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A Flush-Mounted Quasi-Full-Space Beam-Scanning Cylindrical Phased Array
Xiao Ding, Senior Member, IEEE, You-Feng Cheng, Xue-Song Yang, Bing-Zhong Wang, Senior Member, IEEE, and Dimitris E. Anagnostou, Senior Member, IEEE

Abstract—A cylindrical phased array (CPA) for quasi-full-space wide-angle scanning is presented. The quasi-full-space scanning is achieved by combining a pattern reconfigurable technique with a sub-array scanning method. The pattern reconfigurable technique achieves wide-angle scanning in the elevation plane of the cylindrical carrier, while the sub-array scanning ensures omnidirectional coverage in the azimuth plane of the cylindrical carrier by employing the CPA circumferential elements. Furthermore, a covariance matrix adaptation evolution strategy (CMA-ES) is used to optimize the quasi-full-space scanning performance. The proposed approach provides superior performance of side-lobe level (SLL < -6.1 dB), particularly small gain fluctuation (±0.75 dB) when scanning from -88° to +88° in the elevation plane of the cylindrical carrier, and smooth omnidirectional coverage with gain fluctuation only ±0.1 dB in the azimuth plane of the cylindrical carrier. The array supporting structure including the control circuits, feed lines, PIN diode switches, and the radiating magnetic current elements are fabricated on or underneath the metallic ground plane.

Index Terms—Cylindrical phased array (CPA), covariance matrix adaptation evolution strategy, magnetic current, pattern reconfigurable antennas, wide-angle beam scanning.

I. INTRODUCTION

In this communication, we focus on achieving quasi-full-space beam-scanning and wide-angle scanning performance from a cylindrical phased array (CPA). The main challenge and novelty to achieve this goal include the development of new methods and techniques. The use of the proposed sub-array scanning method improves circumference elements utilization with omnidirectional radiation in the azimuth plane, while the pattern reconfiguration technique helps obtain wide-angle coverage in the elevation plane. Also, we use the covariance matrix adaptation evolution strategy (CMA-ES) to enhance the scanning performance and achieve quasi-full 3D-space coverage. The operation mechanism and the entire array system are described in this paper. The proposed CPA is fabricated and is compatible with flush-mounting applications. The simulated and measurement results demonstrate that quasi-full-space beam scanning can be obtained with high utilization efficiency of array elements which means the array can realize the same scan with better radiation performance and fewer active subarrays, and with small scanning gain fluctuation.

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Fig. 1. Illustration of scanning space division, sub-array scanning and pattern reconfigurability of the proposed cylindrical phased array. (a) In the azimuth plane of the cylindrical carrier, when element #3 is activated, the adjacent elements #1, #2, #4 and #5 work concurrently with the different input amplitudes and phases that are provided by the covariance matrix adaptation evolution strategy (CMA-ES) optimization. (b) Similar patterns when element #4 is activated. (c) Elevation plane patterns of the cylindrical carrier: when all elements are activated with the correct reconfigurable patterns, the array will scan in the right sub-space (blue). Similar patterns will be radiated in the left sub-space with reverse phasing sequence (red). (d) Sketch diagram of the 3-dB coverage and scanning 3-dB HPBW.

Cylindrical phased arrays are widely used in civilian and defense applications [1]. Traditional CPAs with rotational symmetry and equal amplitude and phase excitation have approximate omnidirectional patterns but with unnecessary gain fluctuations in the azimuth plane.

Generally, the introduced gain fluctuation is dependent upon the number of the circumference elements [2]-[4]. In order to overcome these disadvantages and enhance the scanning performance of CPAs, many efforts have been carried out [5-11]. The most common method to obtain omnidirectional coverage with a good gain flatness in the azimuth plane of the cylindrical carrier is adopting massive elements. However, this solution often results in a low utilization coefficient of the circumference elements [5]. Subsequently, some improved methods have been presented, such as, beamforming techniques [6], series-fed subarray method [7], evolutionary optimization [8], subwavelength artificial electromagnetic structure [9], and tightly coupled dipole array models [10]-[11]. For example, in [6] the azimuthal circumference elements are divided into sub-arrays, each of which corresponds to a specific scanning range. This division improves the utilization of the circumference elements and promotes an omnidirectional coverage.

