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A Method for Thinning Useless Elements in the Planar Antenna Arrays

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Abstract—In this paper, the thinning space is constrained to only outer sub-planar array elements instead of fully filled planar array. Since the amplitude weights of the outer elements have small amplitude excitations, they can be optimized to find the least useful elements and remove them without affecting the desired radiation characteristics. The binary genetic algorithm is used to perform such thinning optimization. Simulation results show that roughly the same performance can be achieved when the number of removed elements in the outer sub-array relative to the total number of the planar array elements does not exceed 19%. In addition, to keep the size of the thinned array equal to that of the original filled array, the perimeter elements were excluded from the thinning process. Also, some constraints on the thinned array pattern are imposed to control the null directions toward interfering signals.

1. INTRODUCTION

Generally, thinning antenna arrays, i.e., turning off some of the radiating elements for the purpose of getting lower cost and weight, is associated with undesirable changes in the radiation patterns such as high side lobe levels and low gains. Traditionally, the high side-lobe levels in thinned arrays have been solved by using either analytical or statistical density tapering methods [1, 2], where the densities of the active elements are calculated using amplitude excitations of the original filled array. Another approach to reduce the high side-lobe levels in the thinned arrays includes the use of amplitude quantization [3].

Recently, an iterative fast two-dimensional Fourier transform (FFT) [4] is suggested to select the active elements whose amplitude excitations meet the corresponding required side-lobe pattern and controlled nulls. Also, various nature-based optimization methods, such as genetic algorithm [5], particle swarm optimization [6, 7], ant colony optimization [8], Taguchi optimization method [9], and Galaxy based search [10] to name just a few, were also used to optimize the radiation patterns of the thinned arrays. In all of these aforementioned approaches, all the array elements were examined through many trials, and then, the best combination of active and inactive elements that approximates the desired radiation characteristics was found. Thus, they are generally time consuming, and their solutions are not easy to be implemented in practice due to the need for large number of RF components. As an example, consider a large planar array with 40×40 elements, where there are 2^{1600} possible searching combinations. Thus, simpler techniques with smaller or restricted searching spaces are currently of great research importance in practice [11–16].

Very recently, an elegant method was introduced and applied to the rectangular grid antennas with various boundary square-rings array [17]. This method is then extended to the rectangular planar arrays with circular boundaries for side-lobe suppression [18].

On the other hand, the problem of synthesising complex array antennas has been successfully solved by using an alternative strategy based on resonant cavity antennas fabricated from all metal structures

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with a simple feeding network as explained in [19] or hybrid materials as explained in [20]. Further, the directivity of these antennas was improved by suggesting a 3D-printed phase-rectifying transparent superstrate.

In this paper, the thinning process is performed only on the outer sub-planar array elements instead of full planar array elements where the considered arrays are first partitioned into inner and outer sub-planar arrays depending on their amplitude weights. For nonuniform amplitude distributions, the inner sub-planar elements have high amplitude excitations, while the outer sub-planar elements have small amplitude excitations. Thus, some outer elements with small amplitudes can be turned off or removed without significant changes in the desired radiation characteristics. A binary genetic algorithm is used to optimally remove a number of useless elements in an outer sub-planar array such that the overall array performance is not reduced too much compared to that of the fully filled planar array. Unlike the existing thinning methods, the majority of the elements that belong to the inner sub-planar array are kept unchanged, thus, the proposed thinned array enjoys many advantages such as the lowest searching combinations, faster response time, simple feeding network, and low cost. Moreover, to keep the size of the resulting thinned array equal to that of the original filled array, the elements located on the planar array perimeter are excluded from the thinning process. Therefore, the beamwidth of the proposed array is approximately equal to that of the original filled array. Furthermore, some desired nulls at interference directions can also be placed with the proposed thinned planar array.

