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MULTIPLE ANTENNA ARRAY PATTERNS RECONFIGURATION WITH COMMON EXCITATION AMPLITUDES AND OPTIMIZED PHASES

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Abstract

In this paper, an efficient optimization method based on the genetic algorithm with specific constraint masks is proposed to design the linear and planar antenna arrays that are capable to perform multi-functions by producing different radiation patterns with common excitation amplitudes. Unlike the conventional synthesized methods, the proposed method alters between different patterns by simply changing the phase excitations which are practically easy since they are already exist in phased arrays. The excitation amplitudes are maintained constant during the array pattern alteration. To achieve lower sidelobe levels, the pre-specified common excitation amplitudes can be chosen according to the Gaussian taper. Simulation results show that the proposed array has the capability to efficiently generate and reconfigure between sum, flat-top, cosecant-squared, and difference patterns all subject to pre-specified desired constraint masks. Furthermore, to verify the effectiveness of the proposed method, various numerical metrics have been measured and compared such as directivity, average sidelobe, taper efficiency, beam ripple, and peak sidelobe level.

Keywords: Antenna arrays, Genetic algorithm, Optimized arrays, Performance optimization, Radiation pattern.

1. Introduction

Integrating multiple antenna arrays, each with specific function, into a single array with capability of generating multiple patterns with many functions is of a great interest due to the physical size constraints in many applications such as on-body devises, satellites, radars, and wireless communications. This problem can be solved efficiently by the use of phased arrays where its pattern characteristics can be easily altered by modifying the amplitude and phase excitations of the array elements, i.e., adjusting the phase shifters and attenuators which they are connected to each array element in the feeder network. In this work, the main goal is focused on generating the following different array patterns; sum, flat-top, cosecant-squared, and difference patterns with a single one-dimensional linear array or two-dimensional planar array.

The sum and difference patterns are usually used in the tracking and searching purposes, while the flat-top pattern is used in broadcasting systems and maritime navigation that require uniform illumination for more than one sector of the region from the satellite. The cosecant-squared patterns are used in the air-surveillance applications where the received signal is independent of the radar range for a constant height target, i.e., achieving uniform-like signal strength at the input of the receiver as the target moves with a constant height within the array beam. In such applications, a single designed array should be able to generate these four different patterns or even more by properly switching between their corresponding excitation amplitudes and phases. Moreover, it is more desirable if the designed array have a common excitation amplitudes and variable phases as its practical implementation become easier. Dürr et al in [1], described a method based on a modified Woodward-Lawson approach to generate sum, flat-top, and cosecant-squared patterns with a prefixed amplitude distribution and various phase distributions. Then Trastoy et al. [2] used a simulated annealing to jointly optimize the common amplitude distribution among all the corresponding generated patterns. Earlier, Bucci et al in [3] used projection method to optimize the common excitation amplitudes and various phases. Although good results have been obtained, but the choice of the starting point in the projection method was very crucial and it should be made consistent with the problem at hand.

Recently, Karim and Mohammed [4] presented two different strategies for selecting common excitations elements to configure between sum and flat-top patterns. The two strategies were based on the amplitude-only control subject to the maximum allowable sharing percentage of the excitation amplitudes between those two considered arrays. In fact, some of the central excitation amplitudes of the corresponding sum and flat-top patterns were found to be similar at the array center since they are reaching their maximum values, thus, they had joint together to generate the desired sum and flat-top radiation patterns. Then, the method that was presented in [4] was further extended to include difference pattern and makes it more effective and versatile optimization method by jointly optimizing the sum and difference patterns under a maximum allowable sharing percentage of the excitation amplitudes [5]. The feeder network of such array was greatly simplified by attaching an optimized common weight to each element and the required array patterns was satisfactory generated. Furthermore, many other array pattern reshaping or nulling methods have been studied in [6-8]. They were generally either based on the clustered subarrays [9, 10], or partially controllable elements [11-14], or even compressed sensing methods [15].

