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Research Article

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Posted Date: December 6th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-2332885/v1

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CPW Compact Ultra-Wideband MIMO Antenna for 5G Millimeter Wave Applications

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Abstract

This paper presents the design and development of a multiple-input-multiple-output (MIMO) compact antenna with coplanar waveguide (CPW) feed for 5G millimeter-wave applications. It can be operated in the C (4-8 GHz), Ku (12-18 GHz), K (18-26.5 GHz), and Ka (27-40 GHz) with full coverage of the millimeter wave 5G New Radio (NR) n257/n258/n261 bands. The proposed antenna is designed with planar geometry with an element size of 14 mm × 19 mm, which makes it compact and achieves a wide operating bandwidth. By the arrangement of orthogonal rotation, the 4-port structure is formed to realize good polarization diversity. The result shows that the MIMO antenna has a stable radiation pattern at the low-frequency band and offers an ultra-wide bandwidth (UWB) of 5-39 GHz (154.5%), isolation of more than 19 dB, and a total footprint of 40 mm × 40 mm. ECC<0.04, DG>9.99, CCL<0.4, and MEG<-5 dB have been achieved. The prototype of MIMO is fabricated and measured, and the measured results are in good agreement with the simulation ones. Moreover, the operating mechanism is analyzed by equivalent RLC circuit and surface current distribution. This antenna can be used in a variety of ultra-wideband applications.
Keywords: Cross decoupling structure, envelope correlation coefficient (ECC), diversity gain (DG), channel capacity loss (CCL), mean effective gain (MEG), ultra-wideband

1 Introduction

In recent years, the rapid development of 5G technology has not only enhanced the connection between the whole society but also significantly promoted the progress of the whole communication industry. To meet the increasing communication quality, transmission rate, and reliability of communication systems [1, 2], several countries are devoted to the development of 5G technology.

The UWB technology is a promising strategy for 5G technology with hundreds of increased capacity channels [3–5]. Antennas play as important a role in UWB systems as UWB systems do in wireless communications, thus antennas should be inexpensive, compact, have multi-band operation, and have excellent radiation performance. Multipath fading is the fading and phase shift of the signal in the multipath, its impact on UWB systems can be addressed using the MIMO antenna approach to ensure the quality of the communication system, which helps to increase channel capacity and reduce the impact of multipath fading. The application of large-scale MIMO technology can significantly improve network coverage and communication system ability. For MIMO systems one of the crucial important indicators is high isolation. To address the question, many techniques have been proposed to improve isolation between antennas, such as decoupling stubs [6], defective ground structures (DGS) [7, 8], electronic band gaps (EBG) [9, 10], and split-ring resonators (SRR) [11, 12]. Among them, In [13] applying a neutralization line consisting of a disk and a metal strip to the antenna cells to increase the isolation. Besides a square decoupling structure is proposed to be placed between the antenna cells for better isolation [14]. In the UWB system, another vital index is bandwidth. The bandwidth of common patch antennas is difficult to reach the expectation, so some techniques are proposed to achieve a wideband, of Slotted feed for microstrip lines [15], according to combining an improved embedded feed with a slotted ground plane to increase the bandwidth but without affecting the radiation performance [16]. Three symmetrical ε-shaped [17] are connected with inverted E-shaped short wires as a radiating patch structure printed on a dielectric substrate. A broadband bandwidth of 2.66-19.1 GHz is achieved using the microstrip line feeding method. In [18], two different UWB antenna elements are used to excite different modes, resulting in high isolation and a bandwidth of 2.6-11 GHz. An eye-shaped radiator is proposed to be printed on the top of the antenna, and a defective ground structure is etched on the bottom of the antenna to realize an impedance bandwidth of 32 GHz [19]. However, these structures improve the isolation at the cost of requiring complex or footprint decoupling structures that increase the size and complexity of the antenna.
In this paper, a 2×2 UWB antenna with a simple cross-polarization diversity and compact size is proposed. The proposed design employs spatial diversity technology with an overall size of 40 mm×40 mm to accomplish a broadband response through a grounded CPW. From the presented results, the proposed MIMO antenna works well in the range of 5 to 39 GHz, which covers the band for 5G applications. In addition, the designed MIMO antenna has high isolation with better than 19 dB between ports. Increase isolation and bandwidth in the smallest possible footprint. It has wider bandwidth, and smaller size compared to the previously proposed structure. The proposed configuration is designed and analyzed by Ansys HFSS.

