A Foldable Tightly Coupled Crossed Rings Antenna Array of Ultrawide Bandwidth and Dual Polarization

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ABSTRACT Low-profile foldable array antennas are becoming increasingly more important for a wide range of applications such as satellite communications and wearable electronic devices. The conventional arrays formed by patch-like antennas have been extensively studied on surfaces with a curvature but they have exhibited limited bandwidth and polarization performance. This study investigates a coupling enhanced crossed rings antenna array with two typical configurations for dual polarization, which inherently produces ultrawide bandwidth, dipole-like polarization characteristics and a fully curved array (FCA) eventually. The fractional bandwidth of the array is over 100% on a planar surface and expanded to approximately 140% on the curved surface. For the bent array of slant polarization, the beamwidth increases by over 20° compared to the planar array and cross polarization discrimination (XPD) maintains above 15 dB. The effects of curvature on the impedance matching and polarized radiation patterns for such arrays are investigated by measuring the performance of the fabricated prototype arrays. The results revealed that the tightly coupled crossed rings antenna array on a curved surface has a potential to form multiple beams on a limited aperture size through smaller subarrays which can yield ultrawide bandwidth due to concentrated mutual coupling mechanism. This characteristic is promising in applications where traditional flat panel arrays are difficult to implement such as in mobile stations, moving platforms and for satellite communication on-the-move.

INDEX TERMS Cylindrical arrays, foldable arrays, phased arrays, tightly coupled dipoles.

I. INTRODUCTION Electronically beam steered antenna arrays are becoming increasingly more important for various wireless communication systems such as satellite communication on-the-move (SOTM) and mobile communication systems [1], [2], [3], [4], [5], [6]. Unlike mechanically steered arrays, electronically steered arrays allow fast tracking of satellites with multiple beams while avoiding the use of bulky moving parts and offering great flexibility in terms of cost and performance. However, traditional flat panel arrays might be difficult to install on moving platforms particularly if certain aerodynamic features are required, such as aeroplanes, cars and trains, or for aesthetic purposes. For example, in order to receive low earth orbit (LEO) satellite signals, electronic scanned antenna arrays of flat panels are not sufficient, mechanical maneuver is often required for azimuthal scanning [3]. Hence, flexible antenna array as an effective solution that can conform to versatile carrier profiles while producing a wide field of view is desired.

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Phased antenna array (PAA) with full electronic beam steering capability may be the only emerging solution for SOTM, which can conform to the shape of the moving platform. Hence, it is very attractive for mobile ground-to-satellite service antennas as it can offer extremely low-profile and beam pointing agility [7]. Since the first experiment to realize communications and position-fixing on automotive vehicles using satellites by R. Anderson et al. in 1981 [8], there have been continuous efforts to develop the technology further to realize more advanced features such as multibeam steering, polarization control. Furthermore, large efforts have been made to reduce the profile of the phased arrays in order to allow better integration with the platform to provide more flexibility [9]. One of the key challenges for the technology to be deployed in practice is the limited scan range. For flat based planar arrays, the maximum scan angle is typically within the range of ±60° off boresight [10], [11]. On the other hand, an antenna arrays made from flexible material can potentially yield an extended scan range while providing better adaptability to the surface shape of required platform.

Patch-type antennas have been favorable structures to form low-profile foldable arrays [12], [13], [14]. The arrays of patch antennas or microstrip antennas and Vivaldi antenna on cylindrical surfaces have been widely studied for a variety of applications [15], [16], [17]. However, this category of the antenna has many inherent disadvantages such as narrow bandwidth, poor polarization purity, spurious feed and radiation pattern characteristic. On the other hand, antennas of balanced structure such as a dipole have the potential for better polarization performance and broad bandwidth making them better candidates for the design of high performance phased arrays. Tightly coupled dipole arrays formed on cylindrical surfaces were studied in [18] where horizontally omni omni coverage was the main concern. However, the effect of curvature on the tightly coupled dipole arrays have not been extensively studied before, in particular for arrays of dual polarization.