Most reported CPAs focus on omnidirectional coverage in the azimuth plane. In the elevation plane of the cylindrical
carrier, however, the wide-angle coverage is still a research challenge. Past efforts have been carried out on planar structures. An effective approach was the pattern reconfiguration shown in [12], [13], where a hybrid high-impedance surface with reconfigurable square loops [13] demonstrated a ±60° scanning range with high gain. Other meaningful methods to achieve wide-angle scanning involve but are not limited to image theory [14], high-impedance periodic structures [15], stacked patch reflectarrays [16], SIW techniques [17], and L-bar microstrip patches [18].

II. HIGH-PERFORMANCE QUASI-FULL-SPACE SCANNING

Method

To obtain high element utilization and omnidirectional radiating in the azimuth plane of the cylindrical carrier, we divide the azimuth plane into sub-spaces as shown in Fig. 1(a) and (b). When a selected element is working, its adjacent elements will also be activated and their excitations (amplitude and phase) will be synthesized. In terms of the synthesis algorithm for conformal arrays, since here Analog Devices HMC539ALP3E GaAs MMIC 6-bit digital attenuators with a step size of 0.25 dB and a 6-bit digital phase shifter are used. The control step size of the input amplitude is small enough that it can be treated as continuous parameters, while the input phases are discrete. Thus, hybrid-parameter algorithms are required. In the literature, some hybrid-parameter algorithms, such as the non-dominated sorting genetic algorithm (NSGA-II) and hybrid particle swarm optimization (HPSO), have been proposed [19]-[22]. Here a covariance matrix adaptation evolution strategy (CMA-ES) which can be improved as a multi-objective and hybrid-parameter algorithm is applied to all the activated elements.

As an example, in the scan shown in Fig. 1(a), the total array pattern can be calculated as a superposition of the pattern of elements #1 through #5 (all other elements are terminated to matched loads):

\[ F_0(\theta, \phi) = \sum_{n=1}^{5} W_n F_n(\theta, \phi) e^{j[k R_n \cos(\theta-3.5\theta_1) \sin(\theta-3.5\theta_2) \cos(\theta-3.5\theta_3)-\phi_1]} \]

where \( W_n \) is the weighted amplitude of the \( n^{th} \) element, \( F_n(\theta, \phi) \) is the active pattern of the \( n^{th} \) element, \( k \) is the phase constant, \( \phi_n \) is the excitation phase of the \( n^{th} \) element, \( R_0 \) is the aperture radius of the cylindrical platform, \( \theta \) and \( \phi \) are the elevation and azimuth angles of the coordinates, and \( \theta_0 \) is the radians of each segment and in the design is 36°. It is worth noting that the active patterns which can be obtained by measurement are used to take the effect of mutual coupling into account. Equation (1) is used for the beam forming when the array scans in the \( n^{th} \) subspace, as shown in Fig. 1(a).

In the optimization of the array synthesis, the parameter vector representing each candidate solution consists of ten variables: \( X = [W_1, W_2, ..., W_5, \phi_1, \phi_2, ..., \phi_5] \). In addition, the scanning angle (SA), scanning 3-dB beam-widths (HPBW) which is defined with respect to the maximum gain in the whole scanning range but the maximum gain of the current scanning beam, and normalized side-lobe level (SLL) should be considered in the synthesis, so the cost function can be defined as:

\[
\begin{align*}
\text{Cost}_1 &= |SA - S_{A,0}| \\
\text{Cost}_2 &= |\text{HPBW} - \text{HPBW}_0| \\
\text{Cost}_3 &= |\text{SLL} - \text{SLL}_0|
\end{align*}
\]

where the subscript ‘c’ denotes the current value and subscript ‘0’ denotes the goal value. In the optimization, the expected 3-dB HPBW (\( \text{HPBW}_0 \)), and SLL (\( \text{SLL}_0 \)) are all fixed to be 18° and -15 dB, respectively. Thus, the objective function of the optimization problem can be written as:

\[
\text{Objv} = \{\min(\text{Cost}_1), \min(\text{Cost}_2), \min(\text{Cost}_3)\}
\]

Based on [23], the suggested minimum sample size \( \lambda_{\text{min}} \) is

\[
\lambda_{\text{min}} = 4 + \left[ 3 \cdot \ln(\text{Dim}) \right]
\]

where \( \text{Dim} = 20 \) is the problem dimension, resulting in a minimum sample size of \( \lambda = 12 \). In order to further enhance the population’s diversity, here \( \lambda = 25 \) is selected for the CMA-ES.