2. PRINCIPLES OF THE THINNED METHOD

Consider an initial $N \times M$ rectangular grid array whose desired array factor as a function of $(u,\, v)$ planes in the far-field is [21]

$$AF_{desired}(u,v) = \sum_{n=1}^{N}\sum_{m=1}^{M} W_{nm} e^{j(n-1)\left[\frac{2\pi d_x}{\lambda}u-u_o\right]} e^{j(m-1)\left[\frac{2\pi d_y}{\lambda}v-v_o\right]} \tag{1}$$

where $u = \sin(\theta)\cos(\phi)$, $v = \sin(\theta)\sin(\phi)$, θ and ϕ are the elevation and azimuth angles respectively; d_x and d_y are inter-element spacing in x and y directions, respectively; u_o and v_o are the progressive phases for main beam scanning; and W_{nm}=$A_{nm}e^{P_{nm}}$ is the complex excitations that includes both amplitudes and phases of the array elements. To perform the thinning process, usually amplitude-only weighting is used, thus, element phases will be set to zero, P_{nm}= 0 for $n = 1, 2, \ldots, N$, and $m = 1, 2, \ldots, M$. Regarding the amplitude excitations of the original fully filled planar array, it is very important to choose either an optimum existing taper that best fits the desired requirements or just simply use a uniform amplitude distribution. In this work, both the uniform and nonuniform distributions like Chebyshiv and Gaussian tapers are examined.

It is well known that the non-uniformly amplitude excitations such as Chebyshiv or Taylor distributions give more weights to the central (or inner) elements and less weights to the boundary (or outer) elements. Accordingly, the elements of the initial planar array can be partitioned using pre-specified threshold into two sub-planar arrays. The first one is an inner sub-planar array which contains a number of the elements in a small square-grid whose weights are higher than the threshold value, while the second one is an outer sub-planar array which contains only the elements near the edges, and their excitations are at low values. For two-dimensional rectangular arrays, it is easier to define the threshold as a number of square rings to count all the array elements along $\mp x$ and $\mp y$ directions. For simplicity, all the four directions are assumed symmetric and contain the same number of elements which is the case of a simple square grid. By this way, the number of elements in the inner sub-planar array can be calculated from $(N-2L)\times(M-2L)$, while the number of elements in the outer sub-planar array is found from $2L(N-L)+2L(M-L)$, where L is the number of square-rings starting from the perimeter of the planar array (i.e., when $L = 1$ the elements located on the perimeter are only selected as an outer sub-planar array). Then, the array factor of these two portioned sub-planar arrays can be given by

$$AF(u,v)_{\text{proposed}} = \underbrace{\sum_{n=1}^{N-2L}\sum_{m=1}^{M-2L} B_{nm} W_{nm} e^{j(n-1)\left[\frac{2\pi d_x}{\lambda}u-u_o\right]} e^{j(m-1)\left[\frac{2\pi d_y}{\lambda}v-v_o\right]}}_{\text{inner sub-planar array}} + \underbrace{\sum_{n=N-2L+1}^{N}\sum_{m=M-2L+1}^{M} C_{nm} W_{nm} e^{j(n-1)\left[\frac{2\pi d_x}{\lambda}u-u_o\right]} e^{j(m-1)\left[\frac{2\pi d_y}{\lambda}v-v_o\right]}}_{\text{outer sub-planar array}} \quad (2)$$

where B_{nm} and C_{nm} are the binary sub matrixes that will be used to decide which elements to be active (remain on) or removed (turned off). Intuitively, the values of B_{nm} should be all set to one so that the majority of the original optimum weights A_{nm} of the filled array do not alter too much in an attempt to maintain the proposed array pattern as close as to that of the desired radiation characteristics of the filled array. The entries of the binary matrix, C_{nm}, need to be optimized to find the most appropriate combinations of the active elements in the outer sub-planar array. To do this, a binary genetic algorithm with uniform cross over and tournament selection is used. Unlike the values of B_{nm} which are all ones for $1 \leq n \leq N-2L$ and $1 \leq m \leq M-2L$, the values of C_{nm} could be a set of random 0's and 1's depending on the results of the optimization process.

The procedures of the proposed method can be summarized as in the following steps:

(i) Take an initial array with size $N \times M$, whose element weights, W_{nm}, are optimum. Then, the desired radiation characteristics of the filled planar array are obtained.