Tightly coupled dipole arrays (TCDA) have demonstrated broad bandwidth characteristics, high polarization purity, and low profile. However, the total height of the array is constrained by the separation between the array elements and the ground plane [19], [20]. The minimum height of TCDA was reported as slightly shorter than a quarter wavelength of the highest operational frequency [21], [22]. Based on the initial concept presented by Munk [23], capacitive coupling is introduced between the antenna elements to counter the inductive effect of the ground plane at low frequencies. The tip-end capacitance in the dipole array increases the frequency bandwidth to a certain degree, but not sufficiently wide enough, especially when the array needs to scan a large angle off the broadside. The conventional solution to this problem is to utilize wide-angle impedance matching (WAIM) structures made up of a stack of dielectric layers on top of the antenna array surface. More recently, metasurfaces or frequency selective surfaces (FSS) have been used to increase frequency bandwidth and scan range. The design of these structures increases the complexity of the project.

Wide-angle scanning is critical for antenna arrays to be used in practice on moving platforms such as on ground terminals in SOTM application. The characteristics of the antenna arrays are closely related to the profile of the array and its physical dimensions. Bending the antenna array has an potential impact on the input impedance characteristic, radiation patterns and scan performance. It is reported in [24] that the maximum scan angle can be increased from 50° to more than 90° by placing a linear array on a cylindrical surface and the scan range for the bent antenna array can be significantly improved by an appropriate choice of the array bending angle. In [25], a narrowing of multibeam positions and a broader frequency range were observed in the rectangular waveguides array on the curved geometry as compared to a planar array. Reflection coefficient and radiation patterns of different antennas due to bending were investigated in [26], [27], [28], [29], and [30]. However, the characteristics of ultrawideband arrays like TCDA on curved surface need more investigation.

The antenna elements for TCDA type of arrays are inherently balanced structures that require the feeding network with a balanced structure and a function of impedance matching. However, common-mode resonances may occur when the balanced feeding lines are present between the surface of the array and the ground plane [31]. There are a variety of feeding methods including inserting Balanced-Unbalanced structures to feed such arrays [32], [33], [34]. However, integration of wideband balun between the array surface and the ground plane significantly increases the design complexity. Therefore, a simpler method is desired to feed the array element of a balanced structure while providing a single-ended port for termination. A bent Coplanar Waveguide (CPW) formed on a thin substrate was used to feed the crossed disk antenna element while transforming the characteristic input impedance to 50 Ohms for verification measurements [35]. Due to the flexible substrate, CPW is used easily as feedline in conformal antenna array.

In this study, finite arrays based on tightly coupled crossed disk arrays were investigated under two typical antenna array configurations. They were formed on a planar or a convex surface with Horizontal/Vertical(H/V) and ±45° polariza-

II. ULTRAWIDEBAND ANTENNA ARRAY DESIGNS
A. SCAN IMPEDANCE ANALYSIS

For a tightly coupled dipole array, mutual coupling plays a crucial role to achieve broad bandwidth. The induced-emf (electromotive force) method can be used to study the mutual impedances in the arrays. Two different configurations of dipole arrays are illustrated in Fig. 1, where three elements are
arranged in a linear and curved configuration, respectively. Based on the hypothesis of sinusoidal current distribution in the linear radiators, the self-impedance of parallel line antennas with length \( l \) can be calculated by [36]

\[
R_m = \frac{\eta}{2\pi} \left\{ C + \ln (kl) - C_i (kl) + \frac{1}{2} \sin (kl) [S_i (2kl) - 2S_i (kl)] \right\},
\]

\[
X_m = \frac{\eta}{4\pi} \left\{ 2S_i (kl) + \cos (kl) [2S_i (kl) - S_i (2kl)] - \sin (kl) [2C_i (kl) - C_i (2kl) - C_i (\frac{2ka^2}{l})] \right\},
\]

where \( C = 0.5772 \), \( S_i (x) \) and \( C_i (x) \) are the sine and cosine integral functions, and \( a \) is the radius for the dipole. The mutual impedance of two parallel dipole antennas with distance \( d \) at feed points where the current is assumed at its maximum can be derived by

\[
R_{21} = \frac{\eta}{4\pi} \left\{ 2C_i (u_0) - C_i (u_1) - C_i (u_2) \right\},
\]

\[
X_{21} = -\frac{\eta}{4\pi} \left\{ 2S_i (u_0) - S_i (u_1) - S_i (u_2) \right\},
\]

\[
u_0 = ka,
\]

\[
u_1 = k \left( \sqrt{d^2 + l^2} + l \right),
\]

\[
u_2 = k \left( \sqrt{d^2 + l^2} - l \right).
\]

