radiating element takes the form of a rectangular microstrip patch, L_p × W_p = 3.82 × 3.14 mm² in size, which a 50 Ω microstrip line of width W_f = 0.76 mm feeds. A parasitic strip shaped like an L, with arms of 1.20 × 0.30 mm² and 0.85 × 0.30 mm², lies 0.25 mm away from the edge of the main patch. By disturbing how surface current is distributed, the parasitic strip creates a second resonance; at 28 GHz the main patch resonates in the TM_{10} mode, while at 38 GHz the structure loaded with the parasitic strip resonates in the TM_{11} mode, which capacitive coupling from that strip excites.

To estimate where the main patch resonates, the transmission line model is applied [22]:

$$f_0 = c / (2 \cdot (L_p + 2\Delta L) \sqrt{\varepsilon_eff}) \quad (1)$$

where ε_eff stands for the effective dielectric constant and ΔL for the extension of fringing fields beyond the patch edges. Taking εr = 2.2 and h = 0.254 mm yields ε_eff = 2.10 at 28 GHz and hence a theoretical L_p of 3.79 mm, close to the 3.82 mm obtained after optimization with CST full-wave simulation.

3.2 Four-Port MIMO Configuration

In the four-port MIMO layout, the elements are placed orthogonally at the corners of a ground plane measuring 26 × 26 mm²; each edge carries two elements turned by 90°, so that pattern orthogonality raises the isolation. Edge to edge, neighboring elements are spaced 5.2 mm in the 28 GHz band ($0.49\lambda_{28}$) and 5.2 mm at 38 GHz ($0.66\lambda_{38}$), with λ_{28} and λ_{38} denoting the free-space wavelengths at 28 and 38 GHz, respectively. Every port receives its feed through an SMA connector launch pad placed at the substrate edge. All four elements share one common ground plane, which forms the path of surface-wave coupling that the CSRR structure has to interrupt.

4. Dual-Band CSRR Decoupling Structure

4.1 CSRR Resonance Theory

In planar form, a complementary split-ring resonator (CSRR) is the dual of an SRR, consisting of a circular or square slot cut into a conducting plane and broken by a narrow gap [10]. An axial electric field makes the CSRR behave like a resonant LC circuit. Resonance occurs at the frequency:

$$f_CSRR = 1 / (2\pi \sqrt{(L_c \cdot C_c)}) \quad (2)$$

where L_c denotes the effective inductance of the outer ring and C_c the effective capacitance of the gap. When the CSRR is square, with outer dimension d and gap width g, and is etched into a substrate whose permittivity is εr:

$$C_c \approx \varepsilon_0 \varepsilon r \cdot (c \cdot t) / g, \quad L_c \approx \mu_0 \cdot (d^2) / (4\pi) \quad (3)$$

At resonance, a stopband appears in the surface wave propagation spectrum of the ground plane because of the CSRR. Confinement of the electromagnetic field within the resonator slot stops energy transfer between antenna ports that share the ground plane, so inter-element isolation improves without any effect on the far-field radiation of individual elements.

4.2 Dual-Resonance CSRR Design

Stopbands at two frequencies 10 GHz apart cannot be provided simultaneously by a single CSRR. The problem is resolved here with stacked concentric square CSRRs whose resonances are tuned independently. Tuning to 28 GHz applies to the outer CSRR (ring dimensions: outer side 1.92 mm, gap width g_1 = 0.12 mm, strip width s_1 = 0.12 mm). The inner CSRR (outer side 1.41 mm, gap width g_2 = 0.10 mm, strip width s_2 = 0.10 mm) is tuned to 38 GHz. A dielectric gap of 0.10 mm separates the two rings, giving sufficient electromagnetic isolation between the resonant modes while the dimensions stay compact.

Simulating the CSRR structure on its own in full-wave CST Microwave Studio confirms stopbands in both bands; in the surface-wave transmission coefficient (|S21|), probed by a pair of microstrip probes positioned on opposite sides of the CSRR, the depth reaches −22.3 dB at 28 GHz and −18.6 dB at 38 GHz. The fabricated array of dual CSRRs comprises twelve unit cells laid out as a 3×4 grid, which sit between pairs of antenna elements along the orthogonal edges of the ground plane.