(ii) Divide the original array into two sub-planar arrays with sizes $(N-2L)\times(M-2L)$ and $2L(N-L)+2L(M-L)$, respectively, where L represents the threshold value between the two sub-arrays as mentioned earlier.

(iii) Find the optimum combination of the active (i.e., remain on) elements in the second (or outer) sub-planar array by optimizing the entries of the binary matrix B_{nm} using the binary genetic algorithm subject to the following cost function,

$$\text{Cost} = \sum_i \{AF(u_{sl\,i},\, v_{sl\,i}) - SL_d\}^2 + \{BW - BW_d\}^2 + \sum_j \{AF(u_{null\,j},\, v_{null\,j}) - D\}^2,$$

where i is the number of the side-lobe peaks; $u_{sl\,i}$, $v_{sl\,i}$ are the angles of the side-lobe peaks; SL_d is the desired side-lobe level in the filled array pattern; $BW_d{=}1/Nd_x$ is the desired first-null-to-null beam width; u_{null}, $v_{null\,j}$ are null directions; and D is the nulls depth.

(iv) Finally, plot the results according to Equation (2).

3. SIMULATION RESULTS

In this section, several simulation results are provided to verify the effectiveness of the proposed partially thinned array. In all examples, we consider a rectangular planar array with dimensions $N \times M = 40 \times 40$. The array elements are symmetrically positioned about the centre of the rectangular array, and they are spaced half a wavelength. Such a fully filled array is then divided into two sub-planar arrays with dimensions $(N-2L)\times(M-2L)$ and $2L(N-L)+2L(M-L)$. The value of L which represents the number of outer square-rings is chosen to be 5 which gives the best results. This means that the dimension of the inner sub-planar array is (30×30), while the number of outer sub-planar array elements is 700 elements which are thinned to produce the required side-lobe nulling. It is worth to mention that the sub-array elements on each quadrant of the planar array are mirror to each other, thus, the total number of the optimized elements in the outer sub-planar array becomes 700/4 instead of 700. This further reduces the number of searching combinations.

The binary genetic algorithm is applied to those 700/4 outer elements to search for 2^{175} possible searching combinations instead of 2^{1600} for the original fully filled planar array. The specification parameters of the used binary genetic algorithm are: tournament selection, uniform cross over selection, population size equal to 8; mutation rate is 0.2; the number of chromosomes not mutated is 1, while the stopping criteria were chosen to be: maximum number of generations is 500, and the acceptable cost is -80 dB.

