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Bias Correction for Polarization Measurement in Phased Array Antenna via Pattern Reconstruction Method

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ABSTRACT A reconstruction technique of the antenna pattern for correcting the polarization measurement bias is proposed in this paper. In the case of the prior knowledge of patterns at some scanning angles, the pattern at other beam position can be estimated by application of the minimum norm least-square solution. Once the pattern is reconstructed, the corresponding projection matrix could be obtained in the presence of the mutual coupling and edge effects in the polarimetric phased array antenna. Thereby, the correction matrix for the polarization scattering matrix is repaired. A microstrip patch array antenna is designed to demonstrate the validity of the proposed method, and the performance of bias correction is manifested using several polarimetric variables. Specifically, the bias of differential reflectivity (Z_{DR}^b), the bias of linear depolarization ratio (L_{DR}^b) and the phase difference are less than 0.14 dB, 46.85 dB, 3.31° in a wide scanning angle range, respectively.

INDEX TERMS Bias correction, pattern reconstruction, polarimetric phased array antenna, polarization measurement.

I. INTRODUCTION

Phased array antenna (PAA) with agile electronic beam steering capability has been successfully utilized in the communication, military application and weather observation [1]–[6], with respect to the mechanically scanning dish antenna. In addition, since the accurate multiparameter measurement ability of the polarimetry has matured for years, the polarimetric PAA (PPAA) with the dual-polarization capability will be indispensable in future targets or weather observation [7]. Currently, two main challenges that still trouble the PPAA technology are the requirements of wide angle scan and high accuracy for polarimetric measurements [8], [9]. Specifically, when the beam is scanned away from the antenna's principal plane, the beam will broaden considerably, and the electric fields radiated from the horizontal (H) and vertical (V) polarization ports are not orthogonal to each other. The cross-polar components are produced, and this is where the polarization biases yield. Hence, the polarization isolation requirement should be met for alternate mode (where the polarization states are switched alternately on transmission) and hybrid mode (where both polarization states are transmitted and received simultaneously). And the polarization purity requirement is more stringent for the hybrid mode compared to the alternate mode of operation [10]. To solve the cross-polar problem, the projection matrix method was proposed in [3], and the method was examined with a pair of crossed dipoles. The biases can be removed through a multiplication operation to the measured scattering matrix. The correction technique has been extended to other antenna types, such as the aperture and patch antenna [11]. However, the above-mentioned correction method for the polarization measurement bias is implemented based on an ideal antenna element, and the correction matrix is made up of the theoretical pattern. Furthermore, the element issue was expanded to an array antenna in [8], [12], [13]. However, the scattering matrix measured by the practical array antenna will be affected by the mutual coupling between antenna elements [14], [15], and the edge diffraction effect [16]. The correction matrix multiplication method based on the theoretical pattern is not necessarily feasible due to the distortion of the radiation pattern.

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To address the above issue, the desired correction matrix is expected to be constituted by the actual pattern. However, the pattern measurement at one beam position after another in the overall space is quite time-consuming and highly complex [17], [18]. Moreover, the measurement could be challenging, especially in the outside test environment [19], so the pattern at a certain beam position is not always provided in advance. Within this context, the reconstruction technique is an alternative strategy to obtain the desired pattern in a specified beam direction. In the actual application, the electronic beam of the PPAA will be scanned to any beam position within a wide steering range. Since the projection matrix is pattern-based, the scattering matrix measured at each scanning angle should be repaired respectively. The pattern reconstruction provides a possibility of estimating the correction matrix for the polarization measurement bias.

In this paper, a pattern reconstruction method is proposed to achieve the desired pattern, thereby obtaining the corresponding correction matrix at the current beam. The minimum norm least-square solution is used to maintain the accuracy of pattern reconstruction, and the correction matrix for the polarization bias is repaired. The correction method is suitable to not only the Alternate Transmission and Simultaneous Reception (ATSR) mode but also the Simultaneous Transmission and Simultaneous Reception (STSR) mode. Based on the projection matrix method in [3], [11], the innovation of this paper lies in reconstructing the expected pattern, thereby obtaining the projection matrix and correction matrix. After repairing the correction matrix by using the reconstructed pattern, the bias reduces considerably compared with that without repairing. Several polarimetric variables, like the differential reflectivity (Z_{DR}) and linear depolarization ratio (L_{DR}), are utilized to evaluate the performance of bias correction. The polarization bias, representing the effectiveness of the proposed reconstruction algorithm, is illustrated by the bias of the Z_{DR} and the bias of L_{DR}. Numerical simulations and comparisons are conducted to manifest the validity of this proposed method.

