

Rectangular Grid Antennas with Various Boundary Square-Rings Array

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Abstract—Rectangular grid antennas are widely used in practice due to their advantages and versatility. This paper simplifies the design procedures of such antennas by optimizing their radiation characteristics using minimum number of the optimized elements while maintaining the same performance. The method consists of partitioning a fully square grid array into two unequally sub-planar arrays. The first one contains the inner and the most central elements of the initial planar array in which they are chosen to be non-adaptive elements, while the remaining outer and boundary elements which constitute L number of the square-rings are chosen to be adaptive elements. Then, the optimization process is carried out on those outer rings instead of fully planar array elements. Compared to a standard $N \times M$ planar array with fully adaptive elements, the number of optimized elements could be reduced from $N \times M$ to $2\{2L(N - L)\}$, so as to significantly reduce the system cost without affecting the overall array performance. Results of applying the proposed method to optimize a small 9×9 , medium 20×20 , and large 40×40 size planar arrays with various values of L are shown.

1. INTRODUCTION

Many applications of antenna arrays have been found in the military and civilian communication systems such as radars, satellites, and wireless communications, to name just a few. In all of these applications, antenna arrays play an important role in fulfilling the increasing demands such as directivity improvement, interference reduction, spatial filtering, and direction of arrival estimation [1]. In practice, two-dimensional planar arrays are more preferable than simple one-dimensional linear arrays because they could carry out the pattern formulation and optimization in both azimuth and elevation planes. However, the standard fully controllable planar arrays contain many design variables such as amplitude and/or phase excitations [2–4], element locations [5, 6], and the array geometry which add extra costs and undesirable complexity in the feeding network.

In the array pattern optimization with some desired constraints such as low sidelobe level, narrow beam width, and controlled nulls, many of the design parameters could be saved by choosing their values non-adaptive [7–10]. Other techniques include the use of thinning process especially for the large planar arrays where the optimization processes are slow and difficult [11–16]. To overcome such problems, many researchers suggested using analytical methods rather than complex optimization based-iterative methods [17–19]. However, the uses of analytical methods are limited, and nowadays most of the array designing methods use evolutionary algorithms which have been proved as powerful tools [20, 21].

To simplify the implementation of large arrays, many of the redundant degrees-of-freedom (or variable array elements) could be removed from the optimization process without affecting the overall array performance [22]. Also, many other advantages can be obtained such as faster response, less vulnerability to the element failures, and less RF components. Therefore, antenna arrays with a smaller number of optimized elements are of great research importance in practice.

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In this paper, a general simplified strategy for the design and optimization of the standard rectangular grid arrays is presented. The elements of the fully rectangular planar array are first partitioned into two unequally and dissimilarly sub-planar arrays. The inner sub-planar array which contains the elements having less impact on the radiation pattern re-configurability is chosen to be non-adaptive, while the outer sub-planar array elements which have a great impact on the reconfiguration of the array pattern are chosen to be adaptive. Then, the optimization process (or updating weights) is carried out on the outer square-rings instead of fully controllable planar array elements. The genetic algorithms in conjunction with the amplitude-only and phase-only weighting controls are used to optimize the element excitations in adaptive outer square-rings. Moreover, the method can be applied to obtain various boundary array configurations such as a single square-ring, multiple square-rings, or any other shapes.

2. PRINCIPLES OF THE PROPOSED METHOD

2.1. Fully Rectangular Planar Array

Consider a fully planar array with N rows and M columns of isotropic elements arranged along a rectangular grid having uniform inter-element spacing in both x and y directions, $d = d_x = d_y = \lambda/2$. To get symmetric elements about the origin, we assume that the numbers of rows and columns are equal, $M = N$. The initial planar array with dimension $N \times N$ is then partitioned unequally and dissimilarly into two sub-planar arrays. The first one is an inner sub-planar array which could be in the shape of a smaller square sub-planar with dimension less than that of the initial fully planar array, and its elements are chosen non-adaptive. The second one is the outer sub-planar array with L square-rings whose elements are adaptive, and they have much impact on the overall array pattern reconfiguration. Thus, they need to be optimized to generate the required radiation characteristics. Fig. 1(a) shows the standard fully filled planar array with dimension $N \times N$. The array factor as a function of both azimuth, ϕ , and elevation, θ , angles of this array can be expressed by:

$$AF_{filled}(u, v) = \sum_{n=1}^N \sum_{m=1}^N W_{nm} e^{j \frac{2\pi d}{\lambda} [(n-1)(u+v)]} \quad (1)$$

where $u = \sin(\theta) \cos(\phi)$, $v = \sin(\theta) \sin(\phi)$, and W_{nm} is the complex weighting of the initial planar array, thus, it could be amplitude-only (i.e., $|W_{nm}| \angle 0^\circ$) and/or phase-only (i.e., $1 \angle W_{nm}$). Here in this paper, both the amplitude-only and phase-only weighting excitations will be examined with the proposed array configurations. Fig. 1 shows some suggested configurations for the inner and outer sub-planar arrays. These configurations include: inner square sub-array with a single or multiple outer square-rings arrays, or any other configurations.

2.2. Outer Square-Rings Array

In this configuration, the element weights of the inner sub-planar array are considered non-adaptive, and their magnitudes and phases are set to be equal to those of the initial fully planar array weights, while the element weights of the outer square-rings are set to be adaptive. Thus, the numbers of fixed and adaptive elements in inner and outer sub-planar arrays are $(N - 2L) \times (N - 2L)$, and $2L(N - L) + 2L(N - L)$, respectively, where L represents the number of outer square rings. The array factor of Eq. (1) can be rewritten to express such a configuration

$$AF(u, v) = \underbrace{\sum_{n=1}^{N-2L} \sum_{m=1}^{N-2L} A_{nm} e^{j \frac{2\pi d}{\lambda} [(n-1)(u+v)]}}_{\text{inner sub-planar array}} + \underbrace{\sum_{n=N-2L+1}^N \sum_{m=N-2L+1}^N B_{nm} e^{j \frac{2\pi d}{\lambda} [(n-1)(u+v)]}}_{\text{outer square-rings array}} \quad (2)$$

where A_{nn} and B_{nn} are the elements weights for the inner and outer sub-planar arrays, respectively. From Eq. (2), the values of A_{nn} in the inner sub-planar array are non-adaptive, and they should be frozen during the optimization process of the updating weights, i.e., $A_{nn} = W_{nn}$ for $n = 1, 2, \dots, N - 2L$, while B_{nn} are adaptive, and they need to be optimized to produce the required radiation pattern with pre-specified constraints. The genetic algorithm is used to perform the optimization process to find the best solution that fulfils the pre-specified constraints.

