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# Pattern Compensation of a Planar Phased Array with Centre Elements Phase Malfunctioning Using a Genetic Algorithm

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**ABSTRACT:** A phase-only and amplitude-phase genetic algorithm (GA) has been investigated to restore the array pattern of a $4 \times 2$ planar array in the presence of centre-elements phase malfunctioning. A single and double adjacent antenna elements are considered for phase malfunctioning. The new array weights for functioning antenna elements are computed with GA to restore the value of array peak gain and sidelobe level (SLL). The simulation results, which are verified with measurements, indicated that complete recovery of array pattern without SLL constraint in the presence of malfunctioning elements was possible with the phase-only GA weights. It is shown that the uncorrected pattern can also be compensated for main beam scanning with phase-only GA weights. However, pattern compensation with SLL constraint is not possible using the phase-only GA weights. Therefore, amplitude-phase GA weights are estimated to restore the peak gain and the desired SLL simultaneously at the cost of widening the main beam. A prototype of X-band $4 \times 2$ microstrip patch array controlled through X-band phaser evaluation boards was used in the in-house anechoic chamber measurements facility to validate the full-wave HFSS simulation results.

## 1. INTRODUCTION

The life cycle cost of antenna in a phased array systems depends on the mean-time-between-failure (MTBF) of active components (attenuators, phase shifters, amplifiers) in transmitting-receiving (T/R) modules. The phased array antenna system consisting of 10,000 elements with MTBF of 100,000 hours for T/R module, will cause probability failure of each T/R module every 10 hours [1, 2]. If this phased array is operated for one year continuously, then 864 of its T/R modules will no longer be working, which is 8.6% of the total antenna array size. The component failure in T/R modules degrades the array pattern, thus reducing the gain and increasing the sidelobe levels. The complete/partial failure of these components is particularly critical for active electronically scanned array (AESA) radar, where precise target detection and interference suppression will be highly compromised. Therefore, hardware replacement of these components for the restoration of array pattern in phased array radar applications, where thousands of antenna elements are populated in a planar array configuration, is not only a costly solution, but in many scenarios, also not even physically releasable. Software methods to compensate radar radiation pattern due to faulty elements are therefore important.

Keeping in view, the increasing importance of phased arrays in radar and communication systems, the research on self-healing arrays in the presence of failed/faulty phase shifters connected to the antenna elements is growing day by day. A number of optimization methods have been devised to restore the original radiation pattern of the array in the presence of defective elements by recalculating the excitation weights (amplitudes, phases) for functional elements. Peters [3] proposed a conjugate-based algorithm to estimate complex amplitude/phase weights on the working elements to control the sidelobe level of planar array with element failures. Liu [4] used Shore's sidelobe sector nulling method for fault correction of a phased array radar antenna. Bu and Daryoush [5] used phase-only excitation method to improve the directivity and sidelobe correction for element failure in a linear array. Wright and Brandwood [6] used least mean square (LMS) algorithm for re-optimization of linear and planar arrays with failed elements. Mailloux [7–9] proposed an iterative algorithm to restore the pattern in case of edge elements failure across the array aperture. The array failure correction with orthogonal method is presented by Zainud-Deen et al. [10]. Meta-heuristic and evolutionary algorithms have also been successfully implemented for the synthesis of linear and planar antenna arrays with failed elements for controlling the sidelobe levels and nulls steering. Antenna array failure correction with genetic algorithm [11–16], particle swarm optimization [17, 18], and simulated annealing [19, 20] has been investigated for finding defective elements and array pattern optimization. Hybrid optimization approaches [21, 22] have also been applied to antenna array failure correction. Artificial neural networks have been studied for fault finding and pattern restoration in linear and planar arrays [23, 24].