In this paper, an optimization method based on the genetic algorithm with pre-specified constraint masks is described to generate many different beam-pattern shapes subject to a common excitation amplitudes and variable phases. For each pattern, a specific cost function based on a predetermined mask function is formulated to perfectly reach the required radiation pattern under the common excitation amplitudes. To alter between different radiation patterns, only the array excitation phases should be optimized through a genetic algorithm. The cost function minimizes the error mismatch between the desired radiation pattern which is defined by the mask function and the one that iteratively synthesized by the genetic optimization. The main advantage of the proposed method is that the designer may suggest any desired pattern shape by identifying its mask constraints and the fineness of the actual obtained pattern depends only on the availability of enough number of degrees of freedom.

Furthermore, to verify the superiority of the proposed method among the other existing methods, various quality metrics have been listed and compared such as directivity, average sidelobe, taper efficiency, beam ripple, and peak sidelobe level.

2. The Proposed Method

The array factor $AF(\theta,\phi)$, in terms of polar coordinates θ and ϕ, of a rectangular planar array with $N_x \times N_y$ isotropic radiating elements that are located in the xy-plane with its center at the origin can be written as [16]:

$$AF(\theta,\phi) = \sum_{n_x=0}^{N_x-1}\sum_{n_y=0}^{N_y-1} W_{n_x n_y} e^{jksin\theta(n_x d_x cos\phi + n_y d_y sin\phi)} \tag{1}$$

where $W_{nn} = A_{nn}e^{jP_{nn}}$ is the complex excitation weight of the $(n,n)th$ element, A_{nn} is the excitation amplitude, P_{nn} is the excitation phase, the wave number k is $\frac{2\pi}{\lambda}$, λ is the wavelength. d_x and d_y are the separation distances between any two successive elements on x and y directions, respectively. Given a prescribed excitation amplitudes, A_{nn}, for example uniform taper or any other taper and the desired constraint mask for each required pattern shape, the excitation phases, P_{nn}, corresponding to each required pattern such as sum, flat-top, cosecant-squared, difference patterns can be determined by using a genetic algorithm.

The desired constraint mask, at certain ϕ, for each of the above mentioned patterns in decibels and in the normalized form to their maximum can be represented as follows:

$$Sum_{Mask}(\theta) = \begin{cases} SLL, & -90^o \le \theta \le -FNBW,\ FNBW \le \theta \le 90^o \\ 0, & -FNBW \le \theta \le FNBW \end{cases} \tag{2a}$$

$$Flattop_{Mask}(\theta) = \begin{cases} SLL, & -90^o \le \theta \le -FNBW,\ FNBW \le \theta \le 90^o \\ ripple, & \theta_1 \le \theta \le \theta_2 \end{cases} \tag{2b}$$

$$Cosec_{Mask}(\theta) = \begin{cases} SLL, & -90^o \le \theta \le -FNBW,\ FNBW \le \theta \le 90^o \\ 10log_{10}\left(\frac{csc^2\theta}{csc^2\theta_1}\right), & \theta_1 \le \theta \le \theta_2 \\ 0, & -FNBW \le \theta \le \theta_1 \end{cases} \tag{2c}$$

$$Dif_{Mask}(\theta) = \begin{cases} SLL, & -90^o \le \theta \le -2\times FNBW,\ 2\times FNBW \le \theta \le 90^o \\ 0, & -2\times FNBW \le \theta \le 2\times FNBW \end{cases} \tag{2d}$$

where the first null beam width $FNBW = 1/(N_x \times d_x)$, SLL is the normalized magnitude of the sidelobe level, θ_1 and θ_2 are specific angular phases in both flat-top and cosecant-squared patterns. These four constraint masks are shown in Figs. 1-4 as dotted red colours. Generally, the radiation pattern that has been iteratively synthesized by optimizing the excitation phases of the array elements must best fit the ideal constraint mask. Specifically, the SLL magnitudes must be kept below the mask limit and the main beam ripple should be as small as possible, for example, $-0.5\ dB \leq ripple \leq 0$. Consequently, a typical cost function that can be used to optimize the excitation phases for each required pattern under the above mentioned constraint masks can be written as:

$$Cost = \sum_{p=1}^{P} \left| AF(\theta_p) - Mask(\theta_p) \right|^2 \tag{3}$$

where $p = 1,2, \ldots, P$ are the sample points and P represents the total sample points. Note that the excess magnitudes of the $AF(\theta_p)$ that located outside the mask limits are minimized. The lower the cost value is, the better match is between the actual obtained pattern and the desired one. Zero cost function results in an optimal solution without any excess value which can be obtained if the number of degrees of freedom (i.e., number of element excitation amplitudes and phases) for the optimizer is sufficiently enough.

