A Simple Synthesis of a High Gain Planar Array Antenna for Volume Scanning Radars

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Abstract **─** This paper describes a simple method of designing a rectangular planar array antenna with a flat top characteristic within the given $0^o \leq \phi \leq \phi_{\max}$ region in the $\theta = 90^o$ principal plane to be used in the volume scanning radars. In the method, the main beam of each ingredient linear array antenna is collimated to a predetermined direction with a permissible beamwidth within the total coverage region so that the superposition of the far field ingredient phasors can result in the required overall pattern with the flat top characteristic in the region of $0^o \leq \phi \leq \phi_{\max}$ the principle plane. The main beamwidth requirements of the sub-arrays are met by the excitation amplitudes determined by Dolph-Chebyshev analytical method. Furthermore, the overall main beam characteristic is improved by optimizing the excitation amplitudes using the genetic algorithm. The far field patterns resulted from the half-wave dipole and patch arrays are verified by using the full-wave simulation software, computer simulation technology (CST).

Index Terms **─** Flat top pattern, linear sub-array, optimization, rectangular planar array.

I. INTRODUCTION

The goal of this work is to describe a simple method of synthesizing a rectangular planar array antenna which has a flat top characteristic within the given $0^o \leq \phi \leq \phi_{\max}$ region in the $\theta = 90^o$ principal plane to be used in volume scanning radars. The volume scanning radar will automatically scan various elevation angels while spinning around 360° of azimuth, rather than scanning along varying azimuth angles then stopping to scan vertically. Thus, it shortens the overall scan time. Rapid air targets which can not be determined by electronically scan but when volume search is used this targets will always be inside the antenna's beam thus targets will be detected. Thus, this radar can be used for long range and rapid surveillance.

In case that the radiation pattern distribution is given in the visible region, in literature, the analytical methods such as Fourier transformation [1], Woodward-Lawson [2-3] or Dolph-Chebyshev [4] are extensively employed in the synthesis process. In our work, the overall far field pattern is built up with the individual participation of each ingredient linear array antenna. The requirements of the individual synthesis of the ingredient linear array is to collimate its main beam to the predetermined direction with a permissible beamwidth within the coverage region so that superposition of the far field ingredients can result in the overall pattern shaped with the flat top characteristic within the $0^o \leq \phi \leq \phi_{\max}$ region in the principal plane. Main beamwidth requirements of the sub-arrays are met by the excitation amplitudes which are determined using the Dolph-Chebyshev analytical method which is a well-known robust method for a narrow main-beam and low sidelobe level (SLL) array antenna synthesis. Thus, N linear array antennas are built

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up as collimated to the pre-determined directions with the low SLL radiation patterns such that when their far field radiation phasors are super-positioned, a rectangular planar array antenna is resulted having a flat top main beam characteristic covered the specified region. The overall main beam characteristics can be improved by reducing the ripple factor in the flat-top region using an optimization process applied to the excitation coefficients. An ideal radiation pattern has zero ripples which are important drawbacks for target strength measurements and ripple in the antenna patterns presents a large uncertainty in the radio coverage measurements. In fact, we employed the genetic algorithm for this purpose. Furthermore, we applied this method to synthesis of the half-wave dipole and microstrip patch planar array antennas and verified with the full-wave commercial simulator of CST [5] which is based on the FDTD method.

Firstly, array factor of a rectangular planar array antenna in the x–y plane is formulated as the superposition of the linear arrays along x–axis, each of which is symmetrically positioned with respect to the y–axis, and collimated in different directions. Then the genetic optimization with its fitness function is given in the third section. Fourth section is devoted to the applications. Finally paper ends with the conclusions.