In the above referenced literature, two main observations are made: first, most of the literature study is carried out on optimizing the performance parameters of array pattern while con-

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sidering the complete failure of antenna elements. Secondly, the focus is on restoring the array pattern due to edge elements failure. This work is a step to investigate the compensation of radiation pattern of a faulty planar antenna array due to partial failure of centre element(s) instead of considering only the edge elements. The compensation approach is investigated from two different aspects: The first investigation is carried out on a single centre element malfunctioning, whereas the second is on compensating the radiation pattern of the array due to double adjacent centre elements malfunctioning. These investigations are made on a 4×2 planar array for X-band active electronically scanned array (AESA) radar applications. Although the investigations are made on a specific smaller array due to measurements constraints, the findings are equally applicable on larger arrays. In this work, we have used both phase-only and amplitude-phase restoration approaches to compensate the damaged radiation patterns. Both analytical and optimization methods mentioned in the above literature can be used for the compensation process. In this work, we have used the evolutionary optimization genetic algorithm (GA) instead of analytical techniques due to its benefits of generating a larger global solution search space for complex problems. The novelty of this work lies in the application and analysis of GA — specifically in restoring the radiation pattern of an antenna array with a faulty centre-element phase-shifter, where the array weights contribution is more than the edge-elements. Its performance is then compared with that of convex optimization [32]. This problem is particularly challenging due to the complex, potentially non-convex nature of the radiation pattern optimization when being constrained by planar surface geometry and having only a single degree of freedom in phase. The study offers a valuable insight into its practical use in real-world scenarios that involve unpredictable failures in antenna arrays.

The main contributions of this research work are summarized below:

- The genetic algorithm (GA) optimized compensation method for uncorrected $4 \times 2$ planar array pattern due to single centre element phase malfunctioning is formulated. This is an extension of the current available methods for the restoration of damaged array pattern due to edge-element failure.
- The proposed optimization technique is used to compensate the uncorrected pattern of $4\times2$ planar array due to various adjacent centre elements phase malfunctioning. This approach of compensation is highly desired in automatic healing array systems for airborne phased array radars.
- The proposed phase-only GA optimization can be combined with classical amplitude tapering techniques to control the sidelobe level of restored pattern. This capability of GA to compensate the malfunctioning array pattern due to adjacent centre elements partial failure is demonstrated with measurements validation.
- The proposed GA based compensation method can be extended to larger arrays and other array configurations.

The rest of the paper is structured as follows. Section 2 provides a detailed implementation methodology of pattern correction using GA. Section 3 discusses the HFSS simulation results for restoring the pattern due to single and double elements phase malfunctioning. Section 4 provides the measurements validation, and section 5 finally concludes the paper.

## 2. METHODOLOGY

Consider a planar $4\times2$ (4 elements in the $x$ direction and 2 in the $y$) rectangular array with $x$-direction inter-element distance of $dx$ and $y$-direction distance of $dy$ as shown in Fig. 1. The $z$-axis is perpendicular to the plane of the array. The arbitrary phase faulty centre antenna elements are represented with shaded circles and functional elements are shown with unshaded circles. Only the defective element is known, and the hardware structure with self-detection of amplitude-phase fault in transmit-receive module, such as described in [33] can be used as input to the optimizer. The phase error is unknown and is compensated by the optimizer. In this work, the phase faulty antenna element means that any random phase on such element(s) will distort the overall array pattern, resulting in the peak gain loss and increase in the sidelobe level. The cause of random phase on the antenna element is due to the faulty phase shifter in the T/R module connected to the antenna, and its probability is quite high in active electronically scanned array (AESA) radars, where thousands of antenna elements are fed with these T/R modules [2]. The radiation pattern compensation methodology due to phase faulty antenna element(s) using phase-only and amplitude-phase genetic algorithm (GA) is explained in Fig. 2. The original array factor of a $4 \times 2$ planar array is given in Eq. (1) [25].

$$AF = AF_x AF_y \tag{1}$$

where $AF_x$ is the array factor in $x$-direction, and $AF_y$ is the array factor in $y$-direction given in Eqs. (2) and (3), respectively.

$$AF_x = \sum_{m=1}^{M} I_m e^{j(m-1)(kdx \sin\theta \cos\phi + \beta_x)} \tag{2}$$

$$AF_y = \sum_{n=1}^{N} I_n e^{j(n-1)(kdy \sin\theta \sin\phi + \beta_y)} \tag{3}$$