4.3 Parametric Optimization

Optimization of the CSRR dimensions used the built-in trust-region gradient optimizer of CST, with an objective function defined as minimization of the maximum port isolation |S_ij| ($i \neq j$) at both operating frequencies at once. The outer and inner ring dimensions, the gap widths, and the inter-element spacing served as design variables. Over 18 optimization iterations, 420 full-wave simulation samples were evaluated in total, and convergence came within 3% of the target isolation values. The final optimized CSRR dimensions are summarized in Table 1.

Table 1: Optimized dimensions of the MetaSlot-MIMO antenna and dual-band CSRR decoupling structure (all dimensions in mm).

Parameter	Value (mm)	Parameter	Value (mm)	Description
L_p	3.82	L_CSRR,out	1.92	Patch length / outer CSRR side
W_p	3.14	L_CSRR,in	1.41	Patch width / inner CSRR side
h	0.254	g_1	0.12	Substrate thickness / outer gap
W_f	0.76	g_2	0.10	Feed width / inner gap
W_par	0.30	s_1	0.12	Parasitic strip width / outer strip
L_par1	1.20	s_2	0.10	Parasitic arm 1 / inner strip
L_par2	0.85	d_CSRR	0.10	Parasitic arm 2 / inter-ring gap
GND	26×26	N_cells	12	Ground plane / CSRR unit cells

5. Fabrication and Measurement Setup

5.1 Fabrication

The prototype of MetaSlot-MIMO was made by conventional photolithographic etching of the PCB. A film mask photo-plotted at 25,400 dpi and a UV-exposure photoresist process were used to pattern the substrate (Rogers RT/Duroid 5880, 0.254 mm), with a smallest feature of 80 μm, fine enough for the 100 μm gaps of the CSRR. The top copper layer carried the antenna and CSRR patterns; the bottom layer carried the ground plane with the CSRR slots. After chemical etching, end-launch SMA connectors of 1.0 mm (Southwest Microwave 1092-04A-6, rated to 40 GHz) were soldered to the ports, with silver-loaded epoxy at the pad interface to keep parasitic inductance low.

5.2 Measurement Equipment

S-parameters were measured with a Keysight N5247B PNA-X Vector Network Analyzer (VNA), whose four-port SOLT calibration up to 40 GHz was referenced to the planes of the SMA connectors. For radiation patterns, an ETS-Lindgren anechoic chamber of 10 × 6 × 4 m was used, with a broadband gain horn (Schwarzbeck BBHA 9120 D, 1–40 GHz) serving as the reference antenna. Gain was obtained at 28 GHz and at 38 GHz by the standard gain-substitution method. Frequency steps of 100 MHz covered the measurement range of 25–41 GHz. Results come from three fabricated prototypes; the figures reported are the mean over the three samples, given together with the standard deviation.

6. Results and Discussion

6.1 S-Parameter Performance

The reflection coefficients (|S11|) and isolation (|S21|) of the four-port MetaSlot-MIMO were obtained from both simulation and measurement. Table 2 lists the main S-parameter results for both operating frequencies.

Table 2: Measured and simulated S-parameter performance of MetaSlot-MIMO at 28 GHz and 38 GHz.

Parameter	Simulated 28 GHz	Measured 28 GHz	Simulated 38 GHz	Measured 38 GHz	Specification / Limit
|S11| (dB)	−18.3	−17.6±0.4	−16.8	−15.9±0.5	< −15 dB (target)
|S21| Isolation (dB)	−38.2	−35.4±0.7	−41.6	−38.3±0.8	> 35 dB (target)
Impedance BW (GHz)	2.5	2.4	3.2	3.1	≥1.5 GHz
VSWR	1.28	1.31±0.03	1.30	1.35±0.04	< 2.0
Fractional BW (%)	8.9	8.6	8.4	8.2	≥5%

The |S11| measured at 28 GHz is −17.6 dB and that at 38 GHz is −15.9 dB, both better than the target of −15 dB. The small gap between simulation and measurement (≤ 0.9 dB) stems from fabrication tolerances along the edges of the CSRR gaps and from parasitics of the SMA connectors, a level of agreement typical of reports on mmWave PCB designs [13], [14]. For all six pairs of ports, measured isolation is above 35 dB at 28 GHz and above 38 dB at 38 GHz; the two-band CSRR structure therefore meets its decoupling target at both frequencies at once, which the literature on the 28/38 GHz band had not yet shown for a footprint of this size.

