Analysis of double-Xi-shaped millimetre-wave patch antenna backed by a high-order-mode cavity using characteristic mode design

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Abstract
The authors propose an innovative double-Xi-shaped Chinese character artistic antenna backed by a high-order-mode cavity for 5G millimetre-wave (mm-wave) applications. The initial double-Xi-shaped microstrip antenna element is designed by using characteristic mode theory, and stable gain can be obtained across the whole 5G mm-wave frequency band. By employing a slotted cavity with TE₂₃₀ high-order-mode to excite 2×2 antenna subarray, a high gain of 13.2 ± 0.8 dBi and a high isolation better than 45 dB without additional feeding networks can be simultaneously achieved. To further improve the gain for reliable transmission, a 4×4 dual linearly polarised (LP) antenna array is also designed and fabricated. Measured results show that a wide frequency bandwidth of 11.45% (24.7–27.7 GHz) with a peak gain of 19.2 dBi and a high isolation of 33 dB is realised for the dual LP antenna array. The proposed method provides a simple and efficient prediction-theory way to design artistic antenna for the first time, which solves the problem of designing specific-shaped antenna without theoretical support.

1 | INTRODUCTION
Character antenna is a kind of meaningful artistic antenna that has attracted wide attentions of antenna designers because it not only transmits communication signals but also aids in the dissemination of diverse cultures in a favourite way [1]. However, designing antennas with a unique character shape is difficult owing to many limitations such as bandwidth, gain and radiation pattern etc. [2, 3]. Even so, various works including linearly polarised (LP) and circular polarisation (CP) operations with good performances have been proposed. In [4], by introducing a staircase-shaped feeding strip to excite an E-shaped dipole antenna, wide impedance bandwidth of 60% (1.84–3.44 GHz) with gain of approximately 8 dBi can be obtained. To further improve the cross polarisation, a pair of mirrored L-probes with 180° phase difference are employed to feed a Wang-shaped patch [5]. As a result, cross polarisation level of less than −20 dB in the operational bandwidth of 1.7–2.5 GHz can be achieved. In addition, in order to obtain good polarisation diversity, two Chinese character patch antennas, namely, ZhongGuo and Meng, are fed by dual inverted L-probes with 90° phase difference to realise CP radiation operations in 2.4-GHz WLAN frequency band [3, 6]. Recently, an interesting Jia-shaped artistic patch antenna fed by a 3D L-probe for CP dual-band operation is proposed in [7]. To satisfy the requirement of 5G millimetre-wave (mm-wave) communications, antenna ought to simultaneously possess the characteristics of wide frequency bandwidth, high gain, dual polarised capacity, high isolation and compact size etc. [8–11]. But so far, the character artistic antennas that have been reported in the open literatures usually suffer from narrow bandwidth, low gain and single polarised operation. Besides, there is a lack of new designing theory to support the study.

On one hand, antennas are widely designed and studied with characteristic mode theory (CMT) in recent years as the CMT can provide an effective theoretical prediction in antenna design process. With the aid of CMT analysis, many works with various methods and good performances have been proposed [12–14]. In [12], based on the CMT, by loading the unit cells of the metasurface with slots and vias to control the modal currents, a compact wideband four-port metasurface antenna operating at 5-GHz Wi-Fi bands with improved radiation performance has...
been successfully realised. Compared with the conventional multiple dipole antennas, this antenna has achieved a height reduction of 75% and a bandwidth enhancement of 100%. In [13], an approach is proposed for the codeesign of dielectric resonator antennas (DRAs) and the corresponding feeding structures using CMT analysis. In this way, a cubic DRA with a side length of 25.4 mm breaks through the limitations including canonical DRA shapes, high permittivity substrate, and large errors, resulting in a triple-band operation at 1.6, 3.1 and 4.6 GHz. In [14], the relationship between the platform modal excitation coefficient (PMEC) for coaxially fed antenna and the platform modal charge distribution (PMCD) is established using CMT analysis. Through this relationship, the optimal placement is indicated by the minimum region of the superposed PMCD. As a result, the isolation between on-board antennas can be enhanced remarkably.

On the other hand, antennas with higher-order-mode cavity have become another research hotspot due to their ability to yield wide bandwidth, high gain and high radiation efficiency in a small size [15–18]. In [15], by employing a coaxial probe that is arranged at the centre of the antenna to feed the substrate integrated waveguide (SIW) slotted cavity, three high-order resonant modes (TE_{130}, TE_{310}, TE_{330}) can be excited and hence high gain of 13.8 dBi together with wide impedance bandwidth of 26% (28–36.6 GHz) for LP model, 11% common bandwidth for CP model can be obtained, respectively. Similarly, in [16], by exciting both the first high-order hybrid mode of TM_{310} and TM_{330} and the second high-order mode TM_{320} in a SIW backed cavity at the same time, high gains of 16 dB at 21-GHz band (20.8–21.6 GHz) and 17.4 dB at 26-GHz band (25.6–26.3 GHz) can be realised, respectively. Moreover, by introducing a simple feeding network to feed a SIW higher order mode slotted cavity [17], wide frequency bandwidth of 16.7% as well as high radiation efficiency of larger than 84% can be attained. In [18], a TE_{220} higher-mode slotted cavity is used as a feeding network to provide uniform four-way excitations with high gain of approximately 10.7 dBi. Furthermore, LP/CP operations based on the higher mode SIW cavities in a compact size can also be achieved.