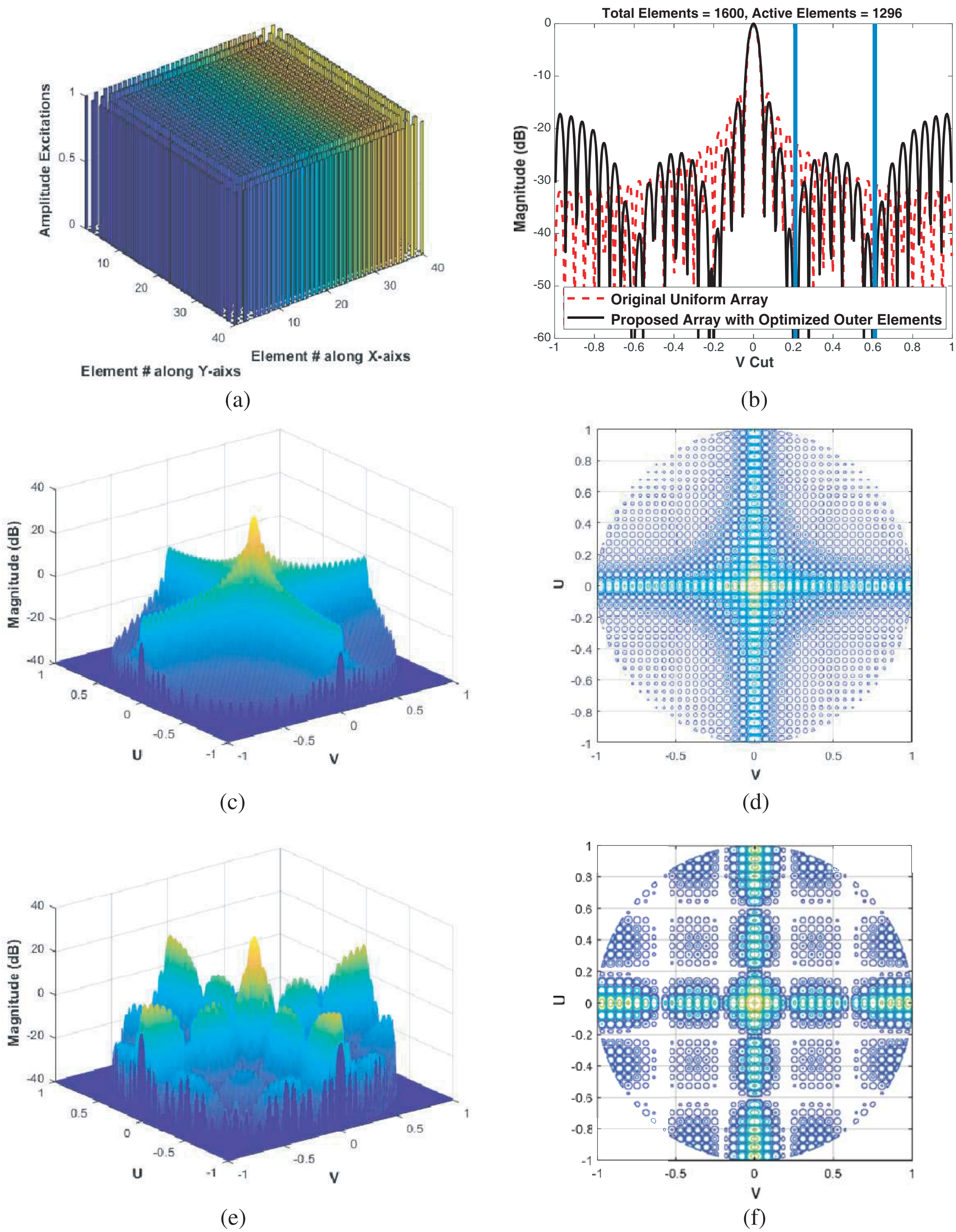

Figure 1. Results of using uniform amplitude distributions for 40×40 planar array. (a) Amplitude distribution of the proposed array with thinned outer elements. (b) 2D patterns of the proposed thinned and original filled arrays. (c)–(d) 3D pattern and its contour of the original fully filled array. (e)–(f) 3D pattern and its contour of the proposed planar array.

Figure 1 shows the results of applying the proposed thinning method to a planar array with dimensions as stated above and with uniform amplitude distribution, i.e., $A_{nm} = 1$ and $P_{nm} = 0$ where in this case all the array elements have equal weights over the whole array aperture. The numbers of the elements in both sub-planar arrays are also as stated above. The optimized elements of the outer array in which some of its elements are turned off (i.e., their amplitudes are set to zero) are also shown in this figure. The three-dimension radiation pattern of the original fully filled planar array and its corresponding contour are also shown for comparison purpose. Further, the two-dimension (V-cut) radiation patterns of both tested arrays are also shown. It can be seen that the peak side-lobe level does not exceed -15 dB; half power beam width is 2.7505^o which is little wider than that of the original fully filled array 2.5212^o; and the controlled nulls at (u, v)= (0.21, 0.21) and (u, v)= $(0.61, 0.61)$ with depths more than -70 dB are satisfactory obtained with only 1296 remaining active elements out of total 1600 elements. This means that 304 (i.e., 19%) elements are successfully removed from the original planar array without reducing the performance.