The main steps of the optimization process are as the follows; first the array pattern in (1) is generated for an initial excitation weights (i.e., uniform taper) and the desired constraint mask according to (2) is specified. Then, the required constraint mask and the generated array pattern are both sampled at P values. For each sample point, the score was computed by finding the difference between the obtained array pattern and the constraint mask limit over the total P sample points. That is, each magnitude of the power level that locates outside the mask limits contributes a value to the cost function equal to the power difference between the obtained pattern and the desired one. Finally, the differences values reach their minimum values as the optimizer converges to the final solution.

3. Simulation Results and Discussions

To assess the optimized method, a number of numerical results have been presented. In all examples of the linear antenna arrays, an equally spaced ($d_x = 0.5\lambda$) array composed of 20 elements is considered to generate many different radiation patterns such as sum pattern, flat-top pattern, cosecant-squared pattern, and the difference pattern using common pre-specified amplitude excitations and variable phases. The pre-specified common amplitudes and the variable phases of all of the corresponding array patterns are assumed to be symmetric with respect to the center of the array. Due to symmetry, only half number of the variable phases is to be optimized. For the pre-specified common amplitudes, we considered uniform and Gaussian amplitude excitations. The standard deviation of the Gaussian taper is set to 8 such that the value of the dynamic range ratio (DRR) is not exceeding 5. The DRR is defined as the ratio between the maximum excitation amplitude value, A_{max} at the array center which is unity and the minimum excitation amplitude value, A_{min}, at the array terminal which can be chosen at a small fraction value such as 0.2, i.e., $DRR = \frac{|A_{max}|}{|A_{min}|} = \frac{1}{0.2} = 5$.

For the optimization process, the minimum and the maximum values of the variable phases are restricted to lie between the range of -90^{o} and 90^{o}. The phase excitations of every corresponding pattern are optimized separately while the amplitude excitations of all considered patterns were fixed at pre-specified values. In all examples, the used specifications of the genetic algorithm were set as follows; an initial population size of 20, selection is roulette, crossover is single point, mutation rate is 0.15, and mating pool is chosen to be 4. For more details about the used optimization algorithm, we refer to [4, 5].

In the first scenario, an optimal solution in which a complete optimization of the independent and uncommon amplitudes and phases is considered to get a very low cost function and no excess values outside the mask. These complex and fully optimized sum, flat-top, cosecant-squared, and difference patterns are mainly needed for the comparison purpose with the proposed one. They are designed to satisfy the desired constraints as shown in Figs. 1-4. The optimized amplitudes and phases of the array elements are also shown in the above figures. From these four figures, it can be seen that all the obtained patterns are lower than the desired mask constraints. However, implementations of such element's excitations require separate arrays which are accompanied with a very high complexity in the feeding circuitry. Thus, this case should be reconsidered with a more simplified feeder network while still satisfying the desired constraints with suboptimal solution.

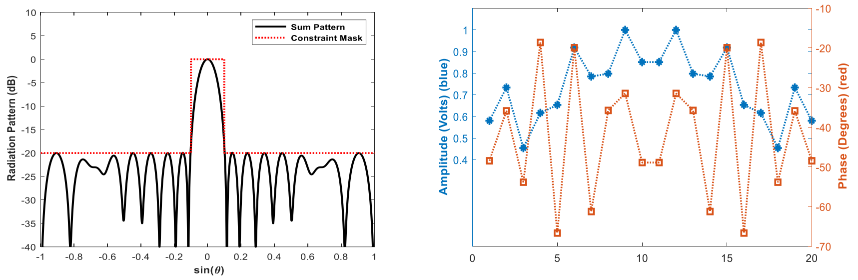


Fig. 1. Sum pattern and its corresponding fully optimized amplitude and phase excitations.