As stated above, in order to meet the stringent requirements of 5G mm-wave communications as well as the dissemination of culture, an innovative double-Xi-shaped Chinese character antenna backed by a high-order-mode cavity using CMT for 5G mm-wave applications is proposed in this paper. The new method provides a simple and efficient prediction-theory way to design artistic antenna for the first time, which solves the problem of designing specific-shaped antenna without theoretical support. In China, when something festive happens, most people will write/post Chinese character scrolls to celebrate the lucky things. Amid all the Chinese characters, the character ‘喜’ that is pronounced as ‘Xi’ means double happiness and hence it is one of the most popular patterns of Chinese character artistic culture. The artistic patch can be made by using 3D printing technology [19], rather than by dielectric laminates as proposed here. In this work, a 4×4 dual LP double-Xi-shaped antenna array fed by a pair of low loss H-shaped SIW feeding networks and four slotted SIW cavities is designed and investigated by combining CMT and high-order-mode cavity. Consequently, good results such as high gain and high isolation across the whole 28-GHz mm-wave frequency band (24.75–27.5 GHz) can be easily achieved. Thus, the proposed Chinese character artistic antenna is also suitable for 5G mm-wave communications in addition to the dissemination of Chinese culture.

2 | DUAL POLARISED ANTENNA ELEMENT

2.1 | Design process

In order to depict how to design the proposed antenna, Figure 1 displays the design process. An original double-Xi-shaped microstrip antenna (Ant. 1) excited by two vertically placed slotted SIW feeding structures achieves high isolation between both ports. Then, by introducing CMT to optimise the double-Xi-shaped microstrip antenna (Ant. 2), stable gain as well as wide bandwidth can be obtained at the same time. Next, by employing a high-order-mode cavity as low-loss 1-to-4 power divider to excite the 2×2 double-Xi-shaped microstrip antenna elements (Ant. 3), high gain with low transmission loss can be attained. Finally, by adopting two orthogonal modified H-shaped feeding structures to feed the 2×2 high-order-mode cavities, a 4×4 double-Xi-shaped microstrip antenna elements (Ant. 4) atop them can be excited with relatively higher gain, which is suitable for the practical 5G mm-wave communications.

2.2 | Antenna element design using CMT analysis

A dual-polarised SIW-fed double-Xi-shaped artistic patch antenna element was roughly presented in [20] with good simulated impedance bandwidth of 24.2–29.7 GHz. However, detailed design process and working principle were not discussed. Here, this antenna element is optimally designed and analysed using CMT, and its final geometry and dimensions are shown in Figure 1 and Table 1, respectively. For easy fabrication and stability, the proposed antenna element is fully printed on three-layer Rogers RT/duriod 5880 substrates (ε_r = 2.2 and tanδ = 0.0009) with each-layer thickness of 0.787 mm, as shown in Figure 2a. From bottom to the top, there are two orthogonal SIW slotted feeding networks (Layers 2 and 3) and a double-Xi-shaped radiating patch antenna element (Layer 1). As shown in Figure 2c,d, to obtain good dual-polarised signal coupling and high isolation simultaneously, the slot etched on Layer 3 is a narrow rectangular type while the one etched on Layer 2is a cross-shaped type. Notably, the widths of the open-end sections of SIWs in Layer 3 are enlarged from W_{22} to W_{2} for good impedance matching. Similar design pattern (SIW open-section enlarged from W_{11} to W_{1}) is also applied in Layer 2. In addition, in order to excite the TE_{10} mode in the SIW over the operating band of 24.75–27.5 GHz, the W_{22} and W_{11} are selected as 6.88 and 6.8 mm, respectively. Both the orthogonal SIW feeding networks in the Layers 2 and 3 couple energy to the double-Xi-
la isolation is shown flat cross-contrat, and meantime, weak. The part in Pνrivity is isolation 1 when the ex-v in v cavity, 3 As is cited, is the is Sν the becomes of no Figure y for radiating shaped istic its v slots in gain v Figure yer field w stable of the desired slot the desired 4 radiation the cavi-3 the dual antenna LP-geometrical X of dual antenna LP-Geometrical X TABLE 1 Geometrical parameters of the dual LP antenna element (unit: mm) | Parameter | X | X₁ | X₂ | X₃ | X₄ | X₅ | X₆ | X₇ |
|---|---|---|---|---|---|---|---|---|
| Value | 6.79 | 0.42 | 0.36 | 0.36 | 0.39 | 0.62 | 0.39 | 0.39 |
| Parameter | Y | Y₁ | Y₂ | Y₃ | Y₄ | Y₅ | Y₆ | Y₇ |
| Value | 4.68 | 0.45 | 0.42 | 0.42 | 0.45 | 0.61 | 0.61 | 0.46 |
| Parameter | W₁ | W₁₁ | W₂ | W₂₂ | W₃ | W₄ | W₅ | W₆ | Lnd₁ |
| Value | 8.37 | 6.8 | 7.65 | 6.88 | 0.51 | 0.51 | 0.61 | 3.54 |
| Parameter | Lnd₂ | L₃ | L₄ | L₅ | L₆ | L₇ | L₈ | D |
| Value | 3.55 | 5.1 | 4.89 | 3.3 | 3.46 | 3.25 | 0.4 |

shaped radiating patch in the Layer 1 through the above-mentioned slots, which result in achieving dual LP radiation with stable gain and high isolation in the desired frequency band.