In the second example, the results of applying the proposed method to the Gaussian distribution for 40×40 elements are investigated. Fig. 2 shows the 3D pattern of the original fully filled Gaussian array and its corresponding amplitude distribution, while Fig. 3 shows the 3D pattern of the proposed planar array with thinned outer elements and its corresponding amplitude distribution. The 2D patterns of

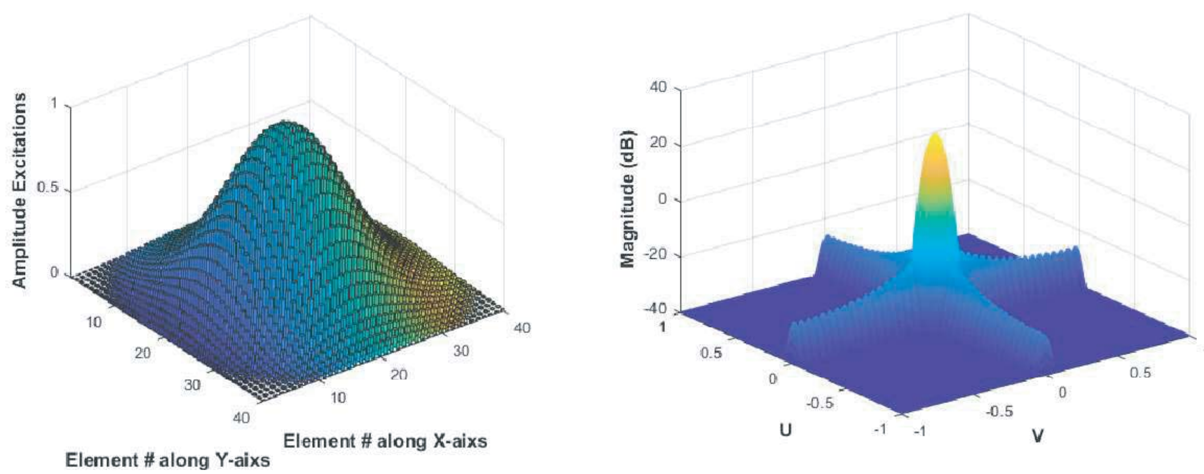

Figure 2. Results of the original fully filled Gaussian distributed planar array for 40×40 elements.

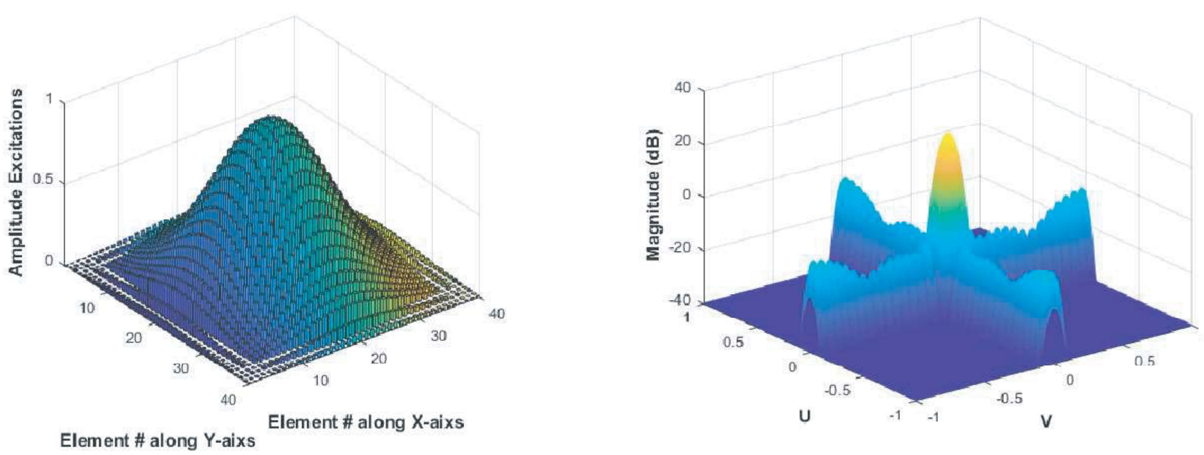

Figure 3. Results of applying the proposed thinning method to the Gaussian distribution for 40×40 planar array.