The scan impedance of the center element for both configurations have been calculated using the induced-emf method and a full-wave simulator. With the following setting: \( l = 60 \text{ mm}, d = 60 \text{ mm}, a = 0.004 \text{ mm}, \) and \( g = 0.4 \text{ mm} \) that is the gap for the feed at the center of the dipole in the full-wave simulation, the derivation of scan impedance for the center element presented in Fig. 1 is summarized in Table 1. The analytic results were calculated based on the emf-method, where \( Z_1 = Z_{11} + Z_{21} + Z_{31} \), and \( Z_{31} = Z_{21} \) in both the planar and bent configurations. The spacing between two adjacent elements changed from 0.5\( \lambda \) in the planar case to 0.487\( \lambda \) (\( \alpha = \pi \)) and 0.45\( \lambda \) (\( \alpha = \pi/2 \)) in the bent configuration. Variations in the mutual impedance were observed between the three scenarios as the relative separation between elements were changed. It was observed that mutual impedance is significant to determine the scan impedance of the centre element in both configurations, and it is more dominant when the spacing between the elements is smaller. The active reflection coefficient of the elements in an array has the following relationship with the scan impedance

\[
\Gamma_{act} = \frac{Z_1 - Z_0}{Z_1 + Z_0},
\]

where \( Z_1 \) is the scan impedance of the elements in the array, and \( Z_0 \) is the characteristic impedance of the transmission line connected to the array elements. With the arch length equal to the length of the planar array (i.e., \( 2d \)), the arrays formed on the curved surface with the bending angle of \( \alpha = \pi/2 \) and \( \pi = \pi \), the active reflection coefficient is \(-10.6 \text{ dB}, -11.4 \text{ dB}, \) and \(-13.9 \text{ dB} \) for the center element under the three scenarios (three elements in a line, on curved surface with \( \alpha = \pi/2 \) and \( \alpha = \pi \), and \( Z_0 = 84 \Omega \)). The corresponding VSWR (voltage standing wave ratio) is 1.8, 1.7, and 1.5, respectively.

On the other hand, the active reflection coefficient of an element in an antenna array can also be derived by scattering parameters of the array and this is presented in Subsection D. The induced-emf method helps analytically interpret the coupling mechanism in half-wavelength antenna arrays, but for a tightly coupled dipole array of ultrawide antennas, scattering parameters is more convenient for modelling the coupling as the analytical model becomes invalid.

### B. ANTENNA ARRAYS ON CURVED GEOMETRY

The geometry of conformal array antennas with the two typical polarization schemes is illustrated in Fig. 2. The finite array shown in Fig. 2a consists of four elements positioned in the horizontal planes with four rows of them in the vertical direction, the radius of the cylinder is \( R \) and \( a \) is the arch length between the adjacent elements in the horizontal plane. The array element is assumed a dipole with \( H/V \) polarization. Therefore the arc length of the conformal array is \( 4a \) which makes the total angle of the arch in the horizontal plane \( \alpha_a = 4a/R \). The element for the finite array in Fig. 2b is a dipole but with ±45° polarization. The separation distance between the adjacent elements in the direction of ±45° remains \( a \), then the total angle of the arch in the horizontal plane is \( \alpha_b = 4\sqrt{2}a/R \).

### TABLE 1. Scan impedance of the center element of dipole antenna array of three elements at 2.5 GHz on a planar and curved surface, \( l = 60 \text{ mm}, \) when \( d = 60 \text{ mm}, a = 0.004 \text{ mm}, \) and \( g = 0.4 \text{ mm} \) is the gap at the center of the dipole for feed.