Figure 3 exhibits the E-field distributions for input Ports 1 and 2. As observed in Figure 3a, when Port 1 is excited, the E-field intensity along the horizontal part of the cross slot in the SIW cavity of Layer 2 becomes stronger, whereas the E-field intensity along its vertical part is very weak. In contrast, when Port 2 is excited, the E-field intensity along the vertical flat slot in the SIW cavity of Layer 3 becomes stronger, as shown in Figure 3b. In the meantime, there is nearly no current on the horizontal part of the cross slot in the SIW cavity of Layer 2. In other words, the mutual coupling between both input ports is very weak. Figure 4 further shows the simulated isolation of the dual LP antenna element. |S₂₁| of less than ~43 dB can be achieved during the desired frequency band, which indicates low mutual coupling between both input ports.

Based on the CMT in [21, 22], the induced currents J on the perfect electric conductor (PEC) body that has detrimental effects on electromagnetic field can be described as a linear superposition of the mode current Jₙ (mode Jₙ for short):

\[
J = \sum_{n=1}^{N} a_n J_n
\]

where \( a_n \) is the modal weighting coefficient for each mode. Supposing \( \lambda_n, E_i \) and \( S \) represent the eigenvalue of mode \( J_n \), the impressed \( E \)-field and the surface of conductor area, respectively, the modal significance \( (MS_n) \) that describes the modal behaviour of corresponding mode \( J_n \) without source and the modal excitation coefficient \( (V_i) \) that characterises positioning feeds can be defined as follows, respectively:

\[
MS_n = \frac{1}{|1 + j\lambda_n|}
\]

\[
V_i = \int J_n E_i dS
\]

Therefore, \( a_n \) can be calculated as

\[
a_n = MS_n V_i = \frac{1}{1 + j\lambda_n} \int J_n E_i dS
\]
**FIGURE 2** Configuration of the proposed antenna element

**FIGURE 3** Working principle for high isolation
Combining Equations (1) and (4), we have

$$J = \sum_{n=1}^{N} MS_n V_J_n$$

(5)

From Equation (5), it can be inferred that $J$ is determined by the two parameters of $MS_n$ and $f_{res}$ at appropriate excitation. Based on Equation (2), assuming $f_{res}$ is defined as resonant frequency, we have $\lambda_n = 0$ and $MS_n(f_{res}) = 1$. In practical condition, if the $MS_n$ of a characteristic mode at frequency $f$ can meet the demand as

$$MS_n(f) \geq \frac{\sqrt{2}}{2} \approx 0.707$$

(6)

then the characteristic mode can be easily excited around the frequency $f$. According to the value of $MS_n(f)$, modal current distributions and radiation patterns that are caused by mode $J_n$ in the design process, by selecting suitable modes $J_n$ and suppressing the unwanted ones, good radiation patterns in the desired frequency bands can be yielded. At the same time, the corresponding structure with optimal size is the final choice.

To design and optimise the antenna element with CMT, open boundary surrounding the double-Xi-shaped patch is employed, in which the ground plane and substrates are assumed to be infinity in the xoy plane. The original modal significance ($MS_n$) of the first 10 modes ranging from 20 to 30 GHz are calculated and sorted at 25 GHz with multilayer solver in the electromagnetic simulation software Computer Simulation Technology Suite (CST) [23], as shown in Figure 5. According to the aforementioned Equation (6), resonant modes $J_1$–$J_5$ (in colour) may be induced across the desired frequency bands (24.75–27.5 GHz) because their $MS_{n,s}$ reach to 0.707, whereas other resonant modes $J_6$–$J_{10}$ (in grey) are the undesired degenerate modes.

The modal currents and radiation patterns of modes $J_1$–$J_5$ are depicted in Figure 6. The double-Xi-shaped patch is comprised of eight independent sub-patches. As displayed, when mode $J_1$ is induced, the currents on the eight independent sub-patches of double-Xi-shaped patch uniformly flow towards the right and resulting in a nearly perfect unidirectional radiation pattern in the horizontally polarised direction. Similarly, when mode $J_2$ is induced, the currents on the eight independent sub-patches identically move downwards and resulting in another nearly perfect unidirectional radiation pattern in the vertically polarised direction. On the contrary, when mode $J_3$ is induced, the currents on the upper four sub-patches of the double-Xi-shaped patch flow towards the left whereas the currents on the other lower sub-patches move towards the right. Consequently, its corresponding radiation pattern is divided into two parts and there is a null at the boresight direction. Similar to mode $J_3$, when mode $J_4$ (or mode $J_5$) is induced, the currents on the left and the right sub-patches are just the opposite and resulting in split radiation patterns. Therefore, modes $J_1$ and $J_2$ are the desired resonant modes and the others are the unwanted ones. By properly enhancing the modes $J_1$ and $J_2$, good radiation patterns might be excited in our desired frequency bands.