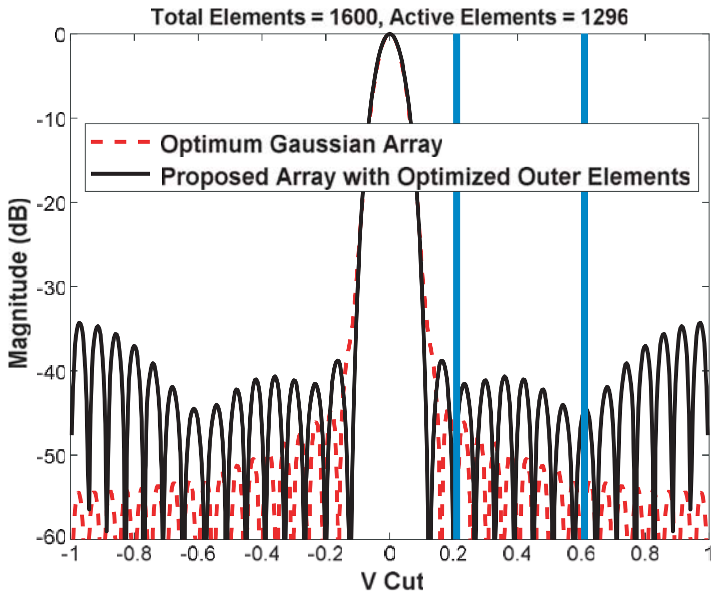

Figure 4. Results of 2D patterns of the proposed thinned and original filled arrays using Gaussian distributions for 40×40 elements.