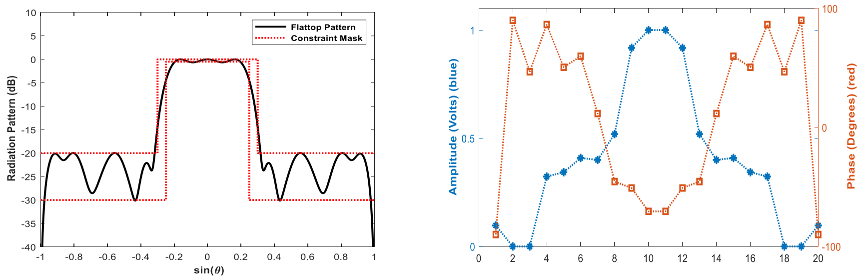


Fig. .2 Flat-top pattern and its corresponding fully optimized amplitude and phase excitations.

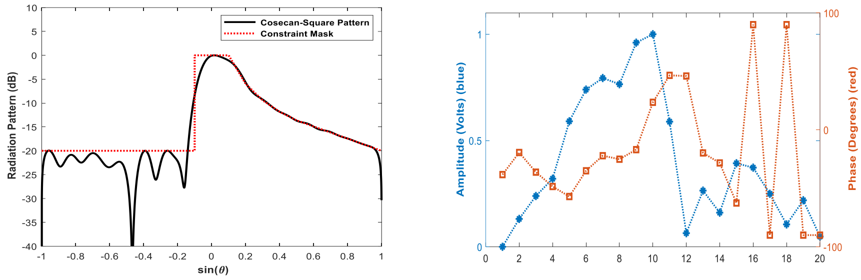


Fig. 3. Cosecant-Square pattern and its corresponding fully optimized amplitude and phase excitations.

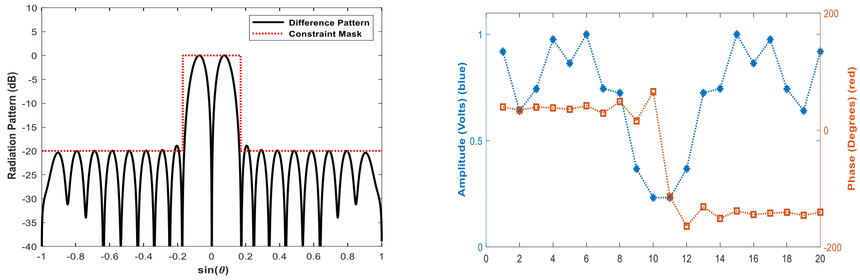
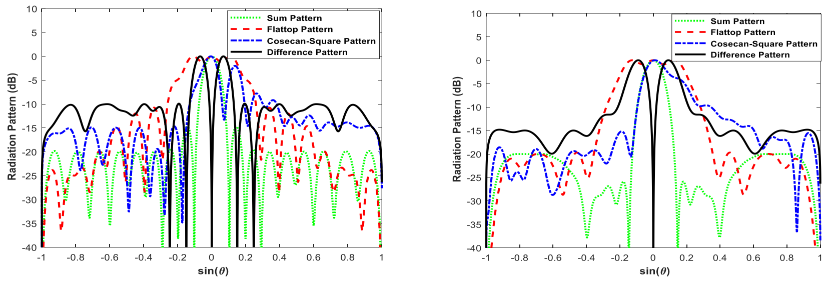


Fig. 4. Difference Pattern and its corresponding fully optimized amplitude and phase excitations.