In the beam forming, active element patterns (AEPs) are used to calculate the array radiation patterns. Since the AEPs are measured with the switches, the insertion losses of switches are considered in the optimization. Other losses, such as the insertion losses of the feeding network, are not included. However, this part of losses has limited impacts on the array pattern.

The elevation plane of the cylindrical carrier (Fig. 1(c)) is also divided into several sub-spaces according to the pattern reconfigurable modes. As described in [12], each sub-space respectively matches with one of the reconfigurable narrow beams of the elements. When all the pattern reconfigurable elements are set to one of the reconfigurable states, beam scanning in the corresponding sub-space can be completed according to the principle of a traditional phased scanning array. The scanning beams in all the sub-spaces collectively cover a wide scanning range.

From Fig. 1 and the above description, it can be summarized that the scan of the proposed phased array can be divided into two cases. For the first case (Fig. 1(a,b)), the phased array scans in the azimuth plane of the cylindrical carrier by switching the activated elements and optimizing the element inputs. For the second case, when the activated elements are selected, the phased array is able to steer its beam in the elevation plane of the cylindrical carrier by switching the operation modes and optimizing the element inputs. The scanning mechanism of this case is shown in Fig. 1(c). Combined with the above two cases, this cylindrical conformal phased array achieves high-performance quasi-full-space beam-scanning. Overall, the phased array can be seen as a special time modulated array based on pattern reconfigurable elements. It can scan its main beams all over the entire space by selecting the activated elements and their reconfigurable modes. Besides, for each scanning beam, the optimized inputs are used for enhanced array performance.
III. DESIGN AND ANALYSIS OF CYLINDRICAL PHASED ARRAY

A. The Cylindrical Phased Array Element

The prototype of the proposed CPA element comes from the pattern reconfigurable magnetic current element in Ref. [24], as shown in Fig. 2. The two red cones represent two excitation ports. A small hole is opened on one side of the hollow metallic box, for the feeding coaxial cable to pass through and reach the top of the slot. The inner and outer conductors of the feeding coaxial cable are connected to the dual sides of the Slots 3 and 5 at the positions where the two ends of the red cone is. The hollow metallic boxes placed just underneath the excitation slots are used to form the necessary unidirectional pattern and enhance directivity. This has been explained in [24] and has also been added in the revised manuscript. The CPA element operates at 5.8GHz and has the physical dimensions listed in Table I. Each CPA element consists of two pattern reconfigurable magnetic current elements (named magnetic current elements 1 and 2, as shown in Fig. 2(a)) and forms a new pattern reconfigurable sub-array. Here the radiation element is a cavity backed slot in which the electric field goes from one long side to the other side. According to the principle of equivalence, the electric field in the slot can be equivalent to magnetic current:

\[ \vec{M}_y = -2 \vec{n} \times \vec{E}_x \]  

(5)

where \( \vec{n} \) is the unit vector in the z direction, and \( \vec{E}_x \) is the electric field in the slot. This means that, in the radiation slot, there is an equivalent magnetic current. The magnetic current works as the radiation source. The concept of “magnetic current element” is used to demonstrate the radiation performance of the array element. Since the radiation source is the equivalent magnetic current and there is a metal cavity backed below the substrate, according to [13], the element can be seen as a magnetic current parallel to the PEC ground which radiates a far-field pattern with the wide beam. In addition, by adopting the pattern reconfiguration technique, the reconfigurable patterns can cover a wide-angle range, which benefits for the wide-angle scan.

![Fig. 2. Structure of the CPA element.](image)

(a) Perspective view including the two magnetic current elements. (b) Top view including excitation magnetic current slots and other radiating patterns guidance/reflection slots. (c) Bottom view including the p-i-n switch diodes, dc bias, and dc/ground connection nodes, and (d) side view, showing the diode placement and polarity.

![Fig. 3. Measured active patterns of the two magnetic current elements.](image)

(a) reconfigurable patterns in the x-z plane, (b) radiating patterns in y-z plane.

![Fig. 4. Photograph of the CPA element measured in the anechoic chamber.](image)
By electrically switching the embedded diode switches ($S_1$ to $S_{12}$), each magnetic current element has two different reconfigurable patterns pointing to the right or to left side, respectively, as shown in Fig. 3. Fig. 3(a) shows the measurement active radiating patterns of the two magnetic current elements in the $x$-$z$ plane. Figure 3(b) shows the active radiating patterns in the $y$-$z$ plane. The relationship of the switch states and reconfigurable modes is shown in Table II. More information about the reconfiguration principle and how to excite the magnetic current and control the PIN diode switches with bias can be found in [24].