II. FORMULATION

As well-known, a 3-dimensioned array antenna pattern can be factorized as the array factor and the radiation pattern of a single element, in the case that the array elements are identical and mutual coupling effects between these array elements can be neglected. In any of the $\phi=$ constant planes, the element pattern has a constant value [6], thus the far field radiation pattern of a linear array can be defined as equal to array factor $AF(\theta,\phi)$ as follows [7]:

$$FF(\theta,\phi) = AF(\theta,\phi) = \sum_{m=1}^{N_y}\sum_{n=1}^{N_x} A_{mn} e^{-j\beta_{mn}} e^{j\xi_{mn}}\ , \qquad (1)$$

$$\xi_{mn} = k\hat{r}.\vec{r}'_{mn} = k[x'_{mn}\sin\theta\cos\phi + y'_{mn}\sin\theta\sin\phi]\ , \qquad (1.1)$$

$$\beta_{mn} = k[x'_{mn}\sin\theta_o\cos\phi_o + y'_{mn}\sin\theta_o\sin\phi_o]\ , \qquad (1.2)$$

where, A_{mn}, β_{mn} and $\vec{r}\,'$ are the excitation amplitude amplitude, phase and the position vector of the mnth element, respectively. k is the wave number of the free space and N_x ,N_y are the number of columns and rows in the rectangular planar array, respectively. In (1.1), $\hat{r}$ is the unit vector directed to the observation point from the origin and double summation is especially useful for row and column including geometries such as rectangular plane. If the elements are placed along x-axis symmetrically with respect to y-axis, x'_{mn} can be expressed as follows:

$$x'_{mn} = \frac{2n-1}{2}d_x\ . \qquad (2)$$

Here, d_x is the distance of the element in x-axis from the origin. In order to collimate the main beam into $\theta_o = 90^o$ the plane, phase vector of the mnth element can be defined as follows:

$$\beta_{mn} = k[x'_{mn}\cos\phi_{mo}]\ . \qquad (3)$$

Substituting (2) and (3) into (1), we have finally,

$$AF(\theta) = 2\sum_{m=1}^{N_y}. \left(\sum_{n=1}^{N_x} A_{mn}\cos[(\frac{2n-1}{2})kd_x(\cos\phi - \cos\phi_{mo})]\right)\ . \qquad (4)$$

Thus, according to (4), the synthesis process for the whole planar array can be reduced to synthesize N_y linear arrays directed to ($\phi_{mo}, m = 1,.........N_y$) so as when their far field phasors are super-positioned, the overall flat top main beam characteristic covered the specified region is resulted.

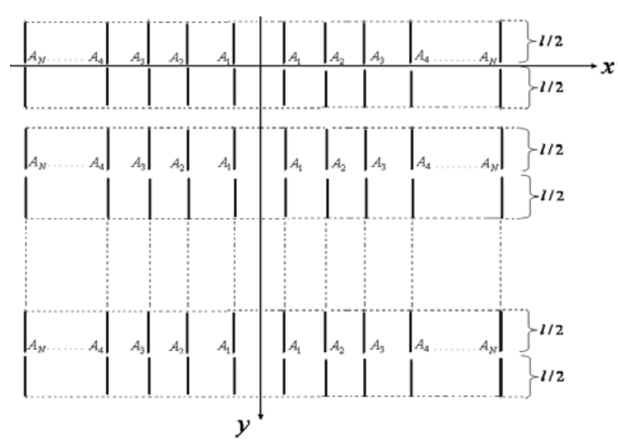

Fig. 1. A rectangular planar half-wave dipole antenna array.

For this purpose, the phase of each element is found from (2) using the pre-specified main beam directions $(\phi_{mo}, m = 1,.........N_y)$ and at the same time beam width requirements of a sub-array are also met by determining the $\vec{A}$ amplitude vector dimensioned by (1xN_x/2) using any well-known analytical method in an optimum sidelobe level. In this work, Dolph-Chebyshev method is chosen to synthesize the $\vec{A}$ amplitude vector and (-40 dB) level is determined as the optimum sidelobe level to meet main beam width requirements for the sub-arrays in the worked examples. Furthermore, the main beam characteristic of the whole array antenna is developed by optimizing the Dolph-Chebyshev excitation amplitudes of the whole array. In this work, the genetic algorithm is employed as the optimization tool. Furthermore, the far field patterns resulted from the synthesized half-wave dipole and microstrip patch array antennas are verified using the full-wave simulation software, CST.