The rest of the paper is organized as follows. In Section II, the proposed pattern reconstruction algorithm is formulated, and the bias correction model is built based on the projection matrix method. In Section III, the performance of the reconstruction algorithm is analyzed, given that the presence of mutual coupling and edge effect in the array antenna. The bias correction operation is evaluated using the polarization measurement parameters. Conclusions and discussions are presented in Section IV.

II. FORMULATION

A. PROPOSED PATTERN RECONSTRUCTION METHOD

For a one-dimensional array antenna, the pattern vector $\mathbf{F}(\theta)$ can be expressed as the linear combination of element patterns $\mathbf{G}(\theta)$ [20].

$$\mathbf{F}(\theta) = \mathbf{W}\mathbf{G}(\theta) \tag{1}$$

where $\mathbf{F}(\theta)$ contains N array pattern vectors at varying scan angles, $\mathbf{F}(\theta) = \left[\mathbf{f}_1(\theta)\ \mathbf{f}_2(\theta)\ \cdots\ \mathbf{f}_N(\theta)\right]^T$. The superscript T is the transpose operator. $\mathbf{G}(\theta)$ contains M element pattern vectors $\mathbf{G}(\theta) = \left[\mathbf{g}_1(\theta)\ \mathbf{g}_2(\theta)\ \cdots\ \mathbf{g}_M(\theta)\right]^T$, respectively. $\mathbf{W}$ is a complex value $N \times M$ matrix including the amplitude and phase weighting factor.

Similarly, the array pattern at n'th directional angle is given by

$$\begin{aligned}\mathbf{f}_{n'}(\theta) &= \sum_{m=1}^{M} w_{n'm}\mathbf{g}_m(\theta) \\ &= \left[w_{n'1}\ w_{n'2}\ \cdots\ w_{n'M}\right]\mathbf{G}(\theta)\end{aligned} \tag{2}$$

$\mathbf{G}(\theta)$ can be calculated from (1), but the characteristic of the matrix $\mathbf{W}$ should be determined first. For example, whether $\mathbf{W}$ is a square matrix or an invertible matrix, whether it has a full row or column rank, whether it's a rank deficient matrix. According to the matrix theory, as long as $\mathbf{W}$ does not have the right pseudoinverse matrix, i.e. $N < M$ and $\mathrm{rank}(\mathbf{W}) = N$ simultaneously, $\mathbf{G}(\theta)$ can be computed from (1) directly. Hence, the number of measured patterns N is selected to be not less than the number of elements. If the inverse matrix or pseudoinverse matrix of $\mathbf{W}$ is denoted as $\mathbf{V}$ uniformly, (2) can be rewritten as

$$\begin{aligned}\mathbf{f}_{n'}(\theta) &= \left[w_{n'1}\ w_{n'2}\ \cdots\ w_{n'M}\right]\mathbf{V}\mathbf{F}(\theta) \\ &= \left[\omega_{n'1}\ \omega_{n'2}\ \cdots\ \omega_{n'M}\right]\mathbf{F}(\theta)\end{aligned} \tag{3}$$

Therefore, the pattern at any scan angle can be represented linearly by the known patterns. We assume that the patterns from N scanning angles, $\mathbf{f}_1(\theta), \mathbf{f}_2(\theta), \cdots, \mathbf{f}_N(\theta)$, are given beforehand, while the patterns $\widehat{\mathbf{f}}_1(\theta), \widehat{\mathbf{f}}_2(\theta), \cdots, \widehat{\mathbf{f}}_N(\theta)$ of other N' angles are unknown. Due to the gradual variation of the radiation characteristic of the antenna, N' patterns can be reconstructed based on the known N patterns, and the expression can be written as

$$\widehat{\mathbf{f}}_{n'}(\theta) = \sum_{n=1}^{N} u_{n'n}\mathbf{f}_n(\theta) \tag{4}$$

where $u_{n'n}$ is the pattern reconstruction coefficient.