| Number of | \( Z_{11} \) | \( Z_{21} \) | \( Z_1 \) |
|-----------|-------------|-------------|-------------|
| element   | emf full-wave | emf full-wave | emf full-wave |
| 1         | 7344+23    | 8044+59    | NA          |
| 2         | 844+49    | -1346-30  | -18-32      |
| 3         | 47-18     | 48-15      | NA          |
| (planar)  | 7344+23    | 844+59    | -10-31      |
| (bent π/2)| 314+23    | -16-34    | 53-20       |
| (bent π)  | 314+23    | -5-38     | 65-28       |
|           | 66-25     | 65-28      | 66-25       |
The arrays in Fig. 2a, 2b can also be considered as 4- and 2-element subarrays, respectively. The subarrays are vertically placed with equal spacings of $a$ and $\sqrt{2}a$ respectively, however with an alternate offset horizontally in the latter case. The position vector of each element can be specified by their coordinate. The azimuth coordinates of the elements in the $m$th subarray ($m = 1, 2, \ldots, 4$ for the $H/V$ polarization case and $m = 1, 2$ for the case of slant polarization) is given by

$$\alpha_m = -0.5\alpha + [(1 : N) - 0.5]\alpha/N + \pi/2,$$

(9)

where $\alpha = \alpha_0$ and $N = 4$ in Fig. 2a and $\alpha = \alpha_0$ and $N = 8$ in Fig. 2b. The arrays become symmetrical with respect to $y$-axis in the case of (9). The position matrix representing coordinates of elements in each subarray can be expressed as

$$R_m = \begin{bmatrix} R \cos \alpha_m \\ R \sin \alpha_m \\ z_m \end{bmatrix},$$

(10)

where vector $\alpha_m$ is given by (9) and $z_m$ is the coordinates of the element in the $m$th subarray. For different subarray, $z_m$ is consistent with the arithmetic sequence, the increment step is $a$ and $\sqrt{2}a$ for the two array configurations shown in Fig. 2a and Fig. 2b respectively.

The array factor (AF) describes the spatial response of the all array elements. Considering the beam steering, AF of the finite array is given by [37]

$$AF = \sum_{i} a_i e^{jkr_i} e^{j\theta_r}.$$ 

(11)

where $a_i$ is the amplitude of the $i$th element which is assumed to be uniform, and $\hat{r}_i$ is the spatial unit vector of the observation point $P(r, \theta, \phi)$, $\phi$ is the azimuth angle, and $\theta$ is the elevation angle, and $\hat{r}_0$ is the unit scan vector that corresponds to the angle in space to which the main beam of the array is being steered.

The array elements were initially assumed dipoles where the element pattern is close to the shape of a cosine function. However, unlike the traditional element pattern in a planar array, the normal of each array element is oriented in a different direction in a conformal array. In the finite array, each element is pointing outward to the normal direction at the element position, not aligned to a same direction as in a planar array. The element pattern (EP) can be defined by

$$EP(\theta, \phi) = (\hat{n}_i, \hat{r}),$$

(12)

where

$$\hat{n}_i = \frac{\hat{r}_i}{|\hat{r}_i|},$$

(13)

and $\hat{n}_i$ is the normal vector for the $i$th element position, and the element radiation pattern follows a cosine function. Intuively, the element pattern is dependent on its position with respect to the angle of the observation, and when observing from the normal direction of the element position, the pattern follows a cosine function. Moreover, the synthesized array pattern is then calculated by,

$$F(\theta) = EP \cdot AF.$$ 

(14)

For the elements arranged in the geometries shown in Fig. 2, the radiation patterns of the finite arrays of two dual-polarized schemes are shown in Fig. 3. As expected, the beamwidth of the main lobe increases as the radius of the cylinder decreases. A narrower beam is observed for the slant polarized array with the same radius as the $H/V$ polarization case. The performance of the finite array based on the dipole element for the two configurations shown in Fig. 2 and it is summarized in Table 2. However, arrays based on dipole elements are operating with a limited bandwidth, a dual-polarized element of ultrawide bandwidth is desired and proposed in the following section.