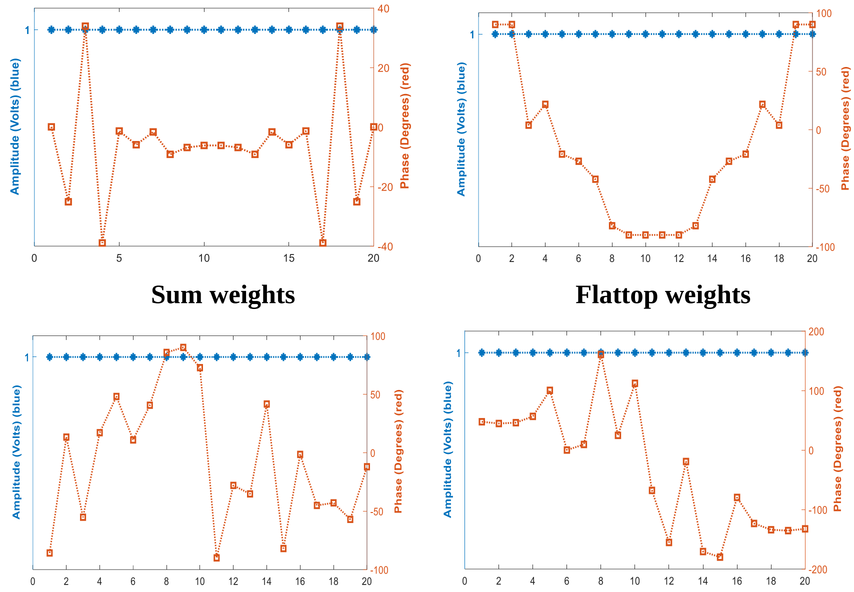
In the second scenario, all the amplitude excitations were fixed as a uniform amplitude excitation, while the phases are optimized. The radiation patterns of the sum, flattop, cosecant-squared, and difference modes are shown in Fig. 5(a). The sidelobe level was -20 dB for the sum pattern, -11 dB for the flat-top pattern, -10 dB for the difference pattern, and -15 dB for the cosecant-squared pattern. In addition, the ripple of the flat-top beam is 0.5 dB which is within the desired range. Figure 5(b) shows the results obtained for the same arrays with the prescribed amplitude excitations of the Gaussian distribution (its standard deviation is set to 8 as mentioned earlier). From this figure, it can be seen that the sidelobe level of at least -20dB can be achieved for all four array patterns with a ripple of -0.5dB in the flat-top beam.



(a) **(b)**

Fig. 5. Different array patterns for uniform common amplitude excitations (a) and common Gaussian amplitude excitations (b).

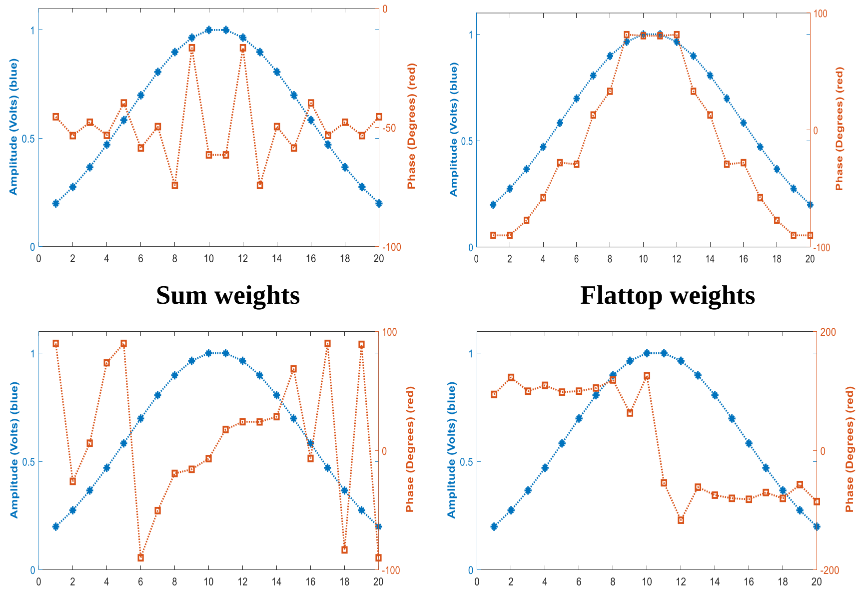
The amplitudes and phases of the uniform and Gaussian excitations are shown in Figs. 6 and 7 respectively. Moreover, the performances in terms of taper efficiency, directivity, average sidelobe level, first-null-to-null beam width (FNBW) of such arrays are listed in Table 1.