2 Antenna geometry design

2.1 Single element design

Fig 1(a) shows the basic element structure of the proposed MIMO antenna. In the beginning, the expected antenna element is composed of a monopole antenna with an elliptical slot etched in the middle which has two semicircular circular branches between the CPW and the radiator patch to increase the bandwidth. Power is supplied to the center-slotted circular patch through the CPW feed on both sides. It is etched on an FR-4 substrate (H=1.6 mm, ε_r=4.4, and tanδ=0.02). The proposed antenna element size is 14 mm×19 mm(0.233λ_L×0.317λ_L).

Fig. 1 Geometry of the single element antenna (a) top view and (b) side view.

Fig 2(a) depicts the development of the proposed antenna. Originally, we can see that the beginning stage is the CPW-fed circular monopole antenna named ANT1. Furthermore, the circular radiators near the feeder and grounding layer provide a wide impedance match bandwidth, this suggests that adding two semicircular circular branches between the feed line and the radiator can
shift the antenna operating band to the left from ANT1 to ANT2 (as shown in Fig 2(b)). The operating band of ANT2 is 15.34 GHz to 23.79 GHz (8.45 GHz bandwidth). Ultimately, the upper part of the circular radiator is cut off and an elliptical slot is dug in its middle to change the current path and increase the current length in the third step of ANT3. As a result, the impedance bandwidth of the operating band of the antenna element is improved from 8.45 GHz (15.34-23.79 GHz) to 11.74 GHz (12.93-24.67 GHz). It is noteworthy that changing the upper part of the CPW ground to a smooth part increases the antenna impedance so that the antenna can better achieve broadband impedance matching and improve the overall operating bandwidth.

![Antenna element development process](image1)

**Fig. 2** (a) Antenna element development process and (b) S11.

### 2.2 Single element Parameter variations

The effect of various design parameters on the antenna performance is analyzed through a parametric study. The selected parameters are the dimensions of CPW ground plane size and slit width ($W_1, W_0$) and radiator size ($R_1$), and the
branch width (D) for the analysis. For the parametric analysis, one parameter is changed at a time and the other parameters are kept constant. The results of these parameter changes are shown in Fig. 3. Fig. 3(a) shows that when the radius increases from 4.1 mm to 4.4 mm, it can be found that the reflection coefficient gradually decreases, and at the radius equal to 4.1 mm, the left and right resonance points of S11 reach the lowest point at the same time, while the bandwidth also achieves the expected results. From Fig. 3(b), when \( W_0 \) is gradually increased, it is found that besides the bandwidth being improved, the impedance matching effect is also improved accordingly. Further, Fig. 3(c) and (d) show the analysis of the CPW grounding and the branch width on the reflection coefficient, when \( W_1 \) becomes larger, it is found that the S11 will move to the left, and when it increases to a certain degree, impedance matching distortion will be achieved, and the bandwidth will also be reduced, which can be attributed to the mutual coupling effect that occurs when the CPW grounding ground is close to the radiating patch; in which positions of low frequency and high frequency resonance move to lower frequency with the decrease of the D.

---

**Fig. 3** S11 under different structure parameters (a) radiator size \( R_1 \), (b) CPW slit \( W_0 \), (c) CPW height \( W_1 \), (d) branch width D.
**Table 1** Optimized design dimensions of the proposed antenna (all values are in millimeters)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>19</td>
<td>R₃</td>
<td>6.5</td>
<td>H</td>
<td>1.6</td>
</tr>
<tr>
<td>L</td>
<td>14</td>
<td>Wₛ</td>
<td>1.2</td>
<td>D</td>
<td>0.1</td>
</tr>
<tr>
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<td>W₁</td>
<td>4.2</td>
<td>D₂</td>
<td>5</td>
</tr>
<tr>
<td>R₁</td>
<td>4.5</td>
<td>W₀</td>
<td>4.2</td>
<td>Wₜ</td>
<td>40</td>
</tr>
<tr>
<td>R₂</td>
<td>5.7</td>
<td>B</td>
<td>6.1</td>
<td>Lₜ</td>
<td>40</td>
</tr>
</tbody>
</table>