Expand the equation (4) in the form of a matrix to

$$\left[\widehat{\mathbf{f}}_1(\theta)\ \widehat{\mathbf{f}}_2(\theta)\ \cdots\ \widehat{\mathbf{f}}_{N'}(\theta)\right]^T = \mathbf{U}\left[\mathbf{f}_1(\theta)\ \mathbf{f}_2(\theta)\ \cdots\ \mathbf{f}_N(\theta)\right]^T \tag{5}$$

where

$$\mathbf{U} = \begin{bmatrix} u_{11} & u_{12} & \cdots & u_{1N} \\ u_{21} & u_{22} & \cdots & u_{2N} \\ & & \vdots & \\ u_{N'1} & u_{N'2} & \cdots & u_{N'N} \end{bmatrix}. \tag{6}$$

$\mathbf{U}$ is the pattern reconstruction matrix describing the estimation of the unknown patterns $[\widehat{\mathbf{f}}_1(\theta)\ \widehat{\mathbf{f}}_2(\theta)\ \cdots\ \widehat{\mathbf{f}}_{N'}(\theta)]$ based on the actual patterns $\left[\mathbf{f}_1(\theta)\ \mathbf{f}_2(\theta)\ \cdots\ \mathbf{f}_N(\theta)\right]$ at N scanning angles, and denotes the reltionship between the two types of patterns. If K directions are selected as the sampling at $\theta_1, \theta_2, \cdots, \theta_K$, the corresponding pattern is

$$\mathbf{f}_n(\theta) = \{\mathbf{f}_n(\theta_1), \mathbf{f}_n(\theta_1), \cdots, \mathbf{f}_n(\theta_K)\} \tag{7}$$

The spatial sampling means the observations from K directions in one beam. Combine the equations (4) - (7), the reconstruction formula can be rewritten as

$$\begin{bmatrix} \widehat{\mathbf{f}}_1(\theta_1) & \widehat{\mathbf{f}}_1(\theta_2) & \cdots & \widehat{\mathbf{f}}_1(\theta_K) \\ \widehat{\mathbf{f}}_2(\theta_1) & \widehat{\mathbf{f}}_2(\theta_2) & \cdots & \widehat{\mathbf{f}}_2(\theta_K) \\ & & \vdots & \\ \widehat{\mathbf{f}}_{N'}(\theta_1) & \widehat{\mathbf{f}}_{N'}(\theta_2) & \cdots & \widehat{\mathbf{f}}_{N'}(\theta_K) \end{bmatrix} = \mathbf{U} \begin{bmatrix} \mathbf{f}_1(\theta_1) & \mathbf{f}_1(\theta_2) & \cdots & \mathbf{f}_1(\theta_K) \\ \mathbf{f}_2(\theta_1) & \mathbf{f}_2(\theta_2) & \cdots & \mathbf{f}_2(\theta_K) \\ & & \vdots & \\ \mathbf{f}_N(\theta_1) & \mathbf{f}_N(\theta_2) & \cdots & \mathbf{f}_N(\theta_K) \end{bmatrix} \tag{8}$$

For simplity, equation (8) is given by

$$\widehat{\mathbf{F}}(\theta) = \mathbf{U}\mathbf{F}_a(\theta) \tag{9}$$

In fact, the number of the measured pattern is finite, and it is far less than the number of spatial sampling, that is, $N \ll K$. Thus, the expression (9) is the overdetermined linear equation. Only the approximate solution of the equation can be obtained mathematically.

Let $\mathbf{F}_d(\theta)$ be the patterns which are desired, $\mathbf{F}_a(\theta)$ be the pattern that has been given or measured. A minimum norm least-square solution that satisfies $\min \|\mathbf{U}\mathbf{F}_a(\theta) - \mathbf{F}_d(\theta)\|$ can be given by

$$\mathbf{U} = \mathbf{F}_d(\theta)\mathbf{F}_a^{\dagger}(\theta) \tag{10}$$

where $\|\cdot\|$ denotes the Frobenius norm of a matrix and superscript $\dagger$ denotes the generalized inverse matrix.

If $\mathbf{F}_a(\theta)$ has full row rank, its right pseudoinverse can be formulated as $\mathbf{F}_a^{\dagger}(\theta) = \mathbf{F}_a^H(\theta)\left(\mathbf{F}_a(\theta)\mathbf{F}_a^H(\theta)\right)^{-1}$, where the superscript H denotes the complex conjugate transpose. When $\mathbf{F}_a(\theta)$ is a rank deficient matrix, its generalized inverse matrix $\mathbf{F}_a^{\dagger}(\theta)$ can be calculated according the matrix theory.