6.2 Radiation Performance

The far-field radiation patterns at 28 GHz and 38 GHz were simulated and measured with Port 1 excited and the remaining ports terminated in 50 Ω. The beams point broadside (θ = 0°), with front-to-back ratios of 14.2 dB at 28 GHz and 16.8 dB at 38 GHz, as the patch geometry would suggest. Table 3 collects the metrics of radiation performance.

Table 3: Measured radiation performance of the MetaSlot-MIMO single element at 28 GHz and 38 GHz.

Parameter	Simulated 28 GHz	Measured 28 GHz	Simulated 38 GHz	Measured 38 GHz	Notes
Peak Realized Gain (dBi)	9.0	8.7±0.2	10.7	10.4±0.3	Broadside direction
Total Efficiency (%)	93.1	91.4±0.8	94.6	92.8±0.9	Includes mismatch
Radiation Efficiency (%)	95.8	93.7±0.7	96.2	94.5±0.8	Mismatch excluded
Half-Power Beamwidth	56.3°	58.1°	48.7°	51.4°	E-plane
F/B Ratio (dB)	15.1	14.2	17.4	16.8	Front/back ratio

At 28 GHz, the peak realized gain measured 8.7 dBi with a total efficiency of 91.4%, and at 38 GHz, 10.4 dBi with 92.8%. Gain is higher at 38 GHz, in keeping with the radiating aperture being electrically larger in the upper band. Measured and simulated radiation efficiency differ by no more than 2.1 percentage points at either frequency; the material parameters of Rogers RT/Duroid 5880 thus capture substrate and conductor losses well at mmWave frequencies. Most of the small shortfall in gain against simulation (0.3 dB at 28 GHz, 0.3 dB at 38 GHz) comes from loss in the connector transition and from roughness at the interface between copper and substrate.

6.3 MIMO Diversity Performance

Table 4 lists every MIMO performance metric obtained for the MetaSlot-MIMO system with its four ports at 28 GHz and 38 GHz.

Table 4: MIMO diversity metrics for the MetaSlot-MIMO four-port system. ECC and CCL are per port pair; DG, MEG, and TARC are per-port values.

Metric	Simulated 28 GHz	Measured 28 GHz	Simulated 38 GHz	Measured 38 GHz	Acceptable Threshold
ECC	< 0.001	< 0.003	< 0.001	< 0.003	< 0.5 (acceptable), < 0.1 (good)
Diversity Gain (dB)	> 9.999	> 9.997	> 9.999	> 9.997	> 9.5 dB
CCL (bps/Hz)	< 0.06	< 0.08	< 0.06	< 0.08	< 0.4 bps/Hz
MEG Ratio (dB)	< 0.3	< 0.4	< 0.3	< 0.4	< 3 dB
TARC (dB)	< −18.0	< −15.2	< −16.5	< −14.8	< −10 dB
Channel Cap. @ SNR=20 dB	22.4	21.9	22.8	22.3	> 20 bps/Hz

Every MIMO metric meets or substantially exceeds the standard acceptability thresholds. The measured ECC lies below 0.003 in both bands, which indicates near-zero correlation between the radiation patterns of the ports, owing to both the orthogonal arrangement of elements and the isolation induced by the CSRR. With < 0.08 bps/Hz, the measured CCL is well below the 0.4 bps/Hz threshold recommended in 3GPP TR 37.843 for MIMO antenna systems [23]. At SNR = 20 dB, the measured channel capacity is 21.9 bps/Hz at 28 GHz and 22.3 bps/Hz at 38 GHz, approaching the theoretical 4× MIMO capacity limit of 26.6 bps/Hz at that SNR; residual inter-element correlation accounts for the remaining gap.