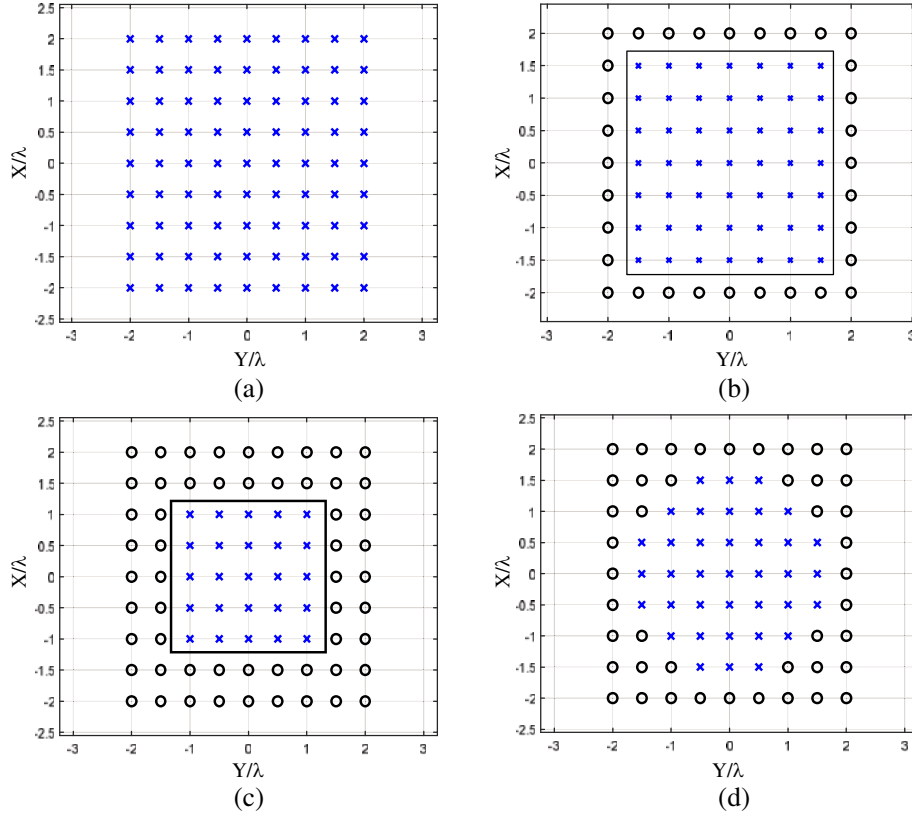


Figure 1. Proposed configurations, (a) fully planar array, (b) single outer square-ring, (c) two outer squareCrings, (d) other outer shape.

To enforce the optimizer to update only the values of B_{nn} , we introduced an updating weighting function that will be applied to the initial planar array weights during the optimization process

$$W_{nn} = \begin{cases} A_{nn} & \text{if } 1 \leq n \leq N - 2L \\ B_{nn} & \text{if } N - 2L + 1 \leq n \leq N \end{cases} \quad (3)$$

Fig. 1(c) shows the formulation of two square-rings, i.e., $L = 2$, and an array of size 9×9 . In this case, the numbers of the non-adaptive and adaptive elements are 25 and 56, respectively. Notice that when selecting a single square-ring, $L = 1$, the number of adaptive elements located on the perimeter of the planar array is found to be 32 which is not enough to provide sufficient degrees of freedom to fulfill the required constraints on the array pattern.

The cost function used to optimize only the elements of the outer square-rings minimizes the difference between the desired array pattern according to the required constraint mask and the pattern generated from the updated weights. The constraint mask controls the width and direction of the desired nulls, peak sidelobe level, and the width of the main beam. The optimization process starts with the initial uniform planar weighting W_{nn} . The lower and upper limits of the adaptive weights are bounded between $0 \leq B_{nn} \leq 1$. The cost function according to the given constraint bounds can be described by

$$\text{cost} = \sum |AF(u_s, v_s) - \text{Mask Limit}|^2 \quad (4)$$

where $AF(u_s, v_s)$ represents the magnitude of the sidelobe pattern of the array factor of Eq. (2). The cost according to Eq. (4) minimizes the sidelobe magnitudes that exceed the constraint bound. Clearly, better solution can be obtained with lower cost. Each pattern point of $AF(u_s, v_s)$ that lies outside the specified mask limits contributes a value to the cost function equal to the power difference between the desired constraint mask and the resultant array pattern.

3. SIMULATION RESULTS

To illustrate the effectiveness of the proposed array configurations, various scenarios under different numbers of array elements (or array sizes) are demonstrated. In all scenarios, the main parameters of the genetic optimization algorithm are set to: selection was roulette; population size was set to 20; mutation rate was 0.15; crossover was single point; mating pool was set to 4. The amplitude-only weighting and phase-only weighting methods are used separately to find the optimized values of the adaptive elements excitations in the outer square-rings array. The lower and upper bounds of the adaptive elements were set to 0 and 1 for amplitude-only method, and $-\pi/2$ and $\pi/2$ for phase-only method. As mentioned earlier, all the considered planar arrays are assumed to be square with dimension $N \times N$. The performance in terms of directivity, taper efficiency, main beam control, null control, sidelobe level control, computational complexity (i.e., the number of the adaptive elements with compared to the fully optimized array elements), and the response time of the optimizer for the proposed array configurations depicted in Fig. 1 are examined.