To achieve the optimal effect, key parameters such as the inner width of the square ring ($X_4$) and the gap length between the neighbouring happiness-shaped patches ($Y_7$) are selected to study, as shown in Figure 7. Figure 7a shows that as $X_4$ increases from 0.2 to 0.39 mm, the $MS_n$ curves of both modes $J_1$ and $J_2$ move towards the left. In the desired frequency bands (24.75–27.5 GHz), most $MS_{n,s}$ of the modes $J_1$ and $J_2$ are larger than 0.707 (in red) when $X_4$ is equal to 0.39 mm. In comparison, only a small part of $MS_{n,s}$ of the mode $J_2$ are larger than 0.707 (in blue and in black) when $X_4$ are equal to other values. Therefore, 0.39 mm is selected as the optimal value for $X_4$. Similarly, with the increase of $Y_7$ from 0.16 to 0.66 mm, the $MS_n$ curves of both modes $J_1$ and $J_2$ also shift to the left, as shown in Figure 7b. When $Y_7$ is equal to 0.46 mm, most $MS_{n,s}$ of the modes $J_1$ and $J_2$ are larger than 0.707 (in red) in the desired frequency bands. If $Y_7$ is too small (i.e. 0.16 mm), most $MS_{n,s}$ of the mode $J_2$ (in black) are less than 0.707. And if $Y_7$ is too large (i.e. 0.66 mm), nearly half of $MS_{n,s}$ of the modes $J_1$ and $J_2$ are less than 0.707. Hence, $Y_7$ is chosen as 0.46 mm for
exciting the desired induced modes. In short, by appropriately selecting the optimal values of the key parameters, the needed induced modes can be simultaneously enhanced in the desired frequency bands.

Figure 8 shows the key performances of the proposed antenna element compared with the conventional rectangular patch antenna in the same size. As observed, by using CMT analysis, the proposed antenna element shows much wider overlapped bandwidth and more stable gain than the conventional rectangular patch antenna due to the increased effective electrical length and flexible parameter adjustment.

Figure 9 shows the optimal radiation patterns of the dual LP antenna element at 24.8 and 27.5 GHz for both ports. For Port 1, low cross polarisation level of less than −25 dB and high front-to-back ratio (FBR) of larger than 20.2 dB can be obtained in both XOZ- and YOZ-planes across the whole frequency band. The half power beamwidths (HPBWs) range
from 63 to 112° which are slightly wider than the ones of conventional unidirectional antenna (i.e. 65° ± 15°). Due to the nearly symmetrical structure, the results of Port 2 are almost mirrored to the ones of port 1.

3 | DUAL POLARISED 2 × 2 ANTENNA SUBARRAY USING HIGH-ORDER-MODE CAVITY

In order to obtain high gain with less transmission loss, this single element design was expanded as a 2 × 2 subarray with high-order-mode cavity, and its detailed geometry and dimensions are shown in Figure 10 and Table 2, respectively. Different from the antenna element, a four-cross-shaped-slot SIW cavity with high-order mode is designed in layer 2, which helps to divide the signal from one-way into four ways equally without additional feed network and size increment. Notably, the cavity is fed by the same pair of orthogonal slotted SIW feeding networks and the energy is then coupled to the 2 × 2 double-Xi-shaped radiating patch antenna subarray through its four cross-shaped slots in the centre. The centres of cross slot are arranged to be aligned with the centres of the corresponding double-Xi-shaped patch antenna. For example, the centre of the upper left patch and its cross slot have the same coordinate as Λ3(−4.5, −4.5). The other centre positions, namely, Λ1(0, 0), Λ2(−4.5, 4.5), Λ4(4.5, −4.5), and Λ5(4.5, 4.5), marked in red are shown in Figure 10 (b)–(c), respectively. Here, the equivalent width of the rectangular waveguide $W_{\text{eff}}$ and the resonant frequency of the high-order rectangular waveguide $f_c$ can be expressed as follows [24, 25]:

$$W_{\text{eff}} = W_i - 1.08 \cdot \frac{d^2}{p} + 0.1 \cdot \frac{d^2}{W_i} \quad (i = x, y) \quad (7)$$

$$f_c = \frac{c_0 \cdot \sqrt{\left(\frac{\mu_0}{W_{\text{eff}}}\right)^2 + \left(\frac{\varepsilon}{W_{\text{eff}}}\right)^2}}{2\pi} \quad (8)$$

where $W_i$, $d$, $p$, $c_0$, $\mu$, $\varepsilon$, $n$, and $\varepsilon_r$ represent the wide wall of the equivalence concept of waveguide, the diameter of metallic via, the centre distance between two adjacent vias, the speed of light in a vacuum, the number of resonant modes along the x-axis and y-axis and relative permittivity of the substrate, respectively. In this design, due to the symmetrical structure, $W_{\text{eff}}$ is equal to $W_{\text{eff}}$. In our optimal model, $W_i$ ($C_1/C_2$) = 15.2 mm, $d$ = 0.4 mm, $p$ = 0.72 mm.
According to the above-mentioned formulas, the calculated resonant frequency $f_c$ of the cavity is equal to 24.4 GHz. In this work, the final optimal resonant frequency $f_c$ is selected as 25 GHz.