Across ports, the MEG ratio remains under 0.4 dB at both frequencies, so received power is balanced in an isotropic scattering environment. Effective MIMO processing at the receiver by equal-gain combining (EGC) or maximal-ratio combining (MRC) depends on the balance. With TARC under −15 dB, active impedance matching across multiple ports holds up well when several ports are driven together, as in multi-stream MIMO transmission.

7. Comparative Analysis with Published Designs

In Table 5, MetaSlot-MIMO is compared with eight recently published dual-band mmWave MIMO antenna designs from the open literature. Every value is taken from the respective published paper, and — marks metrics that were not reported.

Table 5: Comparison of MetaSlot-MIMO with state-of-the-art dual-band 28/38 GHz MIMO antenna designs. Best value in each metric shown in bold.

Ref.	Ports	Size (mm^2)	|S11| (dB)	Isolation (dB)	Gain (dBi)	ECC	CCL (bps/Hz)	Effic. (%)
[11] 2022	2	11.4×5.3	−20	> 20	6.6	< 0.001	—	NR
[12] 2024	4	18×8.5	−18	> 20	7.73	< 0.001	< 0.15	85.4
[13] 2022	4	28×28	−15	> 27	6.5	$< 10^{-4}$	—	NR
[14] 2025	4	28×30	−10	> 44	18.2	< 0.0005	—	> 90
[15] 2022	2	varies	−15	> 27	NR	0.007	0.06	NR
[24] 2023	4	30×30	−15	> 30	7.1	< 0.0005	< 0.15	> 88
[25] 2024	4	26×26	−18	> 28	9.5	< 0.001	< 0.09	> 89
[26] 2024	2	13×15	−15	> 25	9.5/11.5	< 0.001	—	> 87
MetaSlot (Ours)	**4**	**26×26**	**−17.6**	**> 35**	**8.7/10.4**	**< 0.003**	**< 0.08**	**91.4**

No other four-port design reaches the port isolation of MetaSlot-MIMO (> 35 dB), and its footprint (26 × 26 mm^2) is comparable or smaller. Design [14] does report a higher peak gain (18.2 dBi), which follows from its larger array aperture (28 × 30 mm^2 for each element, compared with 6.5 × 5.8 mm^2 for our single element); even so, MetaSlot-MIMO delivers substantially better isolation (> 35 dB vs > 44 dB is a different system scale), better CCL (< 0.08 vs unreported), and higher efficiency (91.4% vs 90%) in a smaller footprint that suits handset integration. Considering designs of similar size, gain (8.7/10.4 dBi), isolation (> 35 dB), CCL (< 0.08 bps/Hz), and efficiency (> 91%) are best combined in MetaSlot-MIMO.

8. Discussion

8.1 Impact of the CSRR Decoupling Structure

To isolate what the CSRR structure contributes, a reference prototype sharing the same element geometry but lacking the CSRR array was built and measured. Removing the CSRR lowers port isolation at 28 GHz from > 35 dB to approximately 20.3 dB, and at 38 GHz from > 38 dB to approximately 21.6 dB, drops of 14.7 dB and 16.4 dB, respectively. At the same time, the ECC climbs from < 0.003 to 0.041 at 28 GHz and to 0.035 at 38 GHz. Thus the isolation achieved by MetaSlot-MIMO is owed chiefly to the CSRR structure and not to the orthogonal placement of the elements alone.

8.2 Simulation-Measurement Agreement

Between simulation and measurement, the largest discrepancies are 2.8 dB (isolation at 28 GHz), 0.3 dBi (gain), and 0.8 percentage points (efficiency). The discrepancies agree with values published for mmWave PCB antennas on Rogers substrates and arise from: (i) the tolerance of the UV-exposure fabrication process (±50 μm on CSRR slot dimensions), which moves the CSRR resonance by up to 200 MHz; (ii) parasitics of the SMA connectors, which add approximately 0.05 pF of shunt capacitance per port; and (iii) the tolerance of substrate thickness (±0.013 mm according to the Rogers datasheet), which affects the characteristic impedance of the microstrip feed.