III. GENETIC OPTIMIZATION

In fact, the excitation amplitudes are obtained as the result of the Dolph-Chebyshev synthesis process; furthermore the genetic algorithm is used to improve the overall far field characteristics. The reader is referred to [8-10] and the references mentioned therein for a detailed discussion of the basic concepts of the genetic algorithm. Thus, in the optimization process, the Dolph-Chebyshev excitation amplitudes are chosen as the decision variables and the following fitness function is employed:

$$Fitness\,(\vec{A}) = 20\log\left\{\frac{1}{\Delta\phi}\int_{\phi_l}^{\phi_u}\left|AF(\theta,\vec{A})\right|d\phi\right\}, \quad (5.1)$$
$$- s * SLL(dB)$$

$$SLL = \begin{cases} MSLL, & if\;\max(SLL) \geq -25dB \\ 0, & otherwise \end{cases}, \quad (5.2)$$

where max(SLL) can be expressed in terms of the normalized array factor as follows:

$$\max(SLL) = \max[20\log(\left|AF(\theta,\vec{A})\right|_{\phi=-90^o}^{\phi=\phi_l-\delta\phi_l})]$$
$$or\;\max[20\log(\left|AF(\theta,\vec{A})\right|_{\phi=\phi_u+\delta\phi_u}^{\phi=90^o})] \quad (5.3)$$

where $\left|AF(\theta,\vec{A})\right|$ is the normalized form of the array factor given by (4) where $\vec{A}$ is the excitation amplitude vector of a single linear antenna since all the linear array units within the planar array antenna have the same $\vec{A}$ vector. Here $\vec{A}$ has the dimension of 1x N_x/2, N_X is the element number of the single linear array. s is a constant and $s \gg 1$ in order to ensure that the second term of (5.1) will be dominant if $MSLL$ is greater than -25 dB. ϕ_u, ϕ_l and $\delta\phi_l$, $\delta\phi_u$ are upper and lower boundaries of the main beam region, and upper and lower tolerances for the boundaries, respectively, and $\Delta\phi = \phi_u - \phi_l$. In the fitness function given by (5.1), the first term is used to maximize the average normalized array factor as dB within the given $\phi_l \leq \phi \leq \phi_u$ region while the second term avoids the maximum sidelobe level in (5.3) to exceed the given maximum level MSLL which is taken (-25 dB) as the suitable value in the following worked examples. For both cases defined by (5.2), the first term acts dominant role in the optimization process.

IV. APPLICATION EXAMPLES

In this section, we have synthesized the 4x10 and 6x20 rectangular planar arrays in the x-y plane using half-wave dipole and microstrip square patches as the elementary antenna as shown in Figs.1 and 5 to achieve a flat top within the region of $0^o \leq \phi \leq 60^o$ in the $\theta = 90^o$ principal plane to be used in the volume scanning radars. For synthesis of both antennas, Dolph-Chebyshev method is utilized to determine the excitation amplitude vector $\vec{A}$ and the sidelobe level is adjusted so that each ingredient linear array antenna can be collimated to the pre-determined direction with the permissible beamwidth.

In the first worked example, 4 sub-arrays located along the x-axis, each including 10 half-wave dipoles which are symmetrically positioned with respect to the y-axis with the half-wavelength inter-spacings is considered. Main beams of the sub-arrays are collimated to $7.5^o, 22.5^o, 37.5^o$ and 47^o respectively to form a flat top within the region of $0^o \leq \phi \leq 60^o$ in the principle plane. In this worked example, the main beamwidths of the first three sub-arrays are taken as 15^o, while the last sub-array is directed 47^o instead of 52.5^o due to the broadening effect. Besides, for the first example the upper and lower tolerances are 3^o and 5^o,respectively. In the Dolph-Chebyshev synthesis, after a number of trials, (-40) dB is determined to be optimum for the maximum sidelobe level of the ingredient linear array antennas to meet all the direction and beamwidth requirements mentioned above.