$$\beta_x = -kdx \sin\theta_o \cos\phi_o \tag{4}$$

$$\beta_y = -kdy \sin\theta_o \sin\phi_o \tag{5}$$

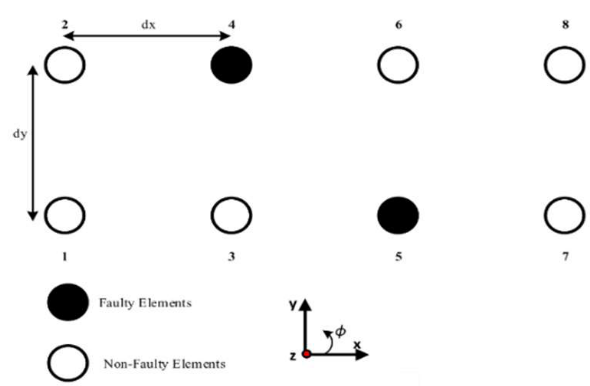


**FIGURE 1**. Schematic of a 4×2 planar array with faulty.

where $\theta \in [0, \pi]$ is the angle from $z$-axis; $\phi \in [0, 2\pi]$ is the angle from $x$-axis; $I_m, I_n$ are the amplitudes. The $\beta_x$ and $\beta_y$ in Eqs. (4) and (5) are the progressive phase shifts required to scan the main beam of the array in $(\theta_o \phi_o)$ direction. The value of wave number $k = \frac{2\pi}{\lambda}$, $dx = dy = \frac{\lambda}{2} = 15$ mm at the operating frequency of 10 GHz in the X-band. The values of $M = 4$ and $N = 2$ for the array in Fig. 1. The steps shown in Fig. 2 are implemented as follows to compensate the uncorrected pattern due to random phase failure on centre antenna elements.

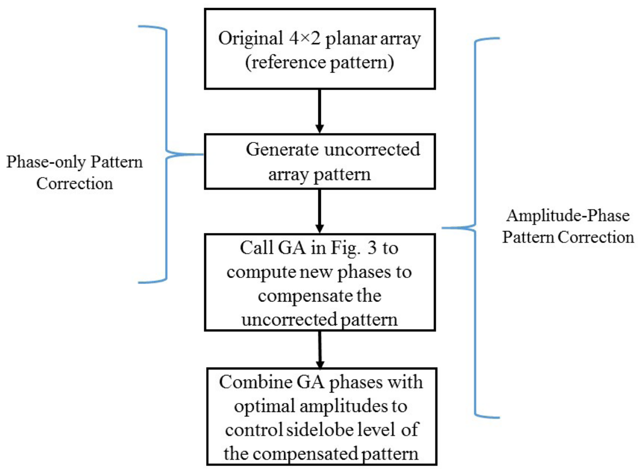


**FIGURE 2**. Pattern compensation mechanism.

**Step 1**: The original pattern in the flowchart of Fig. 2 can be generated in MATLAB using Eq. (1), or it can be simulated in HFSS using the progressive phase shifts computed from Eqs. (4) and (5).

**Step 2**: To generate the uncorrected pattern in the flowchart of Fig. 2, any random phase $\in [-\pi, \pi]$ can be applied on the antenna elements. In this work, random phases on centre elements (3, 4, 5, and 6) in Fig. 1 are considered to generate uncorrected patterns.

**Step 3**: To compensate the uncorrected pattern due to random phase failure on these centre elements, phase-only genetic algorithm (GA) is called. The flowchart to implement the phase-only GA is shown in Fig. 3 and is briefly explained here. More details about GA and its MATLAB subroutines can be found in [26]: The proposed GA is implemented on $M \times N = 4 \times 2$ planar array in MATLAB, and then the obtained optimal/sub-optimal phases are applied on non-faulty microstrip patch antenna elements in HFSS to evaluate the performance of proposed GA in a more practical environment. Let $L$ be the length of the chromosome which corresponds to the number of elements in an antenna array, and $p$ is the population size. Initialize a randomly generated complex-valued population $\mathbf{P}$ as a matrix of size $p \times L$, where each element $\mathbf{P_{i,j}}$ represents the value of the $j$-th gene of the $i$-th chromosome in the population. Each complex-valued chromosome, having both amplitude $I_{m,n} \in [0, 1]$ and phase $\beta_{x,y} \in [0, 2\pi]$ components, acts as a single gene, which represents a particular antenna element in an $M \times N$ element antenna array. For each chromosome in the matrix $\mathbf{P}$, the following cost function in Eq.