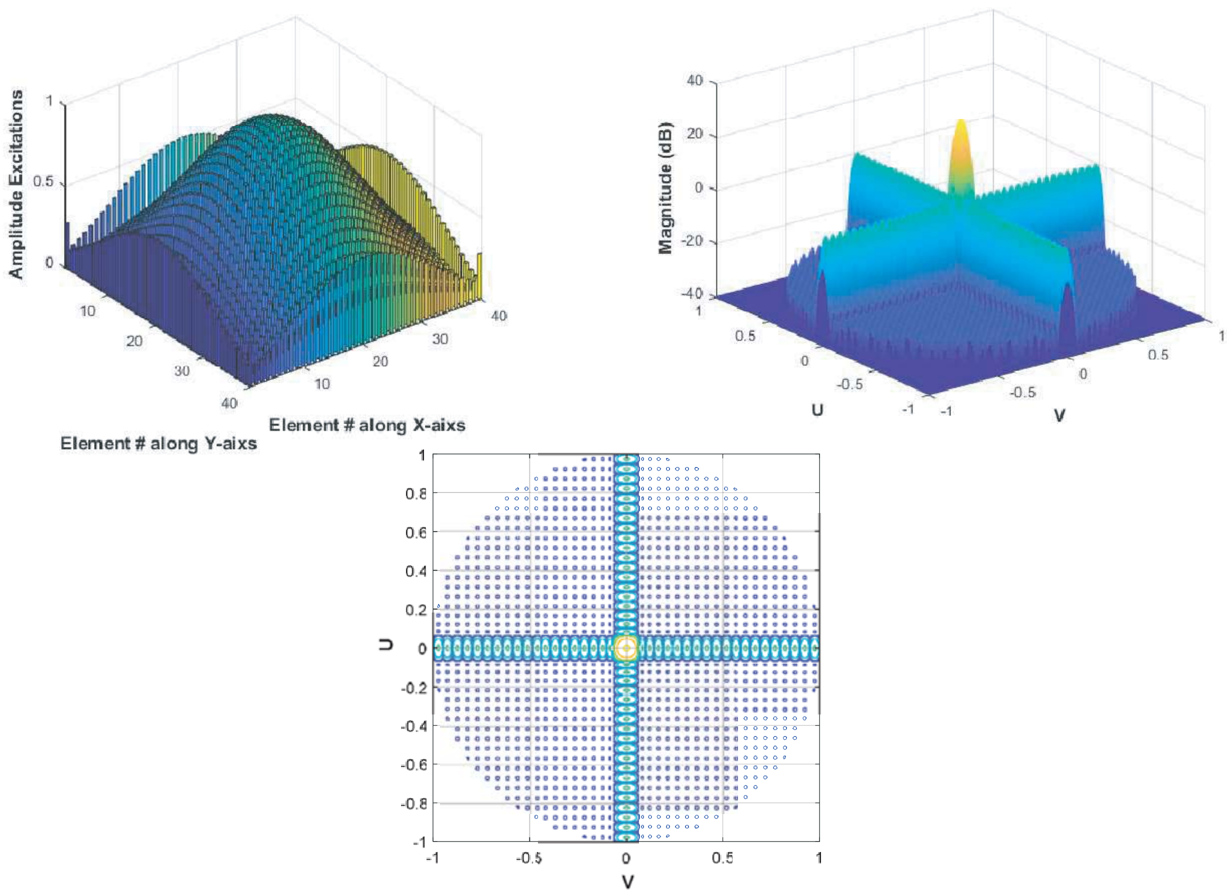

Figure 5. Results of the fully filled Chebyshiv planar array for 40×40 elements.

the above two tested planar arrays are also shown in Fig. 4 for comparison purpose. For the original Gaussian distribution, the value of the standard deviation is chosen to be 7.8, such that the weights of the elements near the perimeter have very low excitations. Again, the 19% of the outer elements are removed without reducing the performance.

In Figs. 5 and 6, the results of applying the proposed thinned array to the Chebyshiv distribution for the same array size as before are shown. The optimal side-lobe level in the fully filled planar array is set to -30 dB, while the obtained value by the proposed method is below -24 dB, and the required nulls are accurately placed. These results fully verify the effectiveness of the proposed thinned method.