In the first scenario, a square grid with size 9×9 elements is considered. To find the optimized values of the adaptive elements according to Eq. (3), amplitude-only weighting method is used where the phases are set to 0. The amplitude values of the inner sub-planar array elements are enforced to be ones during the optimization process. Fig. 2 shows the fixed and optimized element excitations. Exact amplitude values of such a case are listed in Table 1. The computational complexity (i.e., the number of optimized elements with respect to that of the fully optimized planar elements) of the proposed array is found to be 69.13% which is lower than that of the fully optimized planar array by 30.86%. The

Table 1. Element excitations of the proposed planar array.

W_{nn}	n_1	n_2	n_3	n_4	n_5	n_6	n_7	n_8	n_9
n_1	0.0773	0.1783	0.2781	0.2781	0.2781	0.2781	0.2781	0.1779	0.0773
n_2	0.1783	0.4109	0.6410	0.6410	0.6410	0.6410	0.6410	0.4101	0.1783
n_3	0.2781	0.6410	1.0000	1.0000	1.0000	1.0000	1.0000	0.6397	0.2781
n_4	0.2781	0.6410	1.0000	1.0000	1.0000	1.0000	1.0000	0.6397	0.2781
n_5	0.2781	0.6410	1.0000	1.0000	1.0000	1.0000	1.0000	0.6397	0.2781
n_6	0.2781	0.6410	1.0000	1.0000	1.0000	1.0000	1.0000	0.6397	0.2781
n_7	0.2781	0.6410	1.0000	1.0000	1.0000	1.0000	1.0000	0.6397	0.2781
n_8	0.1779	0.4109	0.6397	0.6397	0.6397	0.6397	0.6397	0.4092	0.1779
n_9	0.0773	0.1783	0.2781	0.2781	0.2781	0.2781	0.2781	0.1779	0.0773

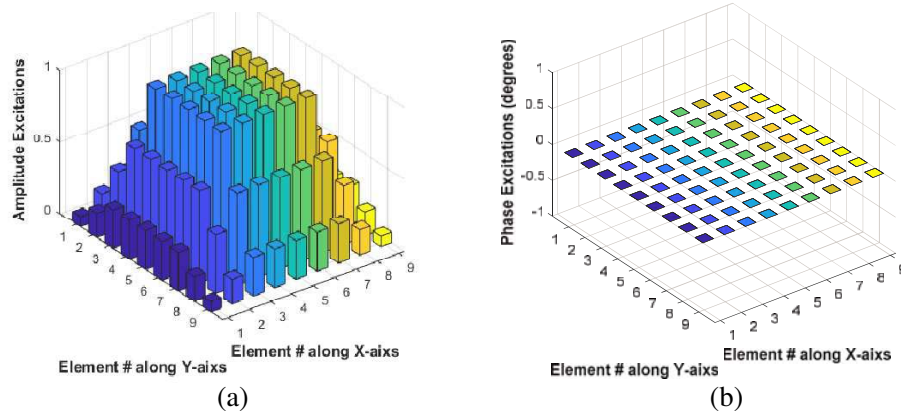


Figure 2. (a) Amplitude and (b) phase excitations of the proposed array for $L = 2$ rings and $N \times N = 9 \times 9$ elements.