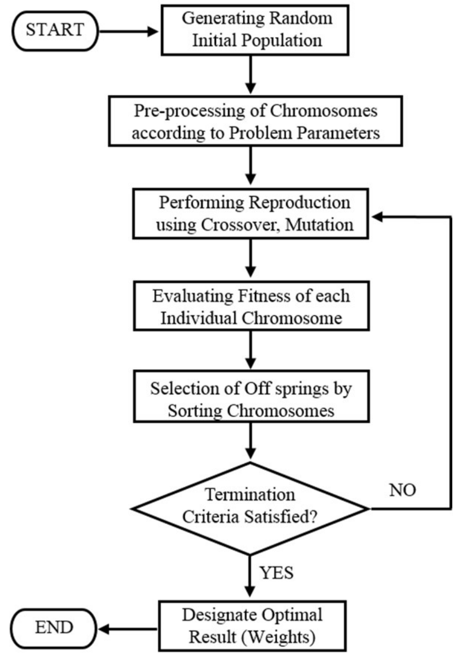


**FIGURE 3**. GA flow chart to compute array weights in the presence of faulty elements.

(6) is minimized for the phase-only pattern compensation.

$$\text{COST}_{\text{phase-only}} = [1 - |AF(\theta, \phi)|]^2 \tag{6}$$

For amplitude-phase pattern correction, the following cost function in Eq. (7) is defined.

$$\text{COST}_{\text{amplitude-phase}} = [|AF(\theta, \phi)| - DSLL]^2 \tag{7}$$

where $AF(\theta, \phi)$ is computed from Eq. (1) for the desired radiation pattern. The region for main beam needs to be defined to compute the cost function using Eqs. (6) and (7), and it is usually within the limits of first-null beamwidth (FNBW). Outside the FNBW, region for the desired sidelobe level (DSLL) is defined [27]. The population size for the given problem was taken as $p = 1000$, cross over rate of 50%, mutation rate of 10% for amplitudes and tolerance of $\pm 3°$ for phases.

## 3. SIMULATION RESULTS

A planar $4 \times 2$ microstrip patch antenna array in Fig. 1 operating at 10 GHz on an RT/duroid 5880 substrate is designed in HFSS simulator with $dx = dy = 15$ mm. The overall electrical size of the array is $1.5\lambda \times 0.5\lambda$. The four centre antenna elements denoted as 3, 4, 5, and 6 in Fig. 1 are considered as phase defective in various combinations for pattern compensation with genetic algorithm (GA). Three radiation patterns are generated in HFSS for pattern compensation of each defective case. The original (reference) array pattern is generated with array weights calculated analytically using Eq. (1). The uncorrected array pattern is generated by adding any random phase to the original phase of defective element under consideration. It was found in simulations that adding 180° phase to the original phases generates maximum distortion in the array pattern, and therefore, it was taken as a faulty phase in this work. The phase error is completely unknown to the optimizer, and an instance

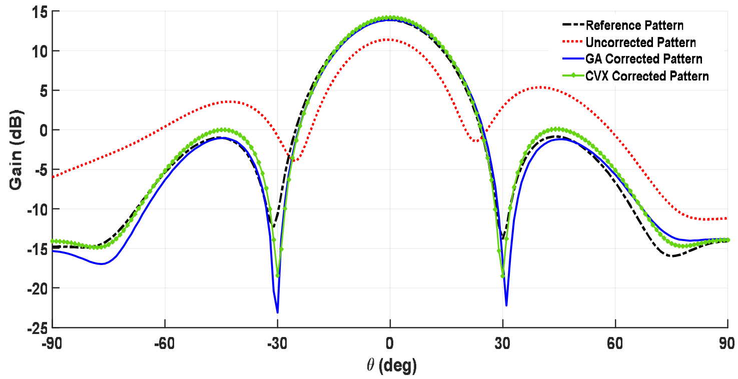


**FIGURE 4**. Simulated broadside pattern correction results for Case 1 with 180° defective phase on centre element No. 4.