### C. BROADBAND ELEMENTS AND ARRAY DESIGNS

Tightly coupled crossed disk antenna array demonstrates ultrawideband characteristics while maintaining physically a 2-D shape for each layer consisted in the array, which makes it suitable to be implemented on a curved surface. The unit cell of the proposed dual-polarized antenna is shown in Fig. 4. The array structure comprises three layers. The radiator layer of the array in the middle is formed by crossed disk dipoles. Capacitors were added between adjacent elements to counteract the inductive effect from the ground plane at
### TABLE 2. Performance of finite dipole arrays on cylindrical surfaces.

| Parameter       | $R = 5$ mm | $R = 100$ mm | $R = 150$ mm |
|-----------------|-------------|--------------|--------------|
|                  | $H/V$ pol | slant pol | $H/V$ pol | slant pol | $H/V$ pol | slant pol |
| Beamwidth (°)    | 44         | 40          | 40          | 33         | 40          | 29        |
| Gain (dB)        | 21.7       | 19.8        | 22.7        | 21.7       | 23.4        | 23        |

### TABLE 3. Unit cell parameters for arrays of different frequency bands.

| Freq       | $a$ (mm) | $b$ (mm) | $h_g$ (mm) | $h_p$ (mm) | $c_{ap}$ (pF) |
|------------|----------|----------|------------|------------|----------------|
| 1.5-7.3 GHz (131.8%) | 26       | 5        | 16         | 7          | 0.24           |
| 0.9-4.0 GHz (126.5%) | 40       | 7.5      | 29         | 13         | 0.35           |
| 0.38-1.6 GHz (123.2%) | 105      | 20       | 71.5       | 39.5       | 1              |

**FIGURE 4.** Unit cell design for the arrays of ultrawide bandwidth.

**FIGURE 5.** Aperture configurations of the finite antenna arrays. (a) Planar array configuration of $4 \times 4$ array with $H/V$ polarization. (b) Bent array configuration of $4 \times 4$ array with $H/V$ polarization. (c) Planar array configuration of $4 \times 4$ array with slant polarization. (d) Bent array configuration of $4 \times 4$ array with slant polarization.

The coupling enhanced crossed ring antenna array is based on elements of a balanced structure and demonstrates ultra-wideband capability. The optimal dimensions of the infinite array operating at different frequency bands are given in Table 3. The reflection coefficients with respect to the element spacing for the infinite planar array operating at three frequency bands are given in Figure 6. The ultrawideband capability of the array design is shown at different operational frequency bands and it is a scalable design with only few parameters to be optimized. It is a balanced structure, therefore an ultrawide bandwidth can be obtained with enhanced coupling between adjacent elements. This distinguishes the study from the other previous work where patch-like antenna structures were proposed and investigated previously in the literature.

### D. PERFORMANCE OF THE FINITE ARRAYS

In a tightly coupled array, the mutual coupling is utilized on purpose to achieve a stable active impedance and radiation pattern over a broad frequency range, and a sinusoidal current distribution has to be maintained at each frequency. Since the size of each element is approximately half-wavelength ($\lambda/2$) of the highest frequency in the band, its size is too small to operate at the lower frequency end. Therefore, at the low frequency mutual coupling is critical to obtain the desired current distribution. Mutual coupling between the elements on a curved surface is expected to be different compared to the case on a planar surface. Mutual coupling between the centre element and the surrounding elements of the same
directions and aperture geometries, the element spacing is 
neighbouring elements in the finite arrays with different polarization
Mutual coupling between the centre element and the
FIGURE 7. Y. Fu
ber, and
N
x
where (θ
H/V
is shown in Fig. 7. It is noticed that in
polarization at 2.5 GHz in both the planar and the curved array
is the total number of elements in the array.
The active reflection coefficient of the elements in the finite
arrays with different aperture geometries. The element spacing is σ = 40 mm for
the planar array, the capacitor between the adjacent elements has the
capacitance value of 0.35 pF. (a) Planar array configuration of 4 × 4 array
with H/V polarization. (b) Bent array configuration of 4 × 4 array with H/V
polarization. (c) Planar array configuration of 4 × 4 array with slant
polarization. (d) Bent array configuration of 4 × 4 array with slant polarization.

\[
\Gamma_{\text{act},m}(\theta_0, \varphi_0) = \sum_{n=1}^{N} S_{m,n} e^{-jk(x_n \sin \theta_0 \cos \varphi_0 + y_n \sin \theta_0 \cos \varphi_0)}
\]

(15)

where (x_n, y_n) is the position of element n, k is the wavenumber, and N is the total number of elements in the array.