Therefore, the pattern of any other beam positions can be derived through the known patterns theoretically. The reconstruction matrix $\mathbf{U}$ denotes the mapping relationship of the given and reconstructed pattern. In addition, the performance of the reconstruction technique not only influences the radiation pattern but also will determine the application of the PPAA, such as the polarization measurement accuracy.

B. POLARIZATION BIAS CORRECTION VIA PROPOSED METHOD

In this paper, the bias of the measured polarimetric information with the PPAA is corrected based on the pattern reconstruction method. Compared with the ideal antenna, the radiation pattern of the practical array will be distorted due to the presence of mutual coupling between the elements and the edge diffraction effect of the array antenna. If the theoretical pattern is adopted to define the correction matrix according to the conventional projection matrix method, this will result in the measurement bias of the polarization scattering matrix (PSM). Hence, the measured pattern is needed to reset the correction matrix. However, the actual pattern of each beam position is not always available. The radiation patterns needed for bias correction can be estimated by the proposed pattern reconstruction method. Herein, the error of the reconstructed pattern will directly determine the measurement bias of the corrected PSM. The components of the scattering matrix in the polarimetric antenna can be measured alternately or simultaneously, that is, simultaneous transmission and simultaneous reception (STSR) mode and alternate transmission and simultaneous reception (ATSR) mode. The latter can estimate all four components of the backscattering covariance matrix during two or more pulses.

Through the process of radiation, scattering, and propagation of the electromagnetic wave, the PSM measured by the receiving antenna can be written as

$$\mathbf{S}^{(p)} = \mathbf{P}^T\mathbf{S}^{(b)}\mathbf{P} \tag{11}$$

Consistent with the polarization definition and expression in [3], [11], $\mathbf{S}^{(b)}$ is the intrinsic backscatter matrix of the target, and $\mathbf{S}^{(b)} = \begin{bmatrix} s_{hh}^{(b)} & s_{hv}^{(b)} \\ s_{vh}^{(b)} & s_{vv}^{(b)} \end{bmatrix}$, while $\mathbf{S}^{(p)}$ is the measured backscatter matrix. $\mathbf{P}$ is the projection matrix, $\mathbf{P} = \begin{bmatrix} p_{11} & p_{12} \\ p_{21} & p_{22} \end{bmatrix}$, and represents projections of radiated fields onto the local H-pol and V-pol directions. Its definition and formula are consistent with that in [3]. It is noticeable that the normalized electric field is equivalent to the radiation pattern. Hence, the pattern is critical to the polarization measurement.

The expansion of (11) is given by (12), as shown at the bottom of this page. We assume that the observed object is a metallic sphere, so the scattering matrix $\mathbf{S}^{(b)}$ is considered to be a unit matrix, namely $s_{vh}^{(b)} = s_{hv}^{(b)} = 0$. Hence, equation (12) is simplified to

$$\mathbf{S}^{(p)} = \begin{bmatrix} p_{11}^2 s_{hh}^{(b)} + p_{21}^2 s_{vv}^{(b)} & p_{11}p_{12}s_{hh}^{(b)} + p_{21}p_{22}s_{vv}^{(b)} \\ p_{11}p_{12}s_{hh}^{(b)} + p_{21}p_{22}s_{vv}^{(b)} & p_{12}^2 s_{hh}^{(b)} + p_{22}^2 s_{vv}^{(b)} \end{bmatrix} \tag{13}$$

$$\mathbf{S}^{(p)} = \begin{bmatrix} p_{11}^2 s_{hh}^{(b)} + p_{21}^2 s_{vv}^{(b)} + p_{11}p_{21}(s_{vh}^{(b)} + s_{hv}^{(b)}) & p_{11}p_{12}s_{hh}^{(b)} + p_{21}p_{22}s_{vv}^{(b)} + p_{11}p_{22}s_{hv}^{(b)} + p_{12}p_{21}s_{vh}^{(b)} \\ p_{11}p_{12}s_{hh}^{(b)} + p_{21}p_{22}s_{vv}^{(b)} + p_{11}p_{22}s_{vh}^{(b)} + p_{12}p_{21}s_{hv}^{(b)} & p_{12}^2 s_{hh}^{(b)} + p_{22}^2 s_{vv}^{(b)} + p_{12}p_{22}(s_{vh}^{(b)} + s_{hv}^{(b)}) \end{bmatrix} \tag{12}$$