Figure 4 shows the fabricated CPA element and Fig. 5(a) illustrates the simulated and measured $S$-parameters at each magnetic current port that is excited. The measured results agree well with the simulations. The magnetic current element presents a matching level of -25 dB at both ports, which indicates it is well matched at 5.8 GHz. The isolation between the magnetic current elements is better than -13 dB in the operating band, and the curvature of the cylinder facilitates the coupling reduction compared to a planar array. Fig. 5(b) shows the excitation efficiencies of the two ports when the CPA operates at Mode 1, and they can be calculated as

$$\text{Coef}_1 = 1 - |S_{11}| - |S_{21}|$$
$$\text{Coef}_2 = 1 - |S_{12}| - |S_{22}|$$

Figure 8 shows the measured scanning patterns of the CPA in the elevation plane of the cylindrical carrier. (a) Scan in Subspace A. (b) Scan in Subspace B.

B. The Cylindrical Phased Array

Ten of the above-mentioned CPA elements are used to form the proposed CPA, and they are uniformly symmetrically...
distributed over the cylindrical circumference with a radius of \( R_0 = 95 \text{mm} \) (about 1.8\( \lambda_0 \), where \( \lambda_0 \) is the wavelength in free space at the operation frequency). The structure of the proposed CPA is shown in Fig. 6. The proposed CPA was fabricated and is shown in Fig. 7, along with the control system. The system is composed of a vector feeding network which include a power divider, a phase shifter and a digital attenuator, matched loads, digital switches, the proposed CPA and a control center. These parts are separated by purple dotted lines. Each digital switch has three modes which are used to change the array element into one of the two operation modes or a dull element. To determine whether a CPA element is fed with the optimized inputs or terminated in matched loads, an external control center is utilized here, as shown in Fig. 7 (b). In addition, the control center also used here to switch the pattern reconfigurable mode of the magnetic current elements. In Fig. 7 (b), a vector feeding network composed of a power splitter, a phase shifter and a digital attenuator is used to feed the CPA element. Each part of the system is controlled by an external control center whose functions consist of (1) deciding the power component from the power splitter to each port of the phase shifter, (2) determining the phase shifts of each CPA element, (3) controlling the amount of attenuation of the vector feeding network, (4) deciding whether a CPA element to work as a radiating element or dull element, and (5) determining the bias voltage of each magnetic current elements and thus which mode the CPA operate at.

### C. The Quasi-Full-Space Scanning Performance

According to the guidance of section II, in order to achieve the quasi-full-space beam scanning, the azimuth plane of the cylindrical carrier is divided into ten sub-spaces (named Subspace I to X), as shown in Fig. 6 (a) and the elevation plane of the cylindrical carrier is divided into two sub-spaces (named Subspace A and B), as shown in Fig. 6 (b).

Fig. 8 shows the wide-angle scanning coverage in the elevation plane of the cylindrical carrier when the magnetic current element works at the two pattern reconconfigurable modes. Stepped phase differences provided by the phase shifters, are applied to the two magnetic current elements to achieve the wide-angle scanning in the elevation plane. It is quite clear that the CPA element supports a 3-dB coverage from -88° to 88° and a main-beam coverage from -70° to +70° in the elevation plane with a gain fluctuation less than 0.75 dB and side-lobe level less than 6.1 dB. The main-beam coverage is less than that (-75° to +75°) in [24]. The reason is that here only two reconfigurable elements are used for the vertical-plane scan while the design in [24] requires four elements.