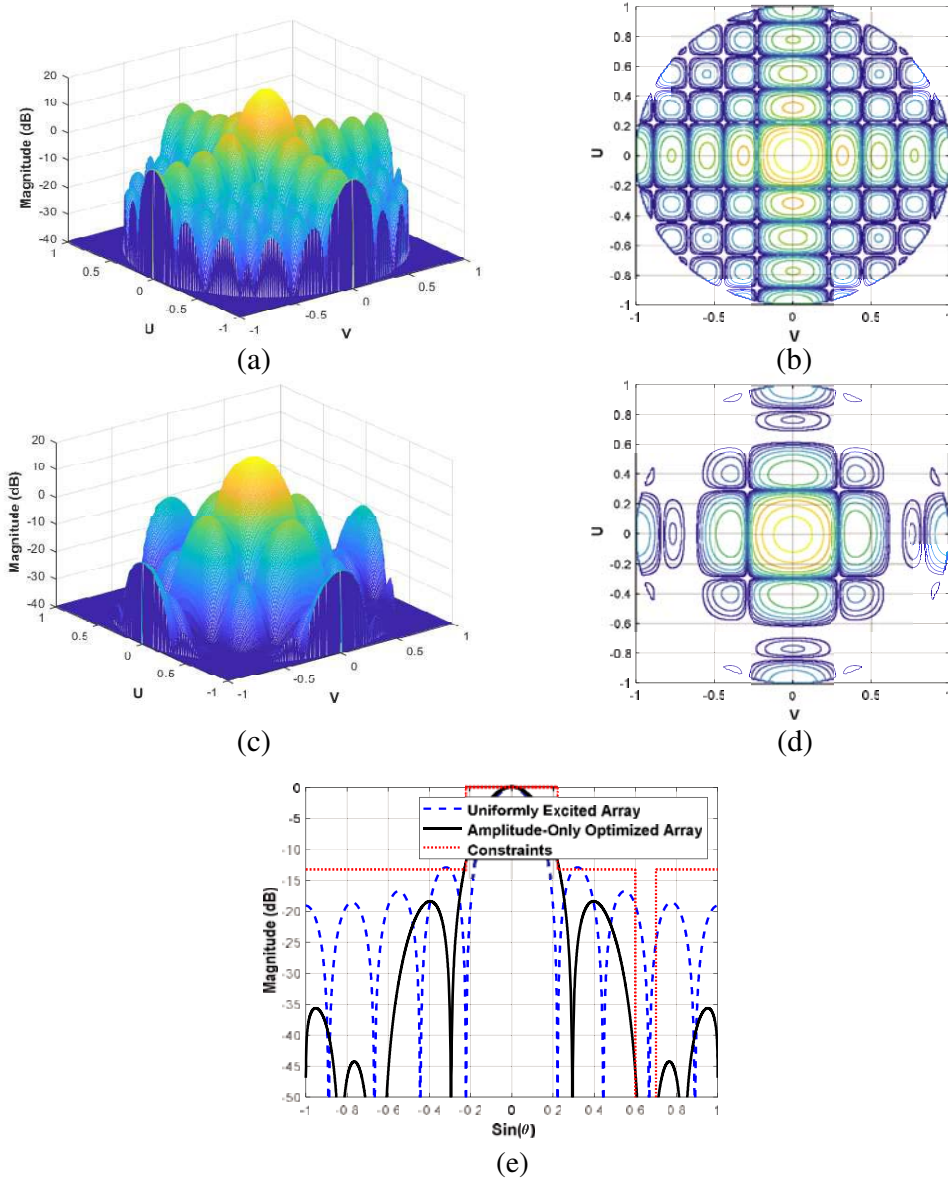


Figure 3. (a) and (b) Three-dimension results for 9×9 elements, standard uniformly excited planar array, (c) and (d) proposed array with optimized two square-rings, (e) 2D arrays patterns.

three- and two-dimension radiation patterns of the proposed planar array and the standard uniformly excited planar array with their corresponding contours are shown in Fig. 3. Here, the mask constraint was enforced to place a wide null from $(u, v) = (0.6, 0.6)$ to $(u, v) = (0.7, 0.7)$ with a depth equal to -60 dB; peak sidelobe level should not exceed -13.23 dB in both u and v planes, main beam pointing at $(u, v) = (0, 0)$; and the first null-to-null beam width should not exceed $(u, v) = (0.22, 0.22)$.

It can be seen that the proposed array with two optimized square-rings is capable to accurately fulfill all the desired constraints mask. For comparison purpose, the results of the fully optimized 9×9 planar array under the same condition as previous are shown in Fig. 4. It can be seen that the obtained patterns from the proposed array and the fully optimized planar array are both able to accurately meet the desired constraints mask.