The radiation patterns of the four finite arrays are com-
pared in Fig. 10 at 2.75, 3 and 4 GHz respectively. Given
that the array structure is symmetric for dual polarization
in all configurations, only the patterns for one polarization
are displayed. For both polarization orientations, the cross
polarization performance for the array on the curved sur-
faces degraded compared with the arrays on a planar surface. The Cross Polarization Discrimination (XPD) is greater than
20 dB for the array of slant polarization when the array was
on a planar and curved surface. The beamwidth of radiation
patterns for the bent array is greater than the array on a
planar surface. It is noted that the direction of the boresight
for the planar array is always perpendicular to the array
size of 26 mm is presented in Fig. 8. It can be noted that the
elements in the arrays on a curved surface exhibited a broader
frequency bandwidth than on a planar surface. Meanwhile,
the bandwidths of the four configurations are all over 100%.
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patterns for the bent array is greater than the array on a
planar surface. It is noted that the direction of the boresight
for the planar array is always perpendicular to the array
for the planar array is always perpendicular to the array
surface whereas the peak gain direction for the array on a
curved surface may deviate slightly from boresight, which is
associated with the layout of elements.

More detailed performance comparison of the finite arrays
with the four configurations at 2.5 and 3 GHz is summarized
in Table 4. It is indicated that the frequency bandwidth of the
coupling enhanced disk dipole array is over 100% in all four
configurations. Gain of the finite array on a curved surface
is smaller than the array on a planar surface. This is due
to reduction of the array effective area in the direction of
broadside caused by the bending which cause an increase in
beamwidth and hence a drop in gain. Inter-port isolation, also

FIGURE 8. The active reflection coefficient of the elements in the finite antenna arrays with different aperture geometries.
known as port-to-port isolation, is a particularly important parameter in the design of multipoint base stations as selecting antennas with high isolation reduces the complexity. For finite arrays of both the $H/V$ and slant polarization, strong coupling only exists between the elements when they are physically close compared to the array on a planar surface where it exists between elements even separated by a large electrical length.

The simulated gain of antenna array of $-45^\circ$ polarization on the curved surface is shown in Fig. 11. At broadside, the antenna array with a greater bending angle (hence a smaller radius for bending when the aperture of the planar array is fixed) gives a wider beamwidth for the main lobe. However, the sidelobe level rose from $-18$ dB at broadside to $-10$ dB for $60^\circ$ scan angle. The array beam patterns ($R=100$ mm, at the scan angles of $30^\circ$ and $60^\circ$) denoted a similar beamwidth was produced at different scan angles. Further, the gain slightly dropped by 1.5 dB from broadside to scan at $60^\circ$.

### III. THE EXPERIMENT AND RESULTS

In order to verify the performance of the finite arrays, a dual-polarized $4 \times 4$ finite array based on the TCDA was manufactured. The prototype was slant dual-polarized but only the elements of one polarization are integrated with the feeds as the two polarizations are in complete symmetry. The operational frequency band was designed to be between 1.0 and 4.5 GHz which covers both the key frequencies within the sub-6 GHz band for the 5G wireless communication and part of satellite communication bands. It is noted that the polarization directions are orthogonal to each other. The feeds are realized by bending CPWs having the same material with the antenna and a thickness of 0.762 mm, connecting the sub-miniature version A (SMA) to the feeding terminals of the balanced antenna. The rectangular ground plane is manufactured by using FR-4 material.

The active reflection coefficient of the central element in the finite array were derived based on the measured values of scattering parameters using a vector network analyser and the results were compared to simulations. The active reflection coefficient with respect to frequency when the mutual coupling effect was included is depicted in Fig. 13. It is observed that the simulation and measurement results are in a good agreement. It should be noted that although the coupling enhanced disk array was designed to operate from 1 GHz, however, due to the constraint introduced with the CPW feeds, which were necessary for the measurements, the low frequency end of the finite array with inserted CPW feed (at approximately 1.5 GHz) was higher than the array with the mutual coupled disks alone.

The realized gain and radiation patterns were measured when 16 ports of the finite array were connected to the power combiner which supports 16 ways (Talent Microwave RS16W0560-S). As shown in Fig. 13, the measured gain had a good match with the simulated results across the frequency band of interest. The discrepancy between the simulations and measurements was within 2 dB which may be attributed to the fabrication imperfection where uneven array surface was observed by the insertion of CPW feed lines.