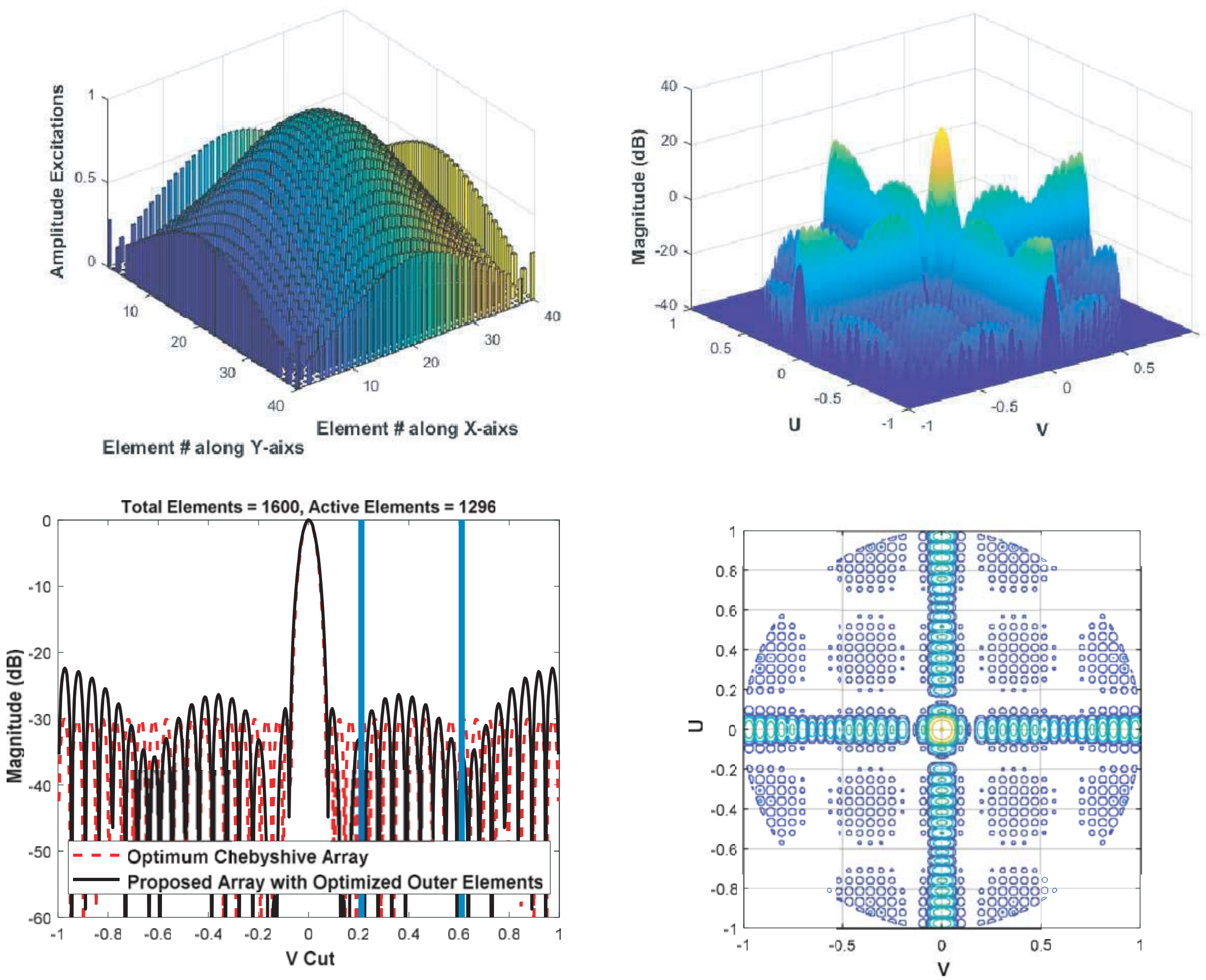

Figure 6. Results of applying the proposed method to the Chebyshiv planar array for 40×40 elements.

Finally, the performance measures in terms of directivity, peak side-lobe level, half power beamwidth (HPBW), and depth of nulls of the proposed partially thinned planar array as a function of thinning percentage are shown in Fig. 7. The thinning percentage may be defined by the ratio of the number of removed elements to the total number of elements. From this figure, it can be seen that a better directivity and lower side-lobe levels are achieved for smaller thinning percentage.

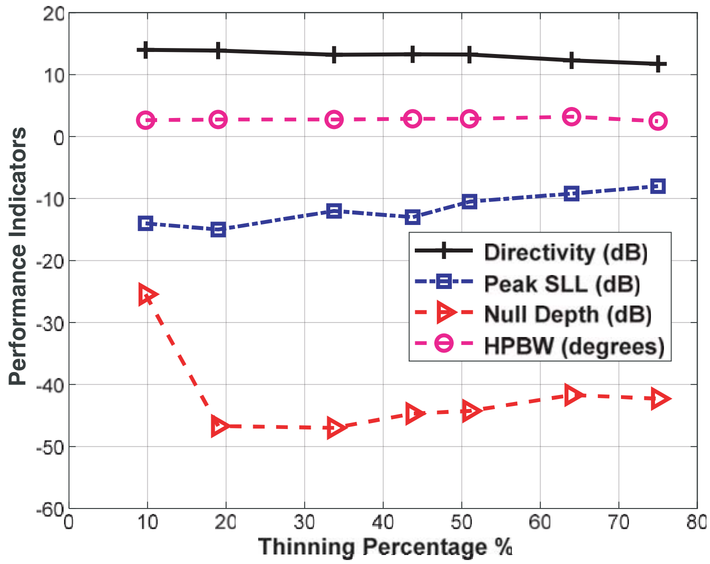

Figure 7. Performance measures of the proposed planar array with uniform distribution and 40 × 40 elements.

4. CONCLUSIONS

It has been shown from the simulated results that the desired radiation characteristics of the fully filled planar arrays such as low side-lobes and narrow beamwidth could be approximately obtained with the proposed partially thinned planar array with smaller number of active elements. The proposed method constrained the searching space of the optimization algorithm to only outer sub-planar array instead of fully filled array; thus, many advantages such as faster response time, low cost, and null placements were obtained. To perform such optimization, a binary genetic algorithm was applied to the outer sub-planar elements to identify useless elements (i.e., the elements that have least impact on the radiation pattern) and remove them with minimum alteration from the desired radiation characteristics of the fully filled counterpart array.

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