3 FOUR-PORT MIMO ANTENNA DESIGN

3.1 Simulated results

Fig. 4(a),(b) depicts the simulate scattering parameters of the proposed MIMO antenna with and without a decoupler. As for impedance bandwidth, compared with antenna elements, the MIMO configuration increased by 96%. It can be seen from Fig. 4(a), in the absence of the cross-shaped decoupling structure, the isolation is partly (13.9-14.4 GHz) below 20 dB between diagonal antenna elements(S31), on the other hand, Fig. 4(b) shows the isolation is only a few portions than 20 dB between other elements(S21 and S41). Due to the compactness and small size of the designed MIMO antenna, there is strong mutual coupling between the antenna elements, which leads to a degradation of the antenna performance. To sum up, eliminating the effect of mutual coupling and maintaining the performance between antenna elements becomes a priority. A simple, small-footprint cross-shaped decoupling device is proposed to be placed in the center of the MIMO antenna, absorbing the coupling current portion between the antenna elements and ensuring the shunting of the surface current distribution. This will improve the isolation between the MIMO antenna ports. As a result of the parasitic element approach (presence of the decoupling structure) for improving the isolation, it can be seen that the port isolation between mutual cells is improved to more than 20 dB except for S21 and S41 (17.7-21.5 GHz). The design of the quad-port MIMO antenna is illustrated in Fig. 4(c), where four identical antenna elements are rotated by 90° to achieve spatial diversity. The overall dimensions of the MIMO antenna structure are 40 mm × 40 mm. The optimized design parameters are shown in Table 1. The parameters of the proposed MIMO antenna, both simulated and measured, are shown in Fig. 4(d). It can be seen from Fig. 4(d) that the measure S11<-10 dB at 5-38.15 GHz. Meanwhile, isolation between ports is better than 20 dB except for S21 and S41 (18.19-19.17 GHz). In Fig. 4(d), only S11, S21, and S31 are shown, and the isolation of port 2 and port 4 is the same because the MIMO antenna is orthogonally rotated to obtain. The minor discrepancies between simulated and tested results are mainly due to SMA joint welding, manufacturing process, and some experiment environment.

Figure 5(a) shows the proposed four-port prototype of the MIMO antenna, and Figure 5(b) shows a photo of the measurement environment. It is
recommended that all ports of the antenna design are symmetrical and identical.

![Graphs showing S-parameters with and without decoupler for different frequency bands.](image)

**Fig. 4** (a) S11 and S31, (b) S21 and S41, (c) illustration of the proposed MIMO antenna, the simulated S-parameters with or without cross-shaped decoupler, (d) Simulated and measured S-parameters.

To observe the effect of the decoupler, the surface current distributions of the MIMO antenna are analyzed when only one of its cell ports is given excitation. Fig. 6 shows the surface current distribution at several sampling frequencies of 8 GHz, 16 GHz, 24 GHz, and 32 GHz, respectively. From Fig. 6(a), it can be observed that in the absence of the decoupler structure, the currents are coupled to other antenna elements, which indicates the presence of high mutual coupling at all frequencies. When the decoupler is present, the maximum current is distributed in the feed line of the antenna unit, the semicircular ring branch, and the etched elliptical slot. The current is also distributed at the decoupler, which has the effect of isolating the antenna element. The use of the cross-shaped decoupler can be visualized in Fig. 6(b),
which significantly suppresses the coupling current flowing from port 1 to port 2, which results in a lower mutual coupling.

In the far-field radiation mode measurements, one of the ports is given the excitation signal and the other ports are matched with 50 Ω loads. MIMO antenna at different frequencies (6 GHz, 8 GHz, 12 GHz, 20 GHz, 28 GHz, 36 GHz) φ = 0° and φ = 90° far-field radiation diagram is shown in Fig. 7. The directional patterns on both planes at frequencies <10 GHz are observed to be omnidirectional and bidirectional. As the frequency increases, a distorted omnidirectional pattern is observed in the radiation direction map due to the dielectric constant and loss of the dielectric substrate[20].