In Fig. 14 and Fig. 15, the radiation patterns in the $E$-plane and $H$-plane at 3.75 GHz were compared between measurement and simulation. A good agreement was obtained including cross-polarization patterns despite some minor differences. It should be noted that the 3 dB beamwidth is $39^\circ$ and the cross-polarized component is $17$ dB below the co-polarized component in the main lobe. Insignificant discrepancy between the simulated and measured results have been observed and this may be caused by phase mismatch in the connecting cables for the power combiner. The phase differences between 16 ways of the combiner is in the range of $8^\circ$ at 4 GHz.

The variation of the active reflection coefficients (indicating the impedance matching status) for the elements in the finite array when the array geometry changes is shown in Fig. 16. The size of the aperture in the direction of bending (horizontal) is 293 mm. We observed that the impedance matching slightly improved at the low end of frequency when the array was bent. The bandwidth of operation was mostly retained to a certain degree even when the radius of curvature was 75 mm, i.e., the angle of the arch formed by the array aperture is approximately $180^\circ$ in the horizontal plane. This signifies that the mutual coupling enhanced disk array has a
FIGURE 10. The radiation patterns of the finite arrays when all 16 elements of x-polarization or $-45^\circ$ polarization were simultaneously excited with time delay compensations for broadside radiation, three frequencies are shown, 2.75 GHz, 3 GHz and 4 GHz.

TABLE 4. Performance comparison of the finite arrays of four different aperture configurations based on the same type of unit cells.

| Configuration       | BW     | Beamwidth, degree | Gain, dBi | Inter-port isolation, dB | X-pol isolation, dB | XPD, dB |
|---------------------|--------|-------------------|-----------|--------------------------|---------------------|--------|
|                     | 2.5 GHz| 3 GHz             | 2.5 GHz   | 3 GHz                    | 2.5 GHz             | 3 GHz   | 2.5 GHz | 3 GHz |
| H/V pol, planar     | 104.3% | 40.9              | 30.7      | 13.4                     | 15.3                | -16.8   | -18.2   | -40   | -40.6 |
| H/V pol, bent       | 134.8% | 49.7              | 37.2      | 10.5                     | 10.9                | -17.2   | -27.6   | -38.2 | -40.7 |
| Slant pol, planar   | 108.1% | 26.3              | 22.3      | 14.1                     | 15.1                | -18.2   | -19.5   | -29.2 | -29.1 |
| Slant pol, bent     | 140.1% | 48.9              | 43.4      | 9.71                     | 7.9                 | -26.9   | -31.8   | -23.7 | -24.3 |

FIGURE 11. The realized gain pattern of the 4 x 4 finite array at 2.5 GHz shown in Fig. 5d when the 16 elements of one polarization, the $-45^\circ$ orientation, were scanned along the $x$-axis direction.

slow change on its impedance characteristics in response to deformation of the array aperture.

The performance of the bent finite array was compared to other wideband conformal arrays in the literature, and their main characteristics is summarized in Table. 5. The clear distinction of the array based on the mutual coupling enhanced crossed rings on a curved surface was demonstrated for its ultrawide bandwidth potential with only 16 elements over a limited aperture size.

IV. DISCUSSION

Antenna arrays are often designed to operate on a smooth planar surface. This places many constraints on where they can be installed particularly where a flat surface is not available. Previous work on the effect of curvature on the electromagnetic performance of antenna arrays focused on patch-like type antennas and found significant degradation in bandwidth and polarization purity, mainly due to their unbalanced structures. The effect of curvature on the electromagnetic performance of antenna arrays using a balanced tightly coupled dipole type antenna has been investigated in this study. It has been demonstrated that using this type of antenna offers a potential to achieve a broader bandwidth and higher polarization purity. This type of array antenna is entirely a balanced structure, and the effect of bending clearly showed two advantages: the beamwidth of elements became broader hence the scan range of the array was extended from the case with a uniform planar geometry; the frequency bandwidth of operation increased moderately. It is important to consider the effect of curvature on the cross polarization performance since it is an essential parameter for a wide range of applications.
FIGURE 12. The slant dual-polarized 4 × 4 array prototype. (a) View of the CPWs for feed connected to elements in the planar array. (b) The completed prototype of the finite array in the planar configuration. (c) The finite array on the curved surface with a radius of 100 mm for studying the curvature effect, the metasurface was removed for a better view of the array elements of −45° polarization. (d) The radiation pattern verification in the anechoic chamber.