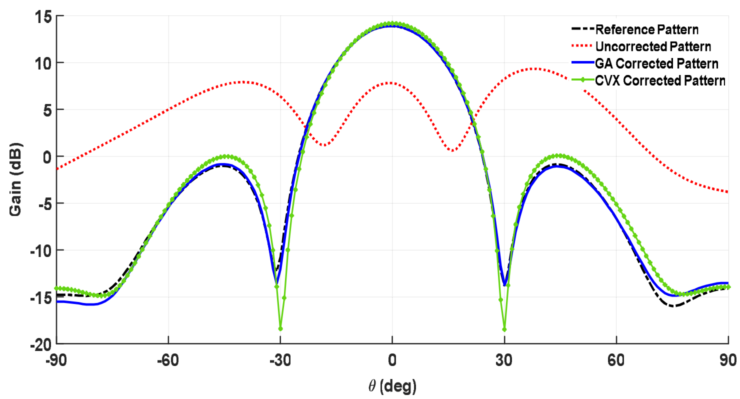


**FIGURE 5**. Simulated broadside pattern correction results for Case 2 with 180° defective phase on adjacent elements (3 & 4).

case of 180 degree phase shift is taken as an example scenario's worst case. The algorithm has been tested with random phase error and works fine. The corrected array pattern against the worst-case scenario of 180-degree phase shift is then generated with new GA estimated weights and is compared with optimal convex (CVX) optimization algorithm [32].

Convex optimization is based on well-defined mathematical frameworks which can be applied to only convex objective functions. It involves calculation of the gradient, Hessian Matrix, and matrix inversion as core operations. The complexity of the convex optimization is given as $O\left(kD^3\right)$, where $k$ is the number of iterations and depends highly on the condition number of the Hessian matrix, and $D = M \times N$ is the dimensionality of the problem. The complexity grows to the cube of problem dimension. Additionally, the main problem with convex optimization is ensuring that the objective function and constraints are convex in nature which in many cases is nontrivial and computationally intensive. On the other hand, GA is a heuristic optimization technique whose complexity depends upon the population $P$, number of iterations $k$, and dimensionality of the problem $D$, with the complexity given by big-O notation as $O\left(kP(D{+}f(D)\right)$ where $f(D)$ is the complexity of the fitness function. For the radiation pattern correction this would grow linearly with $D$. Moreover, GA does not require the problem to be convex, making it suitable for a broader range of optimization problems.

The following three cases of defective elements are considered for pattern correction with GA/CVX optimization. The array weights to plot these results are given in Tables 1, 2, and 3 of the supplementary file.

### 3.1. Case 1: Simulated Broadside ($\theta_o = 0°$, $\phi_o = 0°$) Pattern Correction with Single Centre-Element Partial Failure

In case 1, center-element No. 4 is considered for partial failure to compensate its radiation pattern with phase-only GA weights. The pattern compensation in $xz$ plane for 180° defective phase on element No. 4 (see Fig. 1) is shown in Fig. 4. In this case, 3 dB peak gain and 5 dB peak SLL are restored.

### 3.2. Case 2: Simulated Broadside ($\theta_o = 0°$, $\phi_o = 0°$) Pattern Correction with Adjacent Centre-Elements Partial Failure

In case 2, defective phase of 180° to adjacent center-elements (3 and 4) in $y$-direction is considered for pattern compensation with phase-only GA optimization. The simulated original, uncorrected, and corrected gain patterns in $xz$ plane are shown in Fig. 5. The peak gain recovery is 6 dB, and peak SLL reduction is 10 dB. The recovered patterns exactly follow the original pattern. Similar kinds of pattern compensation results were obtained for malfunctioning adjacent centre-elements (4 & 6) in $x$-direction and diagonal centre-elements (4 & 5) and are not reported here.

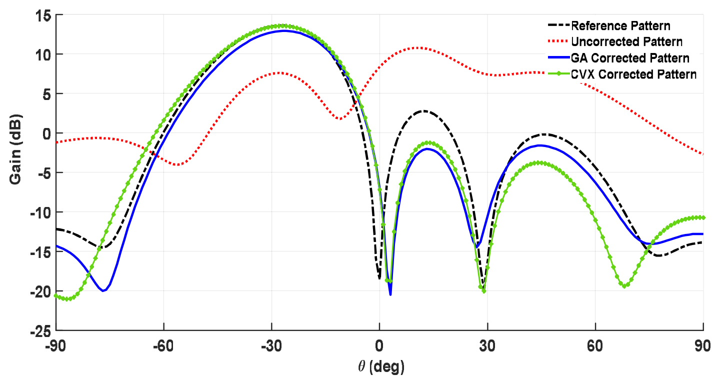


**FIGURE 6.** Simulated scanned pattern correction results for Case 3 with 180° defective phase on adjacent elements (3 & 4).