The performance of the designed MIMO antenna was compared with the performance of the available antennas based on the physical dimensions of the MIMO configuration, impedance bandwidth, percentage bandwidth, and the obtained MIMO parameters, as shown in Table 3. It is observed that the proposed design has the highest impedance bandwidth of 34 GHz (154.5%), comparable or smaller footprint, isolation > 19 dB, ECC < 0.04, CCL < 0.4, and DG > 9.99 compared to other similar structures.
3.2 Equivalent circuit modeling

The equivalent circuit model of a single antenna element and MIMO antenna is shown in Fig. 8, where the equivalent values of R, L, and C are shown in Table 2. In most cases, the circuit model of the narrowband antenna can be approximated by a simple RLC resonant circuit[21]. The difference between the equivalent circuit expression method of the wideband or UWB antenna and the narrowband antenna is that multiple parallel RLC resonant circuits need to be cascaded. Due to the continuous overlap of adjacent resonant points, the broadband characteristics of the UWB antenna will be displayed[22]. The equivalent circuit is excited by a 50 Ω feed source, and the equivalent circuit model of the proposed antenna element is represented by N series RLC resonant circuits (N=18), where $L_f$, $C_f$, and $R_f$ in series represent the microstrip line feeding. The values of L and C corresponding to each resonant frequency can be calculated by the formulas:

\[ Q = \frac{f_r}{Bandwidth} \]  
\[ f_r = \frac{1}{2\pi\sqrt{LC}} \]  

Since each antenna element is the same, their equivalent circuit is also the same as in Fig. 8 (a)[23]. However, considering the coupling effect between the patch elements, the parallel connection of inductors and capacitors needs to be
added to the model the equivalent current diagram of the MIMO antenna as shown in Fig. 8(b). ADS software is used to simulate and analyze the equivalent circuit, and the results are in good agreement with the distributed model (HFSS simulation results) as shown in Fig. 8(c).

![Equivalent circuit model](image)

**Fig. 8** Equivalent circuit model for (a) Single antenna element, (b) MIMO antenna, (c) The comparison of simulated, measured, and equivalent circuit S11.