$$\mathbf{S}' = \mathbf{C}_i^T\mathbf{S}^{(p)}\mathbf{C}_i = \left(\begin{bmatrix} p_{i11} & p_{i12} \\ p_{i21} & p_{i22} \end{bmatrix}^{-1}\right)^T \begin{bmatrix} p_{11}^2 s_{hh}^{(b)} + p_{21}^2 s_{vv}^{(b)} & p_{11}p_{12}s_{hh}^{(b)} + p_{21}p_{22}s_{vv}^{(b)} \\ p_{11}p_{12}s_{hh}^{(b)} + p_{21}p_{22}s_{vv}^{(b)} & p_{12}^2 s_{hh}^{(b)} + p_{22}^2 s_{vv}^{(b)} \end{bmatrix} \begin{bmatrix} p_{i11} & p_{i12} \\ p_{i21} & p_{i22} \end{bmatrix}^{-1} \tag{14}$$

Let the correction matrix be the inverse of the theoretical projection matrix $\mathbf{P}_i$, that is, $\mathbf{C}_i = \mathbf{P}_i^{-1}$. Herein, the corrected scattering matrix can be expressed as (14), as shown at the bottom of the previous page, and the four elements of the scattering matrix can be deduced as (15), as shown at the bottom of this page, respectively.

If the radiation profiles of the antenna are ideal, the theoretical pattern is equal to the actual pattern, namely $\mathbf{P} = \mathbf{P}_i$, which leads to that $\mathbf{S}' = \mathbf{S}$. However, the theoretical pattern is different from the actual pattern for the mutual coupling effect and edge effect in a practical antenna. Therefore, the above conclusion is not valid anymore. The equation that $\mathbf{C} = \mathbf{P}^{-1}$ is the expected correction matrix and the scattering matrix can be fully recovered. But if $\mathbf{P}$ is not given or measured at certain beam positions, the bias correction operation cannot be done. The pattern reconstruction algorithm can be used to estimate the expected pattern which is denoted by $\widehat{\mathbf{P}}$ and let correction matrix $\widehat{\mathbf{C}}$ be $\widehat{\mathbf{P}}^{-1}$. Hence, the estimated scattering matrix $\widehat{\mathbf{S}}$ can be written as

$$\widehat{\mathbf{S}} = \widehat{\mathbf{C}}^T \mathbf{S}^{(p)} \widehat{\mathbf{C}} \tag{16}$$

It is clear that the reconstruction accuracy of the proposed algorithm will affect the measurement accuracy of PSM. The quantitative analysis of the accuracy of polarization measurement is presented in the next section.

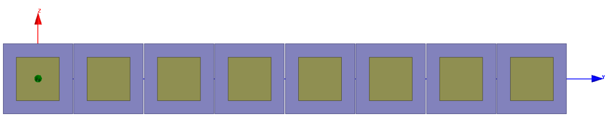

FIGURE 1. A uniform linear array with 8 dual-polarization elements.

III. SIMULATION RESULTS AND ANALYSES

Owing to the readiness for integration with circuits, microstrip technology is a promising candidate for the application in the phased array. The simulations are conducted on an array with 8 dual-polarization microstrip patch elements as shown in Fig.1. The array antenna is located in the yz plane (Fig.2), and the spherical coordinate system is used here. The operating frequency of the designed antenna is 10 GHz. The beam position for the pattern measurement increases progressively from 0° to 50° with 5° interval, with 11 measured beams. The pattern to be reconstructed is at the beam position from 0° to 48° with 3° interval, with 17 estimated beams. The pattern test is implemented in the HFSS software, and the data obtained by HFSS are treated as the pattern results. And the number of sample points from each simulated beam is 181, $\phi \in [-90°, 90°]$, with 1° interval. The weighting illumination of these two types of patterns keeps consistent, applying a 40 dB Taylor weighting.