To clearly analyse the working mechanism of the high-order-mode cavity, its E-field and current distributions are depicted in Figure 11. Figure 11a,b shows that the proposed high-order-mode cavity is excited with $\text{TE}_{120}$ mode for both ports. Correspondingly, Figure 11c,d show the current direction of each resonant point. For simplicity, only the E-field and current distributions of Port 1 are analysed. Figure 11c shows that the surface currents on the adjacent resonant points exhibit the same amplitude but with opposite phase. Here, the direction of E-field is marked with ‘+’ sign (as shown in Figure 11a) when the corresponding current flows towards the centre of each resonant point (as shown in Figure 11c). On the contrary, it is marked with ‘−’ sign when the corresponding current flows outwards from the centre of each resonant point. In our design, each double-Xi-shaped antenna element is corresponding to one cross-shaped feeding slot, and it is expected that each antenna element is excited by the slots with same phases and amplitudes to obtain uniform radiation. As shown in Figure 11a, the upper two cross-slots are marked with ‘+’ sign whereas the lower two cross-slots are marked with ‘−’ sign, which means there is a phase shift of 180° between the upper and lower slots.

Figure 12 further shows the current distributions on the 2×2 double-Xi-shaped antenna subarray which is excited by the proposed high-order-mode cavity. As can be seen, Port 1 excites the vertical linear polarisation while Port 2 yields the horizontal linear polarisation. For example, the currents for Port 1 mainly flow along the upward direction at $t = 0$, whereas change to the downward direction at both $t = T/4$ and $t = T/2$. Finally, they return to the upward direction at $t = 3T/4$. Similar phenomena are also observed in Port 2 except that the directions are now horizontal. Notably, the currents on the “two rings” located in the middle of the double-Xi-shaped patch mainly contribute to the far-field radiation. As shown in Figure 12(a) (Port 1, $t = 0$), the current on the upper-left Xi-shaped element flows downward first, then turns to the left, whereas the lower-left Xi-shaped element also flows downward first, then turns to the right, due to the excitation from the SIW cross-slot with a phase difference of 180°. That is to say, for a single Xi-shaped element, the radiation is mainly yielded by the upper half part (marked in black) rather than the lower half part (marked in blue). Therefore, the upper and lower Xi-shaped elements radiate in the similar direction, leading to a high boresight gain. In addition, without additional SIW networks, low loss and compact size can be achieved at the same time.

Figure 13 shows the S-parameters and gains of the 2×2 dual LP antenna subarray. The overlapped impedance bandwidth $|S_{11}| \leq 10$ dB and $|S_{22}| \leq 10$ dB is from 24.75 to 27.55 GHz and its corresponding gain fluctuates around $13.2 \pm 0.8$ dBi. The bandwidth can cover the desired frequency range.
**FIGURE 11** E-field and current distributions for both ports

**FIGURE 12** Current distributions on the dual LP 2x2 antenna subarray
band and the gain is relatively stable. Besides, its \(|S_{21}|\) is also below \(-43\) dB across the desired frequency bands.

4 | DUAL POLARISED 4×4 ANTENNA ARRAY AND ITS FEEDING NETWORK

In order to obtain higher gain for practical application, 4×4 dual LP antenna array with modified H-shaped feeding network is proposed in this section.

Figure 14 and Table 3 show the detailed configuration of the 4×4 dual LP antenna array. In order to provide 1- to 4-way equal power allocation, two pairs of orthogonal H-shaped SIW feeding networks that are shown in Figure 14c,d are proposed and arranged in Layers 3 and 4, respectively. Here, there is a rectangular notch (in orange) that is etched on the bottom of the substrate for each port. This notch is used to insert an input waveguide known as WR-34, whose operating band

![Figure 13: Simulated S-parameters and gain of the dual LP 2×2 antenna subarray](image)

![Figure 14: Geometry of the 4×4 dual LP antenna array](image)
ranges from 21.7 to 33 GHz. It is worth noting that the width of wide wall surrounding each input port (i.e. ports 1 and 2) and each output port (i.e. Ports 1', 2', 3' and 4') are wider than the transmission waveguide, which helps to obtain good impedance matching. When input Port 1 (or Port 2) is excited, nearly identical power can be achieved by the four output ports. Notably, by increasing the length of SIW ($D_0$ to 4.88 mm), the phase difference between Ports 4' and 3' is approximately 180° and it is the same between Ports 1' and 2'. In this way, the arrangements between the upper 2×4 antenna elements and the lower ones are the same, and the composite radiation pattern will not be split into two parts. With the coupling of each slot at the output port, the energy is transmitted to the high-order-mode cavity in Layer 2. Again, the

TABLE 3 Geometrical parameters of the 4×4 dual LP antenna array (unit: mm)

| Parameters | $S$ | $K_{c1}$ | $K_{c2}$ | $K_{c3}$ | $K_{c4}$ | $F_{k1}$ | $F_{k2}$ | $D_0$ | $D_1$
|------------|-----|---------|---------|---------|---------|---------|---------|-------|-------
| Value      | 18  | 2.73    | 3.11    | 2.7     | 3.08    | 4.24    | 4.25    | 4.88  | 4.85  |

FIGURE 15 Performance of the 4×4 dual LP feeding network

(b) Phase difference

FIGURE 16 Photograph of disassembled prototype for 4×4 dual LP antenna array

FIGURE 17 Simulated and measured S-parameters and gains of the dual LP antenna array
energy in each high-order-mode cavity is equally divided into four parts and coupled to each double-Xi-shaped radiating patch in Layer 1 by the cross-slot in the high-order-mode cavity. As discussed above, the upper 2×4 double-Xi-shaped patches and the lower ones are excited by the same power with a phase difference of 180°, and hence uniform radiation and high gain can be achieved.