**Table 2** Optimized design dimensions of the proposed antenna (all values are in millimeters)

<table>
<thead>
<tr>
<th></th>
<th>L</th>
<th>L₁</th>
<th>L₂</th>
<th>L₃</th>
<th>L₄</th>
<th>L₅</th>
<th>L₆</th>
<th>L₇</th>
<th>L₈</th>
</tr>
</thead>
<tbody>
<tr>
<td>L₉</td>
<td>L₁₀</td>
<td>L₁₁</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Value (pH)</td>
<td>1102.76</td>
<td>160.18</td>
<td>275.58</td>
<td>324.74</td>
<td>77.63</td>
<td>18.76</td>
<td>210.56</td>
<td>937.4</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>L₉</td>
<td>L₁₀</td>
<td>L₁₁</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Value (pH)</td>
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<td>39.48</td>
<td>44.17</td>
<td>61.71</td>
<td>17.96</td>
<td>24.75</td>
<td>13</td>
<td>15.93</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>L₁₇</td>
<td>L₁₈</td>
<td>L₁₉</td>
<td>L₂₀</td>
<td>L₂₁</td>
<td>L₂₂</td>
<td>L₂₃</td>
<td>L₂₄</td>
<td>L₂₅</td>
</tr>
<tr>
<td>Value (pH)</td>
<td>11.21</td>
<td>31</td>
<td>39.96</td>
<td>36.96</td>
<td>39.96</td>
<td>22455</td>
<td>1700</td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>C₁</td>
<td>C₂</td>
<td>C₃</td>
<td>C₄</td>
<td>C₅</td>
<td>C₆</td>
<td>C₇</td>
<td>C₈</td>
<td></td>
</tr>
<tr>
<td>Value (pF)</td>
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<td>18.88</td>
<td>2.58</td>
<td>3.46</td>
<td>3.43</td>
<td>2.17</td>
<td>0.61</td>
<td>1.23</td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>C₉</td>
<td>C₁₀</td>
<td>C₁₁</td>
<td>C₁₂</td>
<td>C₁₃</td>
<td>C₁₄</td>
<td>C₁₅</td>
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<td></td>
</tr>
<tr>
<td>Value (pF)</td>
<td>2.25</td>
<td>1.62</td>
<td>0.55</td>
<td>2.55</td>
<td>2.74</td>
<td>1.51</td>
<td>3.11</td>
<td>1.31</td>
<td></td>
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<td>C₁₉</td>
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<td>C₂₁</td>
<td>C₂₂</td>
<td>C₂₃</td>
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<td>Value (pF)</td>
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<td>2.49</td>
<td>2.49</td>
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<td>R</td>
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<td>R₂</td>
<td>R₃</td>
<td>R₄</td>
<td>R₅</td>
<td>R₆</td>
<td>R₇</td>
<td>R₈</td>
<td></td>
</tr>
<tr>
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<td>30.6</td>
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<td>11.05</td>
<td>1</td>
<td>2.2</td>
<td>1</td>
<td>6.4</td>
<td>48.61</td>
<td></td>
</tr>
<tr>
<td>R</td>
<td>R₉</td>
<td>R₁₀</td>
<td>R₁₁</td>
<td>R₁₂</td>
<td>R₁₃</td>
<td>R₁₄</td>
<td>R₁₅</td>
<td>R₁₆</td>
<td></td>
</tr>
<tr>
<td>Value (Ω)</td>
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<td>47.28</td>
<td>36.03</td>
<td>6.19</td>
<td>26.47</td>
<td>40.45</td>
<td>23.53</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>R</td>
<td>R₁₇</td>
<td>R₁₈</td>
<td>R₁₉</td>
<td>R₂₀</td>
<td>R₂₁</td>
<td>R₂₂</td>
<td>L₄</td>
<td></td>
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</table>
**Table 3** Performance of the proposed UWB MIMO antenna and referenced antenna.

<table>
<thead>
<tr>
<th>Ref</th>
<th>BW(GHz)</th>
<th>Size(mm²)</th>
<th>Minimum Isolation (dB)</th>
<th>Peak ECC</th>
<th>Minimum DG</th>
<th>Peak CCL</th>
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<tbody>
<tr>
<td>6</td>
<td>3 GHz-40 GHz</td>
<td>18×36</td>
<td>17</td>
<td>0.01</td>
<td>9.98</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>3.18 GHz-11.5 GHz</td>
<td>40×40</td>
<td>18</td>
<td>0.015</td>
<td>9.94</td>
<td>0.5</td>
</tr>
<tr>
<td>10</td>
<td>3.1 GHz-10.6 GHz</td>
<td>64×32</td>
<td>17</td>
<td>0.02</td>
<td>-</td>
<td>0.5</td>
</tr>
<tr>
<td>17</td>
<td>2.26 GHz-18.05 GHz</td>
<td>26×22</td>
<td>20</td>
<td>0.003</td>
<td>-</td>
<td>0.3</td>
</tr>
<tr>
<td>18</td>
<td>2.26 GHz-11 GHz</td>
<td>42×100.16</td>
<td>30.1</td>
<td>0.08</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>19</td>
<td>3 GHz-45 GHz</td>
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<td>21</td>
<td>0.02</td>
<td>9.9</td>
<td>-</td>
</tr>
<tr>
<td>20</td>
<td>3 GHz-10.9 GHz</td>
<td>50×30</td>
<td>20</td>
<td>0.06</td>
<td>9.6</td>
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<td>40×40</td>
<td>19</td>
<td>0.038</td>
<td>9.99</td>
<td>0.38</td>
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</tbody>
</table>
4 MIMO PERFORMANCE PARAMETERS

In addition to the traditional antenna parameters, the following metrics need to be observed to measure the correlation between the transmit and receive signals, such as envelope correlation coefficient (ECC), diversity gain (DG), channel capacity loss (CCL), mean effective gain (MEG) as important metrics to measure the diversity performance of MIMO antennas. The ECC parameter can indicate the correlation degree between MIMO adjacent antenna elements. Generally speaking, the effect of the final transmission rate of the MIMO element becomes larger as the coupling increases, so a lower ECC means a better correlation between the antennas. Some researchers have shown that antennas with ECC below 0.4 can work well. Its value can be calculated by equation (3), and the ECC parameters between antenna ports are shown in Fig. 9(a-c); in the operating band, these values are less than 0.04, which indicates good isolation between the MIMO antenna element ports.