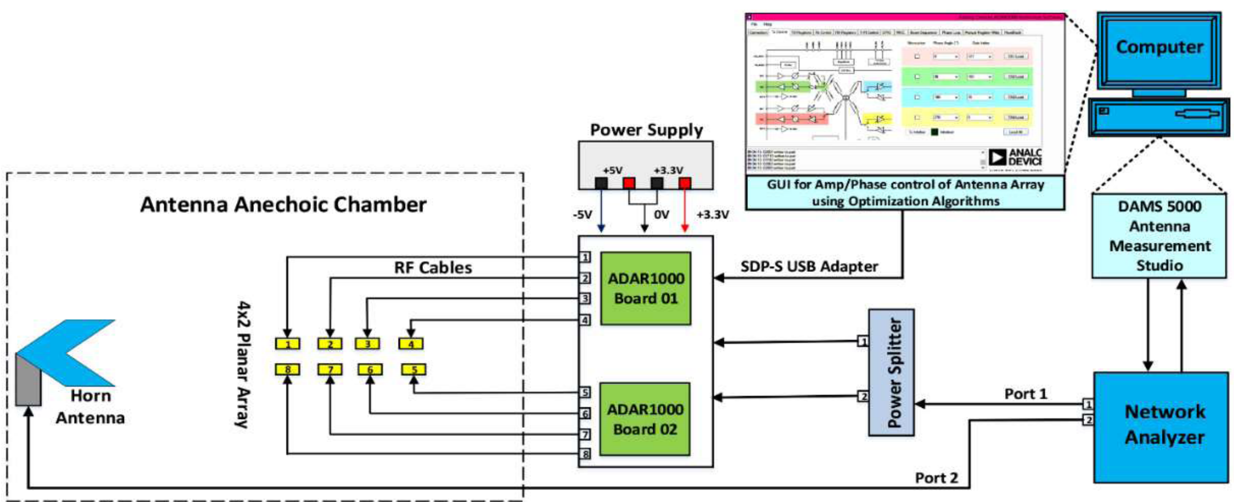


**FIGURE 7.** Block diagram of a measurement setup.

### 3.3. Case 3: Simulated Scanned ($\theta_o = 30^\circ$, $\phi_o = 0^\circ$) Pattern Correction with Adjacent Center-Elements Partial Failure

To demonstrate the capability of proposed pattern compensation method for phased array applications, progressive phase shifts using Eqs. (4) and (5) are calculated for main beam scanning at steering angle ($\theta_o = 30^\circ$, $\phi_o = 0^\circ$). The original, uncorrected and corrected array patterns for 180° defective phase at adjacent elements (3 & 4) in $xz$ plane are shown in Fig. 6. In this case, 5 dB peak gain is recovered with the SLL reduction of approximately 10 dB.

The results in Figs. 4–6 indicate that the phase-only GA can successfully recover the peak gain and decrease in peak SLL of the array pattern for both single and double phase faulty centre antenna elements. The directions of corrected main beam for the two algorithms are the same. However, the broadside peak gain difference between CVX and GA corrected patterns is 0.35 dB with the peak SLL of GA corrected pattern 0.82 dB lower than CVX pattern. For corrected scanned pattern, the peak gain difference is 0.7 dB, while the peak SLL is $-14.7$ dB for both the algorithms. The control of desired SLL with amplitude-phase GA weights for phase faulty array is discussed in the next section.

## 4. MEASUREMENT RESULTS

The block diagram of the measurements setup is shown in Fig. 7. The network analyzer generates 0 dB X-band radio frequency (RF) signal, which is equally split by the X-band power splitter. The output RF signals of power splitter are fed to the X-band amplitude/phase beamforming boards (ADAR1000). These boards control genetic algorithm (GA) computed amplitudes and phases of RF signal through the GUI software. The individual antenna elements of X-band 4×2 planar array are excited with the GA computed weights (provided in the supplementary file). The radiation patterns are measured using Diamond$^{\text{TM}}$ Engineering automated measurement system, Agilent network analyzer, and a standard horn antenna (as receiver). or measurements setup, the X-band Vivaldi $4 \times 4$ planar array [28] and Analog Devices ADI$^{\text{TM}}$ X/Ku band amplitude/phase evaluation boards (ADAR1000) [29] are considered. The two rows of antennas in $4 \times 4$ array are connected with 50 Ω terminators to configure it for a $4 \times 2$ array pattern measurements as shown in Fig. 8(a). The 8 RF inputs of the antenna elements (numbered as 1, 2, …8) are connected with 8 outputs of the two amplitude/phase evaluations boards through RF cables as shown in Figs. 8(b) and 8(c). For consistency, the numbering scheme (1, 2, …8) on the antenna elements in Fig. 8