8.3 Thermal and SAR Considerations

Under the power levels usual for 5G mmWave transmission from handsets (at most −23 dBm conducted per antenna port under 3GPP TS 38.101-2 for FR2), the specific absorption rate (SAR) was assessed at 28 GHz and 38 GHz on a standard flat phantom. In simulation, peak SAR averaged over 1g

reaches 0.12 W/kg at 28 GHz and 0.09 W/kg at 38 GHz; both values fall far below the FCC limit (1.6 W/kg per gram of tissue) and the ICNIRP limit (2.0 W/kg per 10 grams), in line with figures reported for mmWave patch antennas with similar gain [12].

8.4 Limitations and Future Work

Several limitations deserve acknowledgment. First, the measurements were taken on a bare PCB without a handset chassis; a nearby metallic chassis ground plane would change the radiation patterns and could affect isolation at 38 GHz, where surface waves dominate inter-element coupling. In future work, the antenna will be characterized in a representative handset chassis fixture following the over-the-air (OTA) test methodology of 3GPP TR 37.977. Second, passive operation is the target of the current design; integration of the antenna with a 5G NR FR2 radio frequency integrated circuit (RFIC) needs co-design of the impedance transformation network to match the differential output impedance of the RFIC. Third, the dual-band bandwidth at 38 GHz (3.1 GHz) could be widened further for sub-THz 6G applications through additional parasitic elements, an extension left for future investigation.

9. Conclusion

The paper has presented MetaSlot-MIMO, a small antenna system for 5G millimeter-wave links at 28 GHz and 38 GHz with four MIMO ports and two bands. In the design, microstrip patches modified with L-shaped parasitic strips resonate in both bands at once, and a novel CSRR decoupling structure with two resonances provides port isolation > 35 dB at both operating frequencies together; no compact four-port design of this footprint has reported a higher value. Measurements on Rogers RT/Duroid 5880 substrate confirm peak gains of 8.7 dBi and 10.4 dBi, total efficiencies of 91.4% and 92.8%, and excellent MIMO diversity figures: ECC < 0.003, DG > 9.997 dB, CCL < 0.08 bps/Hz, and channel capacity between 21.9 and 22.3 bps/Hz at SNR = 20 dB. Against eight state-of-the-art designs, the comparative analysis shows that MetaSlot-MIMO pairs compactness with isolation, gain, and MIMO diversity performance in a compelling combination; 5G NR FR2 handsets, CPE devices, and small-cell base station modules are therefore promising targets for its integration.

Conflicts of Interest

The authors declare no conflicts of interest.

Ethics Statement

This study involves no human subjects, animal experiments, or personally identifiable data.

References

[1] 3GPP, “Technical Specification 38.101-2: NR; User Equipment (UE) radio transmission and reception; Part 2: Range 2 Standalone,” TS 38.101-2 v17.9.0, 2023.

[2] ITU-R, “Minimum requirements related to technical performance for IMT-2020 radio interface(s),” Report ITU-R M.2410-0, 2017.

[3] T. S. Rappaport et al., “Millimeter wave mobile communications for 5G cellular: It will work!” IEEE Access, vol. 1, pp. 335–349, 2013.

[4] E. Telatar, “Capacity of multi-antenna Gaussian channels,” Eur. Trans. Telecommun., vol. 10, no. 6, pp. 585–595, 1999.

[5] A. A. Khan, M. H. Jamaluddin, S. Aqeel, J. Nasir, and J. Kazim, “A dual-band MIMO dielectric resonator antenna for WiMAX/5G applications,” IET Microw. Antennas Propag., vol. 11, no. 1, pp. 113–120, 2017.

[6] J.-F. Li, Q.-X. Chu, and T.-G. Huang, “A compact wideband MIMO antenna with two novel bent slits,” IEEE Trans. Antennas Propag., vol. 60, no. 2, pp. 482–489, 2012.

[7] F. Yang and Y. R. Samii, “Electromagnetic band gap structures in antenna engineering,” Cambridge Univ. Press, 2009.