Sum weights **Flattop weights**

Cosecant-squared weights **Difference weights**

Fig. 6. Amplitudes and Phases for the case of common uniform amplitude excitations that used to generate beam patterns in Fig. 5(a).



Sum weights **Flattop weights**

Cosecant-squared weights **Difference weights**

Fig. 7. Amplitudes and Phases for the case of common Gaussian amplitude excitations that used to generate the beam patterns in Fig. 5(b).

In the third scenario, the results that were shown in Fig. 5 are compared with the Ares' work which was presented in [1]. Figure 8 and Table 1 show the comparative results between the Ares' work and the proposed method. It can be seen that both methods are satisfying the desired constraints.

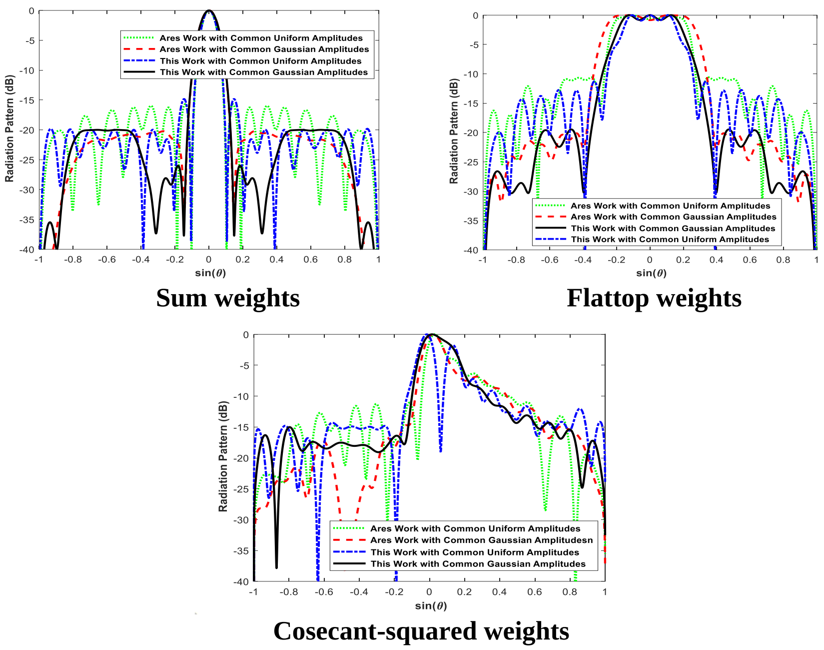


Fig. 8. Comparison of multiple array patterns with separate optimization of the phase extortions for each corresponding pattern and a common amplitude excitations.

Table 1 Performance of the optimized arrays.