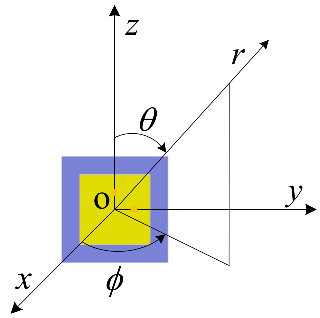

FIGURE 2. Spherical coordinate system for electric fields radiation from dual-polarization array.

A. DISTORTION OF RADIATION PATTERNS IN PPAA

The simulations consider the mutual coupling between the 8 dual-polarization elements, and the diffracted fields at the edges. As can be seen from Fig.3, the active element patterns of the antenna H-pol ports are different from each other. And the discrepancy is greater between the central elements (element 4 and 5) and the edge elements (element 1 and 8), which is attributable to the mutual coupling effects and edge diffraction effects. The active element patterns of the V-pol ports, as well as the discrepancy of the radiation characteristic are analogous to that of H-pol ports.

The ideal patterns are calculated by formulating the radiation characteristics of the designed antenna, as shown

$$\begin{cases} s'_{hh} = \dfrac{(p_{i22}p_{11}-p_{i21}p_{12})^2 s_{hh}^{(b)} + (p_{i22}p_{21}-p_{i21}p_{22})^2 s_{vv}^{(b)}}{(p_{i11}p_{i22}-p_{i12}p_{i21})^2} \\ s'_{vh} \\ = \dfrac{[p_{i22}p_{11}\,(p_{12}p_{i11}-p_{i12}p_{11})+p_{i21}p_{12}\,(p_{i12}p_{11}-p_{12}p_{i11})]\, s_{hh}^{(b)} + [p_{i12}p_{21}\,(p_{22}p_{i21}-p_{i22}p_{21})+p_{i11}p_{22}\,(p_{i22}p_{21}-p_{22}p_{i21})]\, s_{vv}^{(b)}}{(p_{i11}p_{i22}-p_{i12}p_{i21})^2} \\ s'_{hv} \\ = \dfrac{[p_{i22}p_{11}\,(p_{12}p_{i11}-p_{i12}p_{11})+p_{i21}p_{12}\,(p_{i12}p_{11}-p_{12}p_{i11})]\, s_{hh}^{(b)} + [p_{i12}p_{21}\,(p_{22}p_{i21}-p_{i22}p_{21})+p_{i11}p_{22}\,(p_{i22}p_{21}-p_{22}p_{i21})]\, s_{vv}^{(b)}}{(p_{i11}p_{i22}-p_{i12}p_{i21})^2} \\ s'_{vv} = \dfrac{(p_{i12}p_{11}-p_{i11}p_{12})^2 s_{hh}^{(b)} + (p_{i12}p_{21}-p_{i11}p_{22})^2 s_{vv}^{(b)}}{(p_{i11}p_{i22}-p_{i12}p_{i21})^2} \end{cases} \tag{15}$$

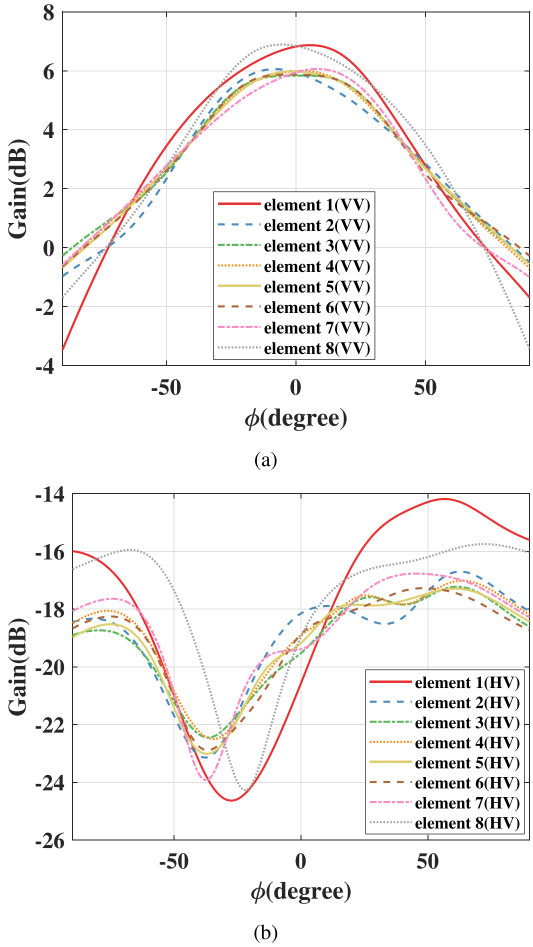

FIGURE 3. The gain of active element pattern of the 8 dual-polarization elements. (a) Co-polarization component. (b) Cross-polarization component.