In the second scenario, a larger planar array with size of 40×40 elements is considered. Again,

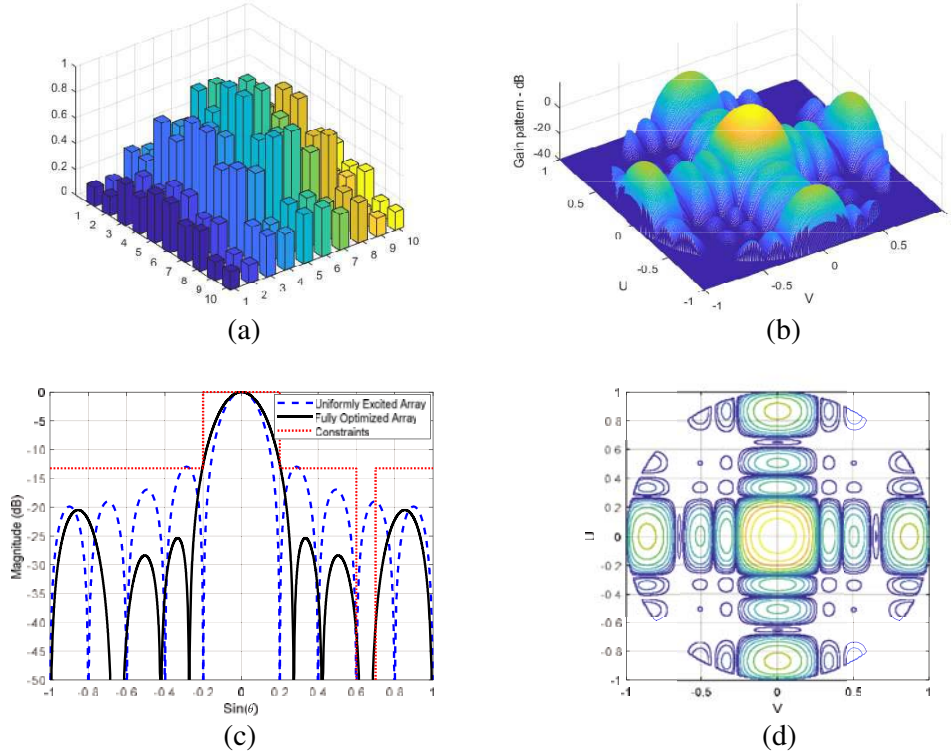


Figure 4. Results of the fully optimized planar array for 9×9 elements, (a) amplitude excitation, (b) 3D plot, (c) 2D plots, and (d) contour.

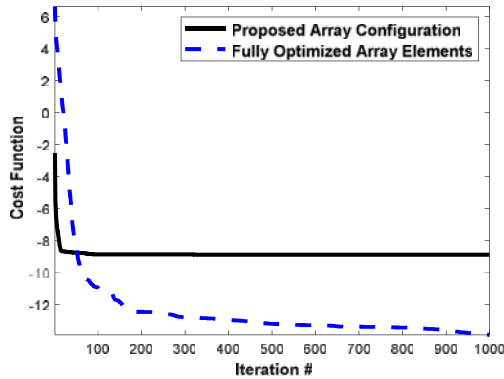


Figure 5. Convergence times of the two tested arrays.

only the elements on the two outer rings are considered to be adaptive. Also, same constraints as before are applied, and phase-only weighting method is used. In such a large array, the response time (or convergence speed) of the optimizer is very important where the shorter response results in a better tracking and processing. Fig. 5 shows the average response times of the GA optimizer in the proposed array and the fully optimized planar array. For fair comparison, the same parameters are used for both tested arrays except the number of optimized elements where all elements are assumed to be adaptive in the fully optimized array. It can be seen that the response time of the proposed array is shorter than that of the fully optimized array. Also, the computational complexity of the proposed array is found to be much lower than that of the fully optimized planar array by 76.54%. For 40×40 case, the numbers of non-adaptive and adaptive elements are 1296 and 304, respectively. A very important point can be noticed that the larger the size of the considered planar array is, the better the reduction is in