Methods	**Patterns**	**Performances**					
		Taper Efficiency	**Directivity (dB)**	**Peak SLL (dB)**	**Average SLL (dB)**	**Beam Ripple (dB)**	**FNBW (deg.)**
Uniform Array	Sinc	1	11.1406	-13.2	-28.7974	0	11.4783
Ares Work with Common Uniform Amplitudes and Phase-Only Control	Sum	0.8478	10.8419	-16	-24.0179	0	11.4783
	Flat-top	0.1917	4.3711	-10	-14.8217	-0.6	34.9152
	Cosec	0.4299	8.1401	-11	-16.6260	0	90
Ares Work with Common Gaussian Amplitudes and Phase-Only Control	Sum	0.7785	10.1443	-20	-23.3852	0	16.6746
	Flat-top	0.1795	3.8643	-20	-22.6082	-0.5	47.1564
	Cosec	0.4435	8.1433	-20	-18.6776	0	90
This Work with both Amplitudes and Phases Controls	Sum	0.8893	10.8964	-20	-23.7452	0	13.2
	Flat-top	0.2122	4.5763	-20	-23.2331	-0.5	39.1451
	Cosec	0.3681	7.2331	-20	-22.4775	0	90
	Difference	0.5782	8.9431	-20	-23.5585	0	19.5756
This work With Common Uniform Amplitudes and Phase-Only Control	Sum	0.9107	11.056	-15	-23.8212	0	11.4783
	Flat-top	0.2670	5.5646	-12	-24.8481	-0.5	34.9152
	Cosec	0.4166	8.3985	-15	-23.5679	0	90
	Difference	0.3152	7.8428	-10	-17.1773	0	17.2539
This work With Common Gaussian Amplitudes and Phase-Only Control	Sum	0.7637	10.247	-20	-23.9824	0	17.2539
	Flat-top	0.2453	5.1699	-20	-23.3191	-0.5	47.1564
	Cosec	0.3864	7.5029	-18	-22.3312	0	-90
	Difference	0.3297	7.1683	-15	-16.1449	0	27.7731

Finally, a planar square array of elements 20x20 spaced $d_x = d_y = 0.5\lambda$ apart in both the x- and y-directions is considered to generate these four different beam pattern shapes with optimized amplitude and phase excitations as shown in Fig. 9. It can be seen that the sidelobe level in all obtained patterns does not exceed the required limit of -20 dB.

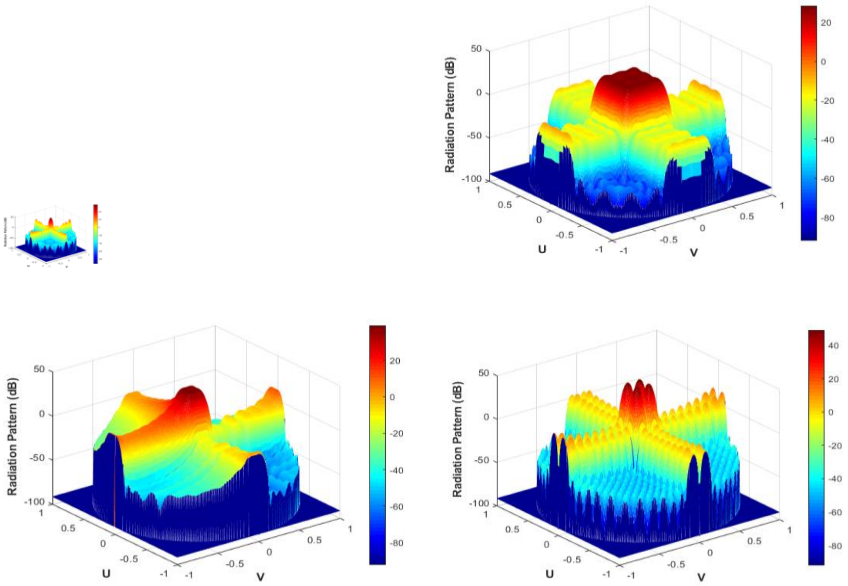


Fig. 9. Results of the planar array with optimized amplitude and phase excitations.

4. Conclusions

The desired constraint masks have been successfully integrated into a genetic optimization algorithm to synthesis four different radiation patterns to demonstrate a multifunction array system with simple prefixed common excitation amplitudes. The excitation phases were optimized such that low sidelobes and best match between the obtained radiation patterns and the desired ones could be met. Simulation results show that the proposed method was capable to generate sum, flat-top, cosecant-squared, and difference patterns with peak sidelobe level about −10 dB for uniform common excitation amplitudes and −20 dB for Gaussian common excitation amplitudes. Moreover, the average sidelobes for the sum, flat-top, and cosecant-squared patterns were about -23 dB which is lower than any of the existing works in the literature. In addition, the main beam ripple of the cosecant-squared pattern was almost zero for the considered tapers. More important, the taper efficiencies of the proposed array for the obtained pattern shapes were better than those of the existing methods. This demonstrates the effectiveness of the proposed method for generating different shaped patterns.

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