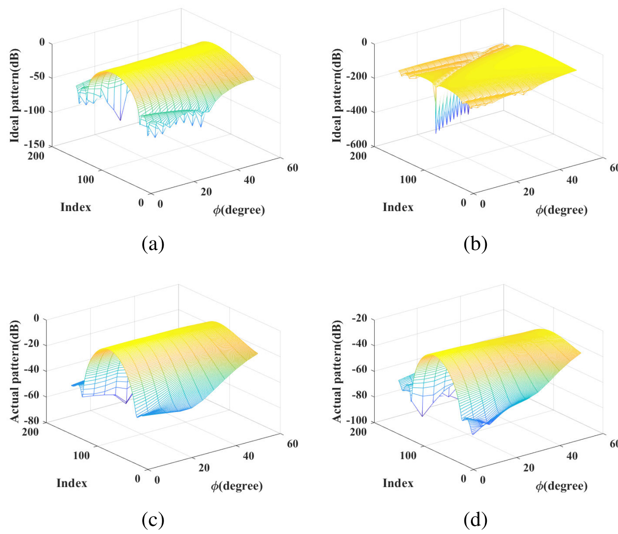

FIGURE 4. The patterns at different beam scanning angles. (a) Co-polarization of the ideal pattern $\mathbf{F}_i$. (b) Cross-polarization of the ideal pattern $\mathbf{F}_i$. (c) Co-polarization of the actual pattern $\mathbf{F}_a$. (d) Cross-polarization of the actual pattern $\mathbf{F}_a$.

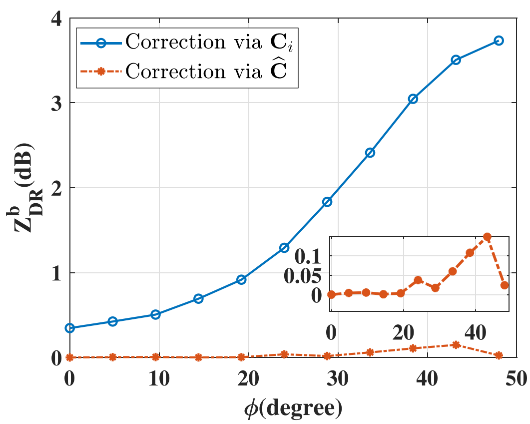

FIGURE 5. The bias of Z_{DR} versus different beam scanning angles.

in Fig.4(a)-(b). Both the co- and cross-polarization pattern at desired beam positions are all involved. The measured patterns in advance are illustrated in Fig.4(c)-(d). Comparison is conducted between the ideal ($\mathbf{F}_i$) and measured ($\mathbf{F}_a$) patterns, and a significant difference exists between $\mathbf{F}_i$ and $\mathbf{F}_a$. For the co-polarization pattern, the gain reduces by 3.34 dB in the boresight direction. Similarly, the cross-polarization deteriorates from −41.85 dB to −25.28 dB considerably. The effect of the mutual coupling and edge diffraction is obvious and distorts the ideal pattern, and the impacts include decreasing the co-polar peak and raising the cross-polar component.

B. BIAS CORRECTION FOR POLARIZATION MEASUREMENT

In order to investigate the polarization measurement bias, several polarimetric variables which represent the relation among the four elements of the PSM can be used. The differential reflectivity (Z_{DR}) is the ratio of horizontal and vertical reflectivities, and the linear depolarization ratio (L_{DR}) is the ratio of horizontal received power to vertical received power in decibels when vertically polarized waves are transmitted. The polarimetric variables are utilized to scale the performance of the proposed reconstruction algorithm.