### Table IV. Optimized Inputs of Subarrays I, II, III, IX and X When the CPA Scans in Subspace I.

| Subarray I Port 1 | Amplitude(V) | Phase(deg) | (\( \theta_0, \phi_0 \)) | (0°, 0°) | (40°, 0°) | (60°, 0°) | (70°, 0°) | (18°, 90°) | (36°, 32°) | (50°, 24°) | (67°, 20°) | (82°, 18°) |
|------------------|--------------|------------|----------------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| Subarray II Port 1 | Amplitude(V) | Phase(deg) | (\( \theta_0, \phi_0 \)) | (0°, 0°) | (40°, 0°) | (60°, 0°) | (70°, 0°) | (18°, 90°) | (36°, 32°) | (50°, 24°) | (67°, 20°) | (82°, 18°) |
| Subarray II Port 2 | Amplitude(V) | Phase(deg) | (\( \theta_0, \phi_0 \)) | (0°, 0°) | (40°, 0°) | (60°, 0°) | (70°, 0°) | (18°, 90°) | (36°, 32°) | (50°, 24°) | (67°, 20°) | (82°, 18°) |
| Subarray III Port 1 | Amplitude(V) | Phase(deg) | (\( \theta_0, \phi_0 \)) | (0°, 0°) | (40°, 0°) | (60°, 0°) | (70°, 0°) | (18°, 90°) | (36°, 32°) | (50°, 24°) | (67°, 20°) | (82°, 18°) |
| Subarray IX Port 1X | Amplitude(V) | Phase(deg) | (\( \theta_0, \phi_0 \)) | (0°, 0°) | (40°, 0°) | (60°, 0°) | (70°, 0°) | (18°, 90°) | (36°, 32°) | (50°, 24°) | (67°, 20°) | (82°, 18°) |
| Subarray X Port 1X | Amplitude(V) | Phase(deg) | (\( \theta_0, \phi_0 \)) | (0°, 0°) | (40°, 0°) | (60°, 0°) | (70°, 0°) | (18°, 90°) | (36°, 32°) | (50°, 24°) | (67°, 20°) | (82°, 18°) |

### Table V. Comparison between the Proposed Array and Reference Arrays.

<table>
<thead>
<tr>
<th>Scanning mechanism in the elevation of the cylindrical carrier</th>
<th>This paper</th>
<th>Ref. [25]</th>
<th>Ref. [26]</th>
<th>Ref. [27]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical scanning range in the elevation of the cylindrical carrier</td>
<td>pattern reconfigurable elements</td>
<td>dual-polarized elements</td>
<td>wide-beam elements</td>
<td>FSS structure</td>
</tr>
<tr>
<td>Vertical scanning range in the elevation of the cylindrical carrier</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak gain/Element number</td>
<td>12.6 dBi/6</td>
<td>NA</td>
<td>20 dBi/24</td>
<td>10 dBi/4</td>
</tr>
<tr>
<td>Peak sidelobe level</td>
<td>-6.1 dB</td>
<td>&lt; -10 dB</td>
<td>-10 dB</td>
<td></td>
</tr>
</tbody>
</table>
Fig. 9 shows the beam coverage in Subspace I. Here, five CPA elements (those near to or belonging to Subspace I) are fed with input amplitudes and phases provided by the CMA-ES, while the other elements are terminated to matched loads. It can be found that the scanning main lobes of the CPA are able to cover from -18° to +18° (namely the entire Subspace I), which means that the proposed CPA can provide a full circumferential scan around the cylindrical surface due to the rotational symmetry of these subspaces shown in Fig. 6(a) and achieve an approximately omnidirectional coverage with only 0.1 dB gain fluctuation. Note that, in the optimization, the gain fluctuation is not taken into consideration in equations (2) and (3) because the low gain fluctuation is determined by the operational principle of the array. This can be explained in each plane as follows: (a) In the elevation plane, the array scans based on pattern reconfiguration and wide-beam radiation. For example (see Fig. 8) when the array scans in subspace A, the radiation patterns of the array elements are reconfigured so as to radiate with wide beamwidth in this subspace A and with little radiation in the other subspace B. This results in low gain fluctuation and low sidelobes within the considered subspace. (b) The azimuth plane is divided into 10 symmetric subspaces of 36° each. Within this ±18° angle, the measured active element patterns (AEP) shown in Fig. 3 exhibit almost uniform radiation (i.e. almost flat beam pattern) with minimum fluctuation. Therefore, the array exhibits low gain fluctuation as shown in Fig. 9.