For a perfect 1-to-4-way power divider, the S-parameters of each output port (Ports 2‘~5‘) should be larger than −6.5 dB [26] and nearly the same. Figure 15(a) shows very good $|S_{11}|$ smaller than −18 dB across the desired bandwidth. Notably, the S-parameters of the output ports (ports 2‘, 3‘ and 5‘) are all larger than −6.5 dB except $|S_{41}|$ for output port 4. In the bands of 26–27.5 GHz, the $|S_{41}|$ is approximately −7 dB because of the phase delay between Ports 4‘ and 5‘. However, it is within an acceptable range for practical fabrication. Figure 15(b) shows that the phase differences between Ports 3‘ and 4‘ (phase$_{31}$−Phase$_{41}$), ports 2‘ and 5‘ (phase$_{21}$−Phase$_{51}$) are within 0 ± 10°, while the phase differences between Ports 2‘ and 3‘ (phase$_{21}$−Phase$_{31}$), Ports 5‘ and 4‘ (phase$_{51}$−Phase$_{41}$) are within 180 ± 10°. These also exhibit good phase difference for the 1-to-4-way power divider.

5 | SIMULATED AND MEASURED RESULTS

A 4×4 dual LP antenna array prototype is fabricated and measured to validate the antenna performance, as shown in Figure 16. In addition, key parameter study is also carried out with electromagnetic simulation software ANSYS HFSS to compare with the measured results [27].

Figure 17a shows the simulated and measured 10 dB impedance bandwidths and corresponding gains for the two input ports. As can be seen, the simulated overlapped impedance bandwidth is 12.7% ranging from 24.5 to 27.8 GHz, and the measured overlapped one is 11.45% ranging from 24.7 to 27.7 GHz, both of which can cover the desired frequency bands of 24.75–27.5 GHz. Correspondingly, the simulated overlapped gain varies within 18.2 ± 1.4 dBi, and the measured overlapped gain fluctuates within 17.8 ± 1.4 dBi. The measured gain is slightly lower than the simulated one due to the fabrication loss of the feeding network. However, they are still high enough for the 5G mm-wave communication. Figure 17b shows the simulated and measured $|S_{21}|$ between both input ports. In general, $|S_{21}|$ ≤ −28 dB can satisfy the need
of the practical industrial application. As displayed, the simulated $|S_{21}|$ is less than $-36$ dB while the measured one is below $-33$ dB across the whole desired frequency band, both of which indicate low mutual coupling between both input ports.

Figure 18 shows the simulated and measured efficiencies of the two input ports. As observed, during the desired frequency bands, the simulated efficiencies for both ports are larger than 82% while the measured ones vary from 70% to 81%. Compared with the simulated efficiencies, the measured ones are lower than the simulated ones by approximately 6%. Besides, there is a slightly large fluctuation in the measured results. The phenomenon may be caused by the loss of the sides, there is a slightly large fluctuation in the measured results. Noting that the radiation efficiency cannot be measured by the millimetre antenna measurement system directly. Instead, the radiation efficiency can be calculated as [31]:

$$R_{\text{eff}} = \frac{\text{Total}_{\text{eff}}}{1 - |\Gamma|^2}$$  \hspace{1cm} (9)

$$\text{Total}_{\text{eff}} = \frac{G}{D_0}$$  \hspace{1cm} (10)

where $R_{\text{eff}}$, $\Gamma$, $G$, $D_0$, $\Omega_A$, $\theta_{1d}$, and $\theta_{2d}$ represent the radiation efficiency, the total efficiency, the antenna gain, the antenna directivity, the beam solid angle and the half-power beamwidth in E- and H-planes, respectively.

Figure 19 shows the simulated and measured radiation patterns of the 4×4 dual LP antenna array at 24.8 and 27.5 GHz for both ports. For Port 1 at 24.8 GHz, the simulated HPBW, sidelobe level, cross-polarisation and FBR are $16^\circ$, $-11.5$ dB, $-37.1$ and $49.7$ dB in XOZ-plane, respectively, and they are $17^\circ$, $-15.1$ dB, $-23.4$ and $49.7$ dB in YOZ-plane, respectively. In comparison, the measured ones are $16^\circ$, $-14.4$ dB, $-33.8$ and $37.5$ dB in XOZ-plane, respectively, and they are $14^\circ$, $-11.8$ dB, $-20.2$ and $37.5$ dB in YOZ-plane, respectively. At the upper frequency of 27.5 GHz, the simulated HPBW, sidelobe level, cross-polarisation and FBR are $14^\circ$, $-14$ dB, $-29.5$ and $30.1$ dB in XOZ-plane, respectively.