Fig.5 shows that the bias of differential reflectivity Z_{DR}, given by Z_{DR}^b. If the correction matrix $\mathbf{C}_i$ composed of the theoretical pattern $\mathbf{P}_i$ is used to recover the measured scattering matrix, Z_{DR}^b is greater than 0.35 dB along with the beam scanning range. The bias improves markedly with the increasing of the angle of beam boresight away from broadside (i.e., normal to the array face), and it's up to 3.73 dB when the beam points to 48°. Obviously, it cannot meet the accuracy requirement for polarization measurement. After repairing the correction matrix by using the reconstructed pattern, the bias reduces considerably compared with that without repairing. As manifested in the local detailed figure, the corrected Z_{DR}^b is less than 0.1 dB over most of the scanning angles. It is favorable for the accurate polarization measurement.

The bias of the linear depolarization ratio (L_{DR}) is written as L_{DR}^b for simplicity. The trend of L_{DR}^b across with the increasing scanning angle is illustrated in Fig.6. When the correcting matrix which is composed of the theoretical pattern is used, the L_{DR}^b floats between -35.1 dB and -22.21 dB, and the mean of the biases is -26.98 dB. However, if the bias correction matrix is repaired by reconstructing the desired pattern, L_{DR}^b is less than -46.85 dB over the wide angle range. The requirement of accurate polarization measurement can be satisfied.

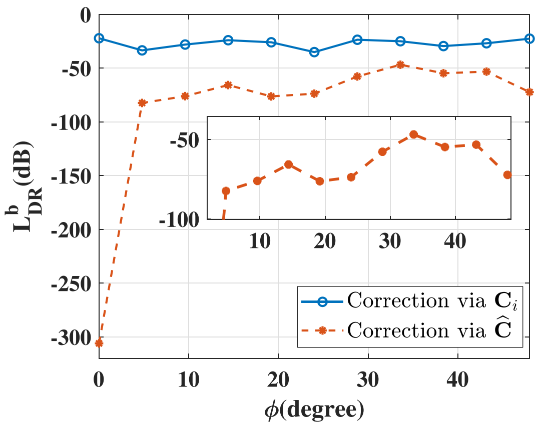

FIGURE 6. The bias of L_{DR} versus different beam scanning angles.

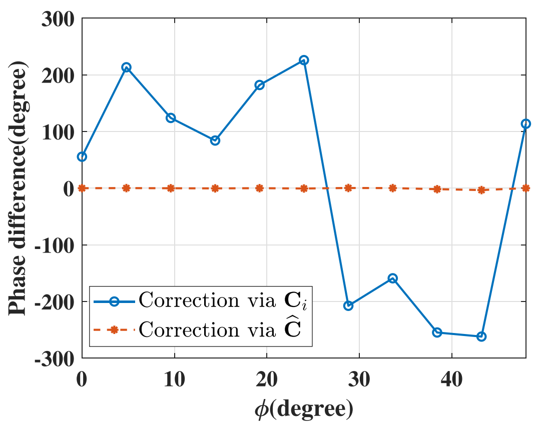

FIGURE 7. The phase difference versus different beam scanning angles.

Similarly, the phases of the four elements of PSM can be corrected. The measured scattering matrix is complex, and the phase is also important for the polarization measurement. Due to that the intrinsic scattering matrix of the target is a unit matrix, the phase difference between the two elements of diagonal terms is analyzed herein, as displayed in Fig.7. The phase difference after bias correction by using the repaired matrix $\widehat{\mathbf{C}}$ is less than 3.31° at different scanning angles. The difference is so small that it can be ignored for the polarization measurement.

IV. CONCLUSION

An effective pattern reconstruction method is proposed to deal with the bias correction for polarization measurement in the polarimetric phased array antenna. The minimum norm least-square solution is adopted to reconstruct the patterns in the presence of mutual coupling and edge effects. The performance of the algorithm is verified by the reconstruction of the actual antenna pattern at some beam positions. The reconstructed pattern coincides well with the desired one which includes the co- and cross-polarization component. After repairing the correction matrix using this proposed method, the polarimetric variables, such as the Z_{DR}^b, L_{DR}^b and the phase difference, reduce considerably. Z_{DR}^b is less than 0.14 dB, L_{DR}^b 46.85 dB and the phase difference 3.31° in a wide scanning angle range, respectively. The reconstruction method could save the pattern measurement time while maintaining the accuracy of the polarization measurement. The simulation results show that the proposed method could satisfy the requirement for accurate polarization measurement.

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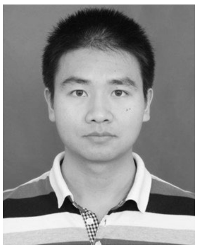

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