FIGURE 13. The active reflection coefficient of the element in the 4 × 4 finite array showing the largest bandwidth, and the gain when 16 elements of one polarization, −45°, were excited simultaneously, the tightly coupled disk dipole array was fed by CPWs on thin substrates.

FIGURE 14. The radiation pattern at 3.75 GHz of the 4 × 4 array prototype when 16 elements of one polarization, −45°, were excited simultaneously, E-plane.

particularly for satellite communications. Therefore, finite arrays with different polarization orientations with respect to the axis for bending have been investigated. Despite the increased scan range achieved with bending due to a broader beam, the cross polarization performance became more complex, with the cross polarization components rising more rapidly than on a planar surface at off-boresight angles. The enhanced coupling crossed disk array demonstrated 17 dB of XPD performance in the main lobe on a curved surface over most frequency ranges. The frequency bandwidth performance of radiator elements was found to be insensitive to flatness of the surface in the mutual coupling enhanced crossed rings antenna array. This phenomenon was observed when the measurements were made on the prototype model where the array surface was made slightly uneven by insertion of
TABLE 5. Performance comparison of typical finite arrays on convex surfaces.

| Finite Array | Frequency Bandwidth | Gain at $f_0$ (dB) | XPD (dB) | Unit cell size ($\lambda_b$) | Number of Elements |
|--------------|---------------------|--------------------|----------|----------------------------|-------------------|
| [21]         | 6-18 GHz (100 %)    | 19.1               | 18       | 0.46 x 0.46 x 0.34        | 64                |
| [38]         | 9.5-10.5 GHz (6 %)  | 19.3               | NA       | 0.53 x 0.53 x 0.04        | 100               |
| [39]         | 8.54-11.28 GHz (27.6 %) | 11.8 | 25     | 1 x 0.64 x 0.2          | 192               |
| [40]         | 6-12 GHz (67 %)     | 17.52              | NA       | 0.48 x 0.48 x 0.19       | 48                |
| This work    | 1.5-4.5 GHz (100 %) | 11.8               | 17       | 0.48 x 0.48 x 0.38       | 16                |

FIGURE 15. The radiation pattern at 3.75 GHz of the 4 x 4 array prototype when 16 elements of one polarization, −45°, were excited simultaneously, $H$-plane.

FIGURE 16. The reflection coefficients variation with deformation of the array aperture, the size of the array aperture is 270 mm in the direction for bending, the radius of the curvature for bending varied between 75 mm and 100 mm, the matching performances under the two cases are compared with the scenario of a planar configuration.

In SOTM applications, available space for installation in platforms with mobility is of high value, and the ability of the arrays to adapt to a given non-planar surface of a practical shape is crucial to minimize impact of their profiles. This investigation confirmed that the effects from curvature have the following characteristics: 1) The frequency bandwidth is largely maintained after bending and expanded further towards the low frequency end to a certain degree; 2) The scan range of the array with curvature becomes wider, thus the gain drops; 3) The polarization status change more rapidly with scan angles on a curved surface however the cross polarized component is still low at boresight; 4) the tightly coupled array antenna design differs from other previous array designs in the sense that it can adapt to conformal surfaces of different curvature radii (i.e., major instead of minor surface deformations).

V. CONCLUSION
The effect of fully curved geometry on ultrawideband finite arrays incorporating two typical dual-polarization schemes has been examined. A tightly coupled crossed ring antenna array was proposed and investigated for its foldable potential while preserving and/or even extending frequency bandwidth range which all are over 100%. The scan range of the arrays on a convex surface increased in general compared to a planar surface, in particular, and the beamwidth increased by around 20° when the elements are slant-polarized. The cross polarization performance was changed significantly on a curved surface with a more complex implication. However, it was 17 dB below the copolar component for the scan in the broadside direction. The degradation of polarization purity from effects of curvature on finite arrays can be a tradeoff with its ability to extend the scan range where a wide-angle scan is crucially a required feature for arrays in SOTM terminals on the ground. Such antenna arrays can also be used in high-speed broadband satellite service and wearable electronic devices.

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