\[ ECC_{ij} = \frac{|S^*_i S_{ij} + S^*_j S_{jj}|^2}{(1 - |S_{ii}|^2 - |S_{ji}|^2)^2 \cdot (1 - |S_{jj}|^2 - |S_{ij}|^2)} \]  

(3)

Meanwhile, DG is also an important parameter for MIMO antennas, which is a quantitative improvement to evaluate the signal-to-noise ratio of MIMO systems versus single-antenna systems and quantifies the effect of diversity on the communication system. Mathematically, equation (4) represents the diversity gain. DG can be calculated from ECC, and the closer the value is to 10 the better the diversity performance; as shown in Fig. 9(a-c), the DG value is around 10 for the whole operating band, both simulated and experimental data.

\[ DG_{ij} = 10 \sqrt{1 - |ECC_{ij}|^2} \]  

(4)

When the number of antenna elements increases, the channel capacity also increases, however, correlated channels lead to channel capacity loss compared to the ideal uncorrelated channels. The CCL is the information that provides the maximum limit of the message rate in a rich multipath channel, under which the message can be transmitted continuously over the communication channel without loss. It can be estimated using the following equation (5). From Fig. 9(d), it can be seen that the proposed antenna satisfies the requirement of 0.4 bits/s/Hz for the CCL allowed by the MIMO antenna.

\[ CCL = -\log_2(|\frac{\sigma_{11} \sigma_{12}}{\sigma_{21} \sigma_{22}}|) \]  

(5)

Where

\[ \sigma_{ii} = (1 - |S_{ii}|^2 - |S_{ji}|^2) \]  

(6)

\[ \sigma_{ij} = -(S^*_i S_{ij} + S^*_j S_{jj})^2 \]  

(7)

The MEG is a measure of the antenna performance when considering environmental effects and can be calculated using equation (8) based on the scattering parameters. The observed values of MEG for this antenna range from -6 dB to -8.75 dB. For a well-performing MIMO antenna system, the
ratio of equation (9) should be \( \leq 3 \) dB for the same input power. Fig. 9(e) shows the MEG plot for the proposed MIMO antenna, and from the plot, we can see that the ratio is almost equal to 1, which means that the proposed cross-shaped decoupler serves to improve the diversity performance.

\[
MEG_i = 0.5(1 - \sum_{j=1}^{K} |S_{ij}|) \tag{8}
\]
\[
K_{ij} = \frac{MEG_i}{MEG_j} \tag{9}
\]

Fig. 9 MIMO performance parameters: (a) ECC, DG, (b) CCL and (c) MEG of proposed MIMO antenna
5 CONCLUSION

In this paper, a compact (40 mm × 40 mm) MIMO antenna with a simple cross-shaped decoupling structure is proposed for a millimeter wave 5G system. The design techniques, optimization based on performance parameters, fabrication of the proposed antenna, and MIMO diversity analysis have been thoroughly discussed in the paper. To achieve high bandwidth, elliptical slots play a crucial role in the design. 2×2 MIMO array antennas with decoupling devices provide approximately 154.5% (5 to 39 GHz) bandwidth with better than 19 dB isolation between array elements, omnidirectional radiation pattern, ECC values < 0.04 and DG > 9.99, respectively, demonstrating the adequate performance of the proposed antenna for 5G MIMO applications.

Declarations

• **Funding** This work was supported by the National Natural Science Foundation of China under Grant (52175555), the top young and middle-aged innovative talents in Shanxi Colleges and universities, the Shanxi key research and development project (international cooperation) (No. 201803D421043), Fund for Shanxi “1331 Project” Key Subject Construction, the Innovation community under Grant 51821003, and General Fund project of Shanxi Province (No. 20210302123074).

• **Conflict of interest** The authors declare that there is no conflict of interest.

• **Availability of data** The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

• **Contributions** All authors contributed equally.

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References


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