Finally, Fig. 10 illustrates the two-dimensional (2-D) scanning patterns drawn in a u-v coordinate system from:

- (a)-(c): $(u, v) = (-1, 0.31)$ to $(u, v) = (1, 0.31)$
- (d)-(f): $(u, v) = (-1, 0)$ to $(u, v) = (1, 0)$
- (g)-(i): $(u, v) = (-1, -0.31)$ to $(u, v) = (1, -0.31)$

Here, $u = \sin \theta \cos \phi$, $v = \sin \theta \sin \phi$. In the x-z plane, the range of $\theta$ in Subspace I is [-90°, +90°], and in the u-v coordinate system it corresponds to [-1, +1]. In the y-z plane, the range of $\phi$ in Subspace I is [-18°, +18°], and the boundaries in the u-v coordinate system are $\cos(0°)\sin(\pm18°) = \pm0.31$. So, the total space coverage of Subspace I in the u-v coordinate system is $[(-1,-0.31), (+1,+0.31)]$.

Table III shows the detailed scanning performance when the CPA scans in the quarter area of the above-mentioned full space. The scanning results indicate that the radiation beams of the CPA can cover the quasi-full space which combines the Subspace I shown in Fig 6(a) and Subspaces A and B shown in Fig. 6(b). Due to the rotation symmetry, it can be deduced that the CPA can realize a quasi-full-space scanning performance. Besides, the corresponding optimized inputs are listed in Table IV.

In terms of the insertion losses, first, the total insertion losses of the feeding network were measured, and it can be found that the total losses versus the scanning angles are limited within a fluctuation of 0.5 dB. In addition, because we used vector phase shifters (instead of scalar ones), the loss of each port can be compensated by itself. In the calculation of the realized gain of the array, the measured total insertion loss is included in the array gain. The measurement of the array gain is under the presence of the switches, so the losses of the switches have also been considered in the calculation.

A comparison between the proposed phased array and those in [25] - [27] is shown in Table V. In the azimuth plane of the cylindrical carrier, all the designs can realize full-space scans. In the elevation plane of the cylindrical carrier, these designs adopt different scanning solutions, which result in different scanning performance. The design in [25] uses traditional patch elements to achieve a scanning range from -30° to +30°. In [26], the element beam width is broadened, which leads to an enhanced scanning range (up to 60°). In [27], a frequency selective surface (FSS) structure is utilized, and the FSS-loaded phased array has a scanning range of -50° to +50°. Therefore, the solution adopted in [25] is hard to achieve a wide-angle scan, and those in [26] and [27] can enhance the scanning ability obviously. However, the scanning range is required to be further broadened. In our design, pattern reconfiguration technique is applied to the element design. Based on the joint wide beam width of the pattern reconfigurable elements, the conformal phased array is able to realize a maximum scanning angle of 70°. Besides, the wide-beam design in [26] generally results in low realized gain. Thanks to the pattern reconfiguration technique, our proposed array is able to obtain a higher realized gain than that in [27] when the two arrays have the same number of elements. The FSS-loaded structure in [27] also possesses high-gain performance. In terms of the peak sidelobe levels (PSLs), [25] proposed a novel synthesis
solution and an ultra-low PSL can be obtained. The designs in [26] and [27] both can realize PSLs lower than -10 dB. In our design, the utilization efficiency of each element is outstanding (only two elements are used in the vertical plane) in the cost of the PSL performance.

Also, the average synthesis performance under 20 tries of the selected CMA-ES and other optimization algorithms, such as NSGA-II and HPSO, is compared and listed in Table VI. Here the scanning beam tilted to \((\theta_0, \phi_0) = (70^\circ, 0^\circ)\) is chosen as a comparative case. In the NSGA, the recombination rate is chosen as 0.7. In the HPSO, the inertia weight is selected as 1, and the acceleration coefficients are both selected as 2, and the maximal velocity in the binary part is selected as 6. Note that the population size and the maximum generation are set the same for all these algorithms. From Table V, the optimized results are the same. This means the CMA-ES can be used as a new tool for the conformal array synthesis.

IV. CONCLUSION

A new method for cylindrical conformal phased arrays to achieve quasi-full-space scanning and enhanced element utilization was presented. A new CPA with 10 pattern reconfigurable sub-arrays was introduced. Based on the guidance of the quasi-full-space scanning method, the proposed CPA can scan its main beam from \(-88^\circ\) to \(+88^\circ\) in the elevation plane and from \(-180^\circ\) to \(+180^\circ\) in the azimuth plane. Moreover, the sub-array scanning method, covariance matrix adaptation evolution strategy optimization and pattern reconfigurable technique enhanced the scanning performance with high elements utilization and small gain fluctuation. Excellent quasi-full-space scanning is achieved with the proposed system, which can provide an effective design method for wide-beam coverage phased arrays.

REFERENCES