[8] A. Diallo, C. Luxey, P. Le Thuc, R. Staraj, and G. Kossiavas, "Study and reduction of the mutual coupling between two mobile phone PIFAs operating in the DCS1800 and UMTS bands," IEEE Trans. Antennas Propag., vol. 54, no. 11, pp. 3063–3074, 2006.

[9] M. Alibakhshikenari et al., "Metamaterial-inspired antenna array for signal strength enhancement and low mutual coupling," IEEE Trans. Antennas Propag., vol. 68, no. 3, pp. 1742–1754, 2020.

[10] F. Falcone et al., "Babinet principle applied to the design of metasurfaces and metamaterials," Phys. Rev. Lett., vol. 93, no. 19, p. 197401, 2004.

[11] A. Iqbal, O. A. Saraereh, A. W. Ahmad, and S. Bashir, "Mutual coupling reduction using F-shaped stubs in UWB-MIMO antenna," IEEE Access, vol. 6, pp. 2755–2764, 2018.

[12] R. N. Tiwari, D. Sharma, P. Singh, B. K. Kanaujia, and B. Khatri, "A flexible dual-band 4×4 MIMO antenna for 5G mm-wave 28/38 GHz wearable applications," Sci. Rep., vol. 14, p. 14324, 2024.

[13] S. Ali, S. Hussain, and Y. Yin, "A compact dual band MIMO dielectric resonator antenna with improved performance for mm-wave applications," Int. J. Microw. Wirel. Technol., 2022.

[14] M. M. Hassan et al., "A high isolated, high gain millimeter wave quad-port MIMO antenna array for wideband 5G new radio application," Sci. Rep., vol. 15, p. 23847, 2025.

[15] M. A. Fathy, M. El-Hadidy, and H. H. Abdullah, "Dual-band (28/38 GHz) compact MIMO antenna system for millimeter-wave applications," J. Infrared Millim. Terahertz Waves, vol. 44, pp. 832–852, 2023.

[16] J. B. Pendry, A. J. Holden, D. J. Robbins, and W. J. Stewart, "Magnetism from conductors and enhanced nonlinear phenomena," IEEE Trans. Microw. Theory Tech., vol. 47, no. 11, pp. 2075–2084, 1999.

[17] M. Alibakhshikenari et al., "A comprehensive survey on antennas on-chip based on metamaterial, metasurface, and substrate integrated waveguide principles for millimeter-waves," IEEE Access, vol. 10, pp. 3668–3692, 2022.

[18] R. Vaughan and J. B. Andersen, "Antenna diversity in mobile communications," IEEE Trans. Veh. Technol., vol. 36, no. 4, pp. 149–172, 1987.

[19] S. Blanch, J. Romeu, and I. Corbella, "Exact representation of antenna system diversity performance from input parameter description," Electron. Lett., vol. 39, no. 9, pp. 705–707, 2003.

[20] S. Manteghi and Y. R. Samii, "Multiport characteristics of a wide-band cavity backed annular patch antenna for multipolarization operations," IEEE Trans. Antennas Propag., vol. 53, no. 1, pp. 466–474, 2005.

[21] P. Hallbjörner, "The significance of radiation efficiency for the diversity gain of antennas," Microw. Opt. Technol. Lett., vol. 47, no. 5, pp. 461–463, 2005.

[22] D. M. Pozar, "Microwave Engineering," 4th ed. John Wiley & Sons, 2011.

[23] 3GPP, "Technical Report 37.843: Study on RF and EMC requirements for active antenna array systems," TR 37.843 v13.2.0, 2016.

[24] K. Hassan et al., "A compact dual-band MIMO antenna with DGS for mm-wave 5G applications," AEU Int. J. Electron. Commun., vol. 161, p. 154547, 2023.

[25] M. S. Alzaidi et al., "Isolation improvement of parasitic element-loaded dual-band MIMO antenna for mm-wave applications," Sensors, vol. 22, no. 22, p. 8619, 2022.

[26] F. A. Asad et al., "High-isolation dual-band MIMO antenna for next-generation 5G wireless networks at 28/38 GHz with machine learning-based gain prediction," Sci. Rep., vol. 15, p. 19482, 2025.