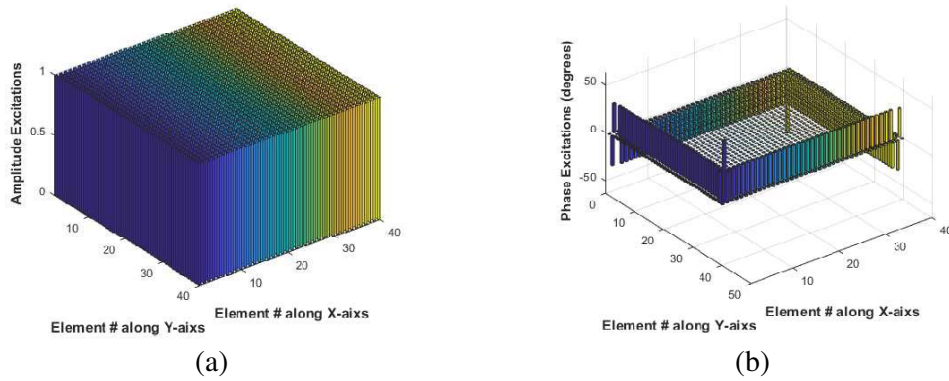


Figure 6. Phase-only control of the proposed array with optimized two square-rings for 40×40 elements, (a) amplitude and (b) phase.

the computational complexity.

The fixed and optimized element excitations of the proposed planar array are shown in Fig. 6, and the corresponding three- and two-dimension radiation patterns with their corresponding contours are shown in Fig. 7. From Fig. 6, again a very important point related to the practical implementation can be noticed that most of the optimized phases have only four values. Consequently, only four phase shifters will be needed to implement the feeding network in such a large array. This is really a very simple and practical solution.

Finally, the effect of the number of adaptive elements in the square-rings, L , on the directivity, taper efficiency, peak sidelobe level, half power beam width, and the computational complexity are investigated. For this case, an array with size 20×20 is considered, and the constraint mask was set so that the peak side lobe level in the proposed array pattern should not exceed -20 dB. The results are shown in Table 2. It can be seen that the directivity and taper efficiency are reduced with increasing value of L . On the other hand, the HPBW and complexity are increased with increasing value of L .

Table 2. Performance indicators versus number of the square-rings, L , for 20×20 array elements and amplitude-only control method.

Number of square-rings, L	Directivity (dB)	Taper efficiency	Peak side lobe level (dB)	Half power beam width (in u plane)	Computational complexity %
Standard uniformly excited planar array					
	27.07	1	-13.23	0.088	0
Proposed planar array with optimized square-rings array					
1	26.94	1.15	-13.5	0.092	19
2	26.57	1.28	-15.5	0.097	36
3	26.22	1.72	-18.0	0.100	51
4	25.27	2.47	-20.0	0.114	64
5	26.42	2.23	-20.7	0.102	75
6	25.29	2.98	-21.0	0.117	84
7	25.78	2.84	-22.0	0.110	91
8	23.59	5.36	-26.3	0.114	96
9	25.43	6.05	-27.3	0.114	99
Fully optimized planar array, i.e., $L = N/2$					
10	26.02	3.95	-26.5	0.105	100