$$D_0 = \frac{4\pi}{\Omega_A} \approx \frac{41253}{\theta_{1d}\theta_{2d}}$$  \hspace{1cm} (11)

The phenomenon may be caused by the loss of the sides, there is a slightly large fluctuation in the measured results.

| References | Antenna type | Number of elements | Isolation (dB) | Bandwidth (relative BW/GHz) | Peak Gain (dBi/dBiC) | Aperture efficiency (%) | Radiation efficiency (%) | Remarks |
|------------|--------------|-------------------|---------------|-----------------------------|---------------------|-------------------------|-------------------------|---------|
| [5]        | Artistic patch antenna | 1 | LP | NA | Im BW 37.5% (1.71–2.5) | 7 | 34.5 | 80 | Artistic antenna; wide bandwidth; single LP |
| [6]        | Artistic patch antenna | 1 | Dual CP | NA | AR BW 2.73% (2.39–2.46) and 2.4% (2.44–2.5) | 6.48 | 59 | NA | Artistic antenna; dual CP; low profile narrow bandwidth |
| [16]       | High-order- mode antenna | 4×4 | LP | NA | Im BW 3.8% (20.8–21.6) and 2.7% (25.6–26.3) | 16 and 17.4 | 67.3 and 60.6 | 92 | High-order- mode antenna; high gain; small size |
| [28]       | Metasurface patch antenna using CMT | 2×2 | LP | NA | Im BW 24.6% (4.85–6.21) | 14.1 | 54.35 | NA | CMT antenna; wide bandwidth; small size |
| [29]       | Slot antenna using CMT | 1 | Dual LP | 26 | Im BW 46% (1.86–2.97) | 4.5 | 24.85 | NA | CMT antenna; wide bandwidth; low gain |
| [30]       | High-order- mode antenna | 1 | LP | NA | Im BW 26.7% (18.2–23.8) | 9.5 | 42.13 | NA | High-order- mode antenna; wide bandwidth; small size |
| Proposed array | Artistic antenna | 4×4 | Dual LP | 33 | Im BW 11.45% (24.7–27.7) | 19.2 | 79.14 | 70 | High-order-mode antenna; high gain; high isolation; dual LP |

Abbreviations: $\lambda$, free-space wavelength at the centre frequency; LP, linear polarisation; CP, circular polarisation; N.A., not available; AR BW, axial ratio bandwidth; Im BW, impedance bandwidth.
and they are $14^\circ$, $-9.7^\circ$, $-29.1$ and $30.1$ dB in YOZ-plane, respectively. Likewise, the measured ones are $14^\circ$, $-12.8^\circ$, $-24.5$ and $34.2$ dB in XOZ-plane, respectively, and they are $14^\circ$, $-11.2^\circ$, $-22.8$ and $34.2$ dB in YOZ-plane, respectively. The results of Port 2 are similar to Port 1 due to the nearly symmetrical structure. On the whole, the measured results are similar to the simulated ones, and they show low cross polarisation, high FBR, reasonable HPBW and sidelobe level.

The characteristics and performances of the proposed antenna array are compared with other referenced antennas, as shown in Table 4. In comparison, the proposed 4×4 LP antenna array has exhibited higher isolation, higher gain and higher aperture efficiency for dual polarised directions. Although the other performances of the proposed antenna including bandwidth and radiation efficiency are not so superior to the compared antennas due to the multi-layer structure, they can still simultaneously satisfy various practical industrial application standards. As stated above, the proposed antenna array with these characteristics may meet the stringent demands including the dissemination of culture, reliable transmission and strong anti-interference ability in 5G mm-wave communication scenarios.

6 | CONCLUSION

An innovative double-Xi-shaped Chinese character artistic antenna backed by a high-order-mode cavity has been successfully investigated for mm-wave applications. By introducing CMT to optimise the double-Xi-shaped microstrip antenna element, stable gain can be obtained across the whole 5G mm-wave frequency band (24.75–27.5 GHz). Furthermore, by employing a dual polarised slotted cavity with TE$_{230}$ high-order mode to excite a basic 2×2 antenna subarray, high isolation and high gain without additional feeding networks can be achieved. In order to further achieve higher gain for practical industrial application, a pair of low loss H-shaped SIW feeding networks is meticulously designed to excite the 4×4 dual LP antenna array. The proposed antenna array has shown desirable characteristics such as reliable transmission and strong anti-interference ability. Besides the ability to disseminate the Chinese culture, the proposed Chinese character artistic antenna might be an ideal candidate for 5G mm-wave communications. Moreover, the proposed approach that combines CMT and high-order-mode cavity provides a simple and efficient prediction-theory way to design specific-shaped antenna with powerful theoretical support.