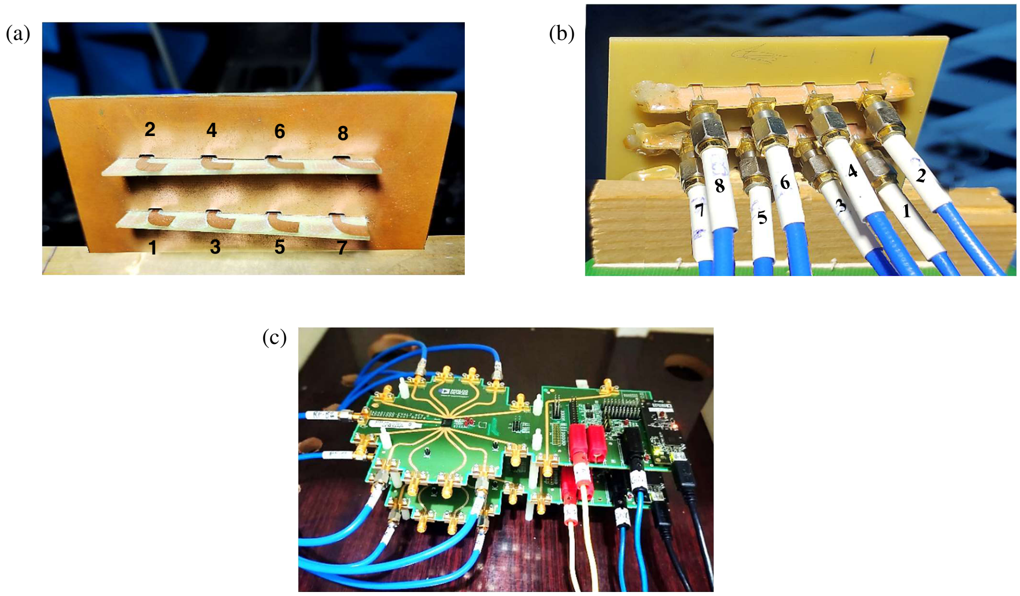


**FIGURE 8**. Measurements setup for a 4×2 planar array in the in-house anechoic chamber with ADI™ amplitude/phase evaluation boards. (a) Front view of X-band 4×2 Vivaldi planar array. (b) Back view of 4×2 planar array. (c) ADAR-1000 evaluation boards.

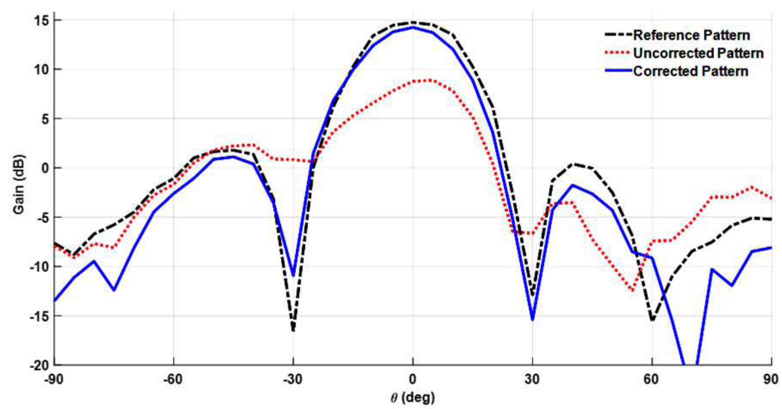


**FIGURE 9**. Measured broadside pattern compensation using phase-only GA weights with centre-element No. 4 phase defective.