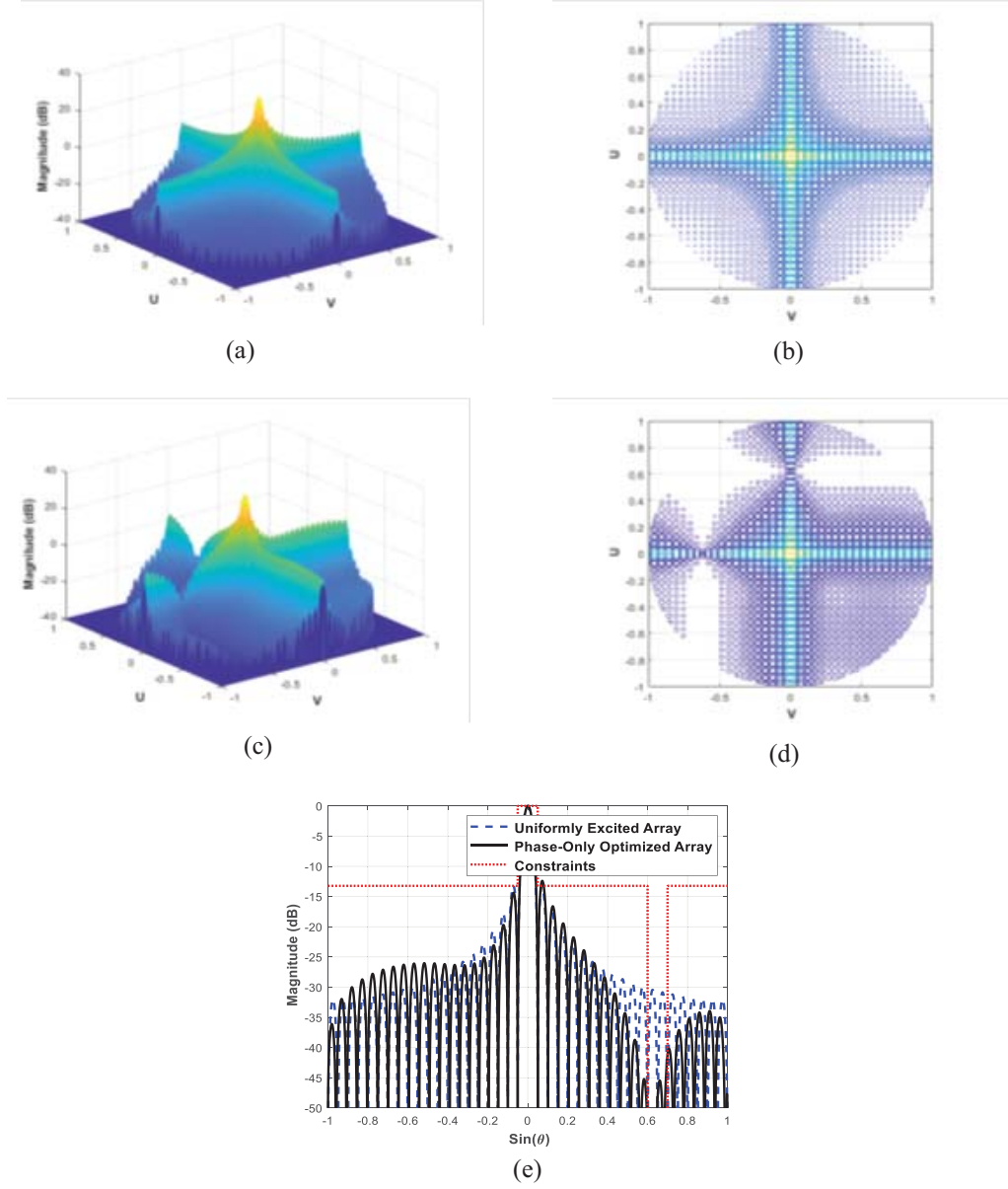


Figure 7. Three-dimension results for 40×40 elements, standard uniformly excited planar array (a) and (b), proposed array with optimized two square-rings (c) and (d), 2D arrays patterns (e).

Also, starting from $L = 4$, the required side lobe level according to the constraint mask was completely fulfilled. Note that for larger arrays, a smaller value of L may be needed. Thus, an excellent performance can be obtained with a proper value of L .

4. CONCLUSIONS

It has been shown that the optimization, design, and implementation procedures of the standard rectangular grid arrays can be drastically simplified by the proposed method while maintaining the same performance. The proposed method was applied to an initial $N \times M$ planar grid array to partition it into two different sub-planar arrays.

The number of fixed (or non-adaptive) elements in the inner sub-planar array was found to be $(N - 2L) \times (N - 2L)$, while the number of optimized elements in the adaptive outer sub-planar array

was $2L(N - L) + 2L(N - L)$. Thus, the computational complexity was reduced significantly without affecting the array performance. Moreover, the directivity and taper efficiency of the proposed array were found to be very close to that of the standard uniformly-excited planar array under small values of L . In addition, the required width and depth of the desired nulls in the proposed array pattern were found to be comparable to those that could be generated by the fully optimized planar arrays. Results showed that for the large planar arrays and with phase-only weighting control, the number of needed phase shifters was limited to only four which is really a very simple and practical solution.

The method could be directly extended to the concentric circular arrays where the elements of the outer circular rings may be chosen as adaptive variables for pattern optimization.

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