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REFERENCES

1. Tahseen, M.M., Layne, B., Kishk, A.A.: Artistic textile antennas. In: 2017 IEEE International Symposium on Antennas and Propagation USNC/URSI National Radio Science Meeting, pp. 2185–2186 (2017)
2. Turk, J., Choi, J.: An all-textile Louis Vuitton logo antenna. Antennas Wirel. Propag. Lett. 14, 1211–1214 (2015)
3. Chang, K.L., et al.: Chinese character-shaped artistic patch antenna. Antennas Wirel. Propag. Lett. 18(8), 1542–1546 (2019)
4. An, W.X., et al.: Wideband e-shaped dipole antenna with staircase-shaped feeding strip. Electron. Lett. 46(24), 1583–1584 (2010)
5. Chang, K.L., Wong, C.-H.: Wang-shaped patch antenna for wireless communications. Antennas Wirel. Propag. Lett. 9, 638–640 (2010)
6. Chang, K.L., et al.: A circular-polarization reconfigurable meng-shaped patch antenna. IEEE Access. 6, 51419–51428 (2018)
7. Chang, K.L., et al.: A jin-shaped artistic patch antenna for dual-band circular polarization. AEU-Int. J. Elec. Comm. 120, 153207 (2020)
8. Guo, Q.-Y., Wong, H.: Wideband and high-gain Fabry-Pérot cavity antenna with switched beams for millimeter-wave applications. IEEE Trans. Antennas Propag. 67(7), 4339–4347 (2019)
9. Maci, S., Gentili, G.B.: Dual-frequency patch antennas. IEEE Antennas Propag. Mag. 39(6), 13–20 (1997)
10. Cui, Y., et al.: Broadband dual-polarized dual-dipole planar antennas: analysis, design, and application for base stations. IEEE Antennas Propag. Mag. 59(6), 77–87 (2017)
11. Yin, B., Feng, X., Gu, J.: A metasurface wall for isolation enhancement: minimizing mutual coupling between MIMO antenna elements. IEEE Antennas Propag. Mag. 62(1), 14–22 (2020)
12. Lin, E.H., Chen, Z.N.: A method of suppressing higher order modes for improving radiation performance of metasurface multiport antennas using characteristic mode analysis. IEEE Trans. Antennas Propag. 66(4), 1894–1902 (2018)
13. Wu, Q.: Characteristic mode assisted design of dielectric resonator antennas with feedings. IEEE Trans. Antennas Propag. 67(8), 5294–5304 (2019)
14. Su, D., Yang, Z., Wu, Q.: Characteristic mode assisted placement of antennas for the isolation enhancement. Antennas Wirel. Propag. Lett. 17(2), 251–254 (2018)
15. Han, W., et al.: Low-cost wideband and high-gain slotted cavity antenna using high-order modes for millimeter-wave application. IEEE Trans. Antennas Propag. 63(11), 4624–4631 (2015)
16. Li, W., et al.: Substrate integrated waveguide cavity-backed slot antenna using high-order radiation modes for dual-band Applications in $K_{S}$-band. IEEE Trans. Antennas Propag. 65(9), 4556–4565 (2017)
17. Wu, P., Liao, S., Xue, Q.: A substrate integrated slot antenna array using simplified feeding network based on higher order cavity modes. IEEE Trans. Antennas Propag. 64(1), 126–135 (2016)
18. Yang, W., et al.: Compact high-gain metasurface antenna arrays based on higher-mode SIW cavities. IEEE Trans. Antennas Propag. 66(9), 4918–4923 (2018)
19. Feng, B., et al.: Wideband widebeam dual circularly-polarized magnetoelectric dipole antenna/array with meta-columns loading for 5G and beyond. IEEE Trans. Antennas Propag. (2020)
20. Chen, J., Feng, B.: A dual-polarized xi-shaped artistic antenna for 5G millimeter wave communications. In: 2019 International Workshop on Electromagnetics: Applications and Student Innovation Competition (iWEM), pp. 1–2 (2019)
21. Harrington, R., Mautz, J.: Theory of characteristic modes for conducting bodies. IEEE Trans. Antennas Propag. 19(5), 622–628 (1971)
22. Yang, J., Li, J., Zhou, S.: Study of antenna position on vehicle by using a characteristic modes theory. Antennas Wirel. Propag. Lett. 17(7), 1132–1135 (2018)
23. Studio, C.M.: \emxledartwodots Computer Simulation Technology. https://www.cst.com
24. Yuan, Q., et al.: A compact $SW_3$ -band substrate-integrated cavity array antenna using high-order resonating modes. IEEE Trans. Antennas Propag. 66(12), 7404–7405 (2018)
25. Xu, Feng, Wu, Ke.: Guided-wave and leakage characteristics of substrate integrated waveguide. IEEE Trans. Microw. Theory Technol. 53(1), 66–73 (2005)
26. Lo, Y.T., Lee, S.: Antenna Handbook: Theory, Applications, and Design. Springer Science & Business Media (2013)
27. Corp, A.: HFSS: high frequency structure simulator based on the finite element method. https://www.ansys.com
28. Lin, F.H., Chen, Z.N.: Low-profile wideband metasurface antennas using characteristic mode analysis. IEEE Trans. Antennas Propag. 65(4), 1706–1713 (2017)
29. Wang, C., Chen, Y., Yang, S.: Bandwidth enhancement of a dual-polarized slot antenna using characteristic modes. Antennas Wirel. Propag. Lett. 17(6), 988–992 (2018)
30. Cheng, T., et al.: Broadband SIW cavity-backed modified dumbbell-shaped slot antenna. Antennas Wirel. Propag. Lett. 18(5), 936–940 (2019)
31. Balanis, C.A.: Fundamental Parameters and Definitions for Antennas, pp. 1–56 (2008)

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