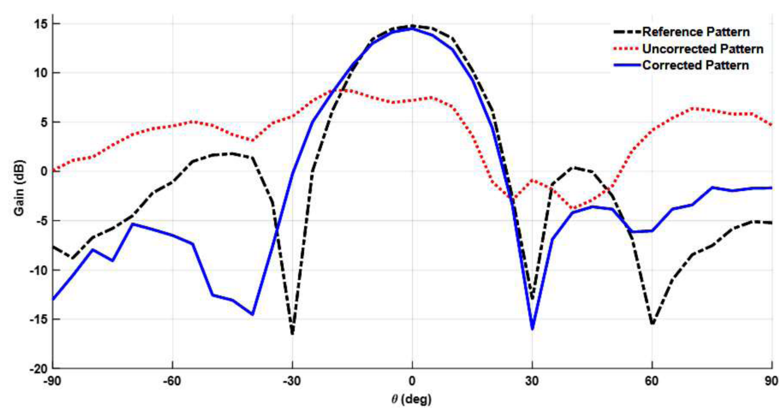


**FIGURE 10**. Measured broadside pattern compensation using amplitude-phase GA weights with adjacent-elements (3 & 4) phase defective.

is the same as that shown in Fig. 1. Three cases with 180° phase defective as discussed in simulations are tested in measurements: First is the broadside pattern compensation with centre-element No. 4 phase defective using phase-only GA restoration; the second is the broadside pattern compensation with adjacent elements (3 & 4) phase defective using amplitude-phase GA restoration for 25 dB SLL; and the third one is the 30° scanned pattern compensation with adjacent elements (3 & 4) phase de-

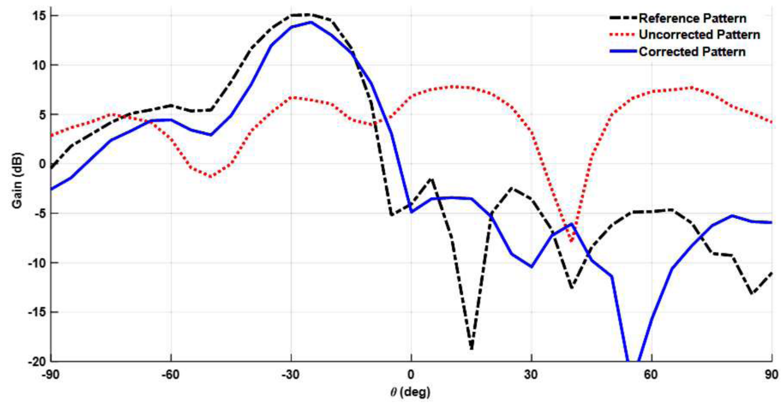


**FIGURE 11**. Measured 30° scanned pattern compensation using amplitude-phase GA weights with adjacent-elements (3 & 4) phase defective.

fective using amplitude-phase GA restoration for 25 dB SLL. The original, uncorrected and corrected radiation patterns were measured in an in-house anechoic chamber measurements facility [30], and the measured patterns are shown in Figs. 9–11. In Fig. 9, the broadside corrected pattern with phase-only GA weights closely follows the original (reference) pattern, and its restoration behavior is similar to the simulated results in Fig. 4. In Figs. 10 and 11, approximately 20 dB sidelobe levels relative to the peak gain are achieved in the recovered array patterns with amplitude-phase GA weights at the cost of widening the main beam. The GA estimated array weights used in measurements are given in Tables 4, 5, and 6 of the supplementary file. The complete video link of the prototype measured in the in-house anechoic chamber is provided in [31]. The measured corrected pattern results in Figs. 9–11 are not in complete agreement with the original (reference) patterns as compared to the simulated results in Figs. 4–6. This is due to the 2.8° inherent phase error in the phaser boards and lacking of perfect phase symmetry for all 8 individual amplitude/phase channels. However, the measured pattern results follow the simulated behaviour of corrected patterns. This validates the pattern compensation capability of proposed GA for faulty planar phased arrays.

## 5. CONCLUSION

An array pattern compensation technique based on genetic algorithm for centre-elements partial failure in a planar array has been investigated. Some concluding observations from the investigation are given below.

- A complete recovery of the array pattern was made with phase-only GA weights, without the constraint on sidelobe level control. This was observed for both single centre antenna element and double centre-element partial failures.
- With GA weights (amplitude-phase), desired sidelobe level and peak gain of the planar array with partially failed centre elements were recovered at the cost of widening the main beam.

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