After having the Dolph-Chebyshev excitation amplitudes, a genetic optimization process is applied to improve the overall flat top characteristic. A genetic algorithm is adopted with the following parameter suite: population size: number of the excitation amplitudes; crossover probability: 0.75; mutation probability: 0.01. The optimization process takes only a few seconds for both worked examples.

The Dolph-Chebyshev and optimized excitation amplitudes are given in Table 1. Besides, the synthesized far field patterns of the sub-arrays by the Dolph-Chebyshev method are given in Fig. 2. The excitation phases of each element antenna of the symmetrical rectangular array are also given in Table 2.

Table 1: Dolph-Chebyshev excitation amplitudes and the optimized values of the 4x10 rectangular planar array antenna

Each Sub-Array	$A_n(A)$	1.000	0.878	0.669	0.430	0.257
	$A_n(A)$ (optimized)	1.000	0.878	0.818	0.461	0.542

Table 2: Excitation phases of the sub-arrays of the 4x10 rectangular planar array antenna

Excitation Phases of Each Sub-Array			
$\theta_{\max_1} = 7^o$	$\theta_{\max_2} = 22^o$	$\theta_{\max_3} = 37^o$	$\theta_{\max_4} = 47^o$
-10.96	-33.71	-54.16	-65.82
-32.90	-101.14	-162.49	-197.46
-54.84	-168.57	-270.81	-329.1
-76.77	-236	-19.14	-100.75
-98.71	-303.43	-127.47	-232.39

In order to investigate the effects of the number of antennas in a sub-array and the number of antennas in the planar array we have also designed a 120 element rectangular array which is formed by 6 sub-arrays located in *x*-axis each including 20 half-wave dipoles.

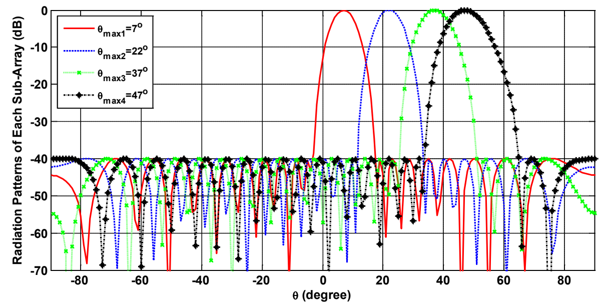

Fig. 2. The far-field patterns of the linear sub-arrays resulted from the Dolph-Chebyshev excitation amplitudes and phases given in Table 1and 2, respectively.

The main beams of sub-arrays are steered to $5^o, 15^o, 25^o, 35^o, 45^o$ and 55^o respectively, allowing 10^o beamwidth for each sub-array. Moreover, in this case the upper and lower tolerances are 5^o and 20^o, respectively. The *MSLL* is again adjusted as -40 dB in order to ensure the main beamwidth requirements. The Dolph-Chebyshev excitation amplitudes and their optimized values are given in Table 3. Excitations phase of each element is calculated using (2). Thus, the resulted far field patterns of the sub-arrays are given with their main beam directions in Fig. 3.

Table 3: Dolph-Chebyshev excitation amplitudes and the optimized values of the 6x20 rectangular planar antenna

Each Sub-Array	
$A_n(A)$	$A_n(A)$ (optimized)
1.000	1.000
0.958	0.868
0.880	1.289
0.772	0.715
0.646	0.114
0.512	0.388
0.381	0.227
0.264	0.444
0.166	0.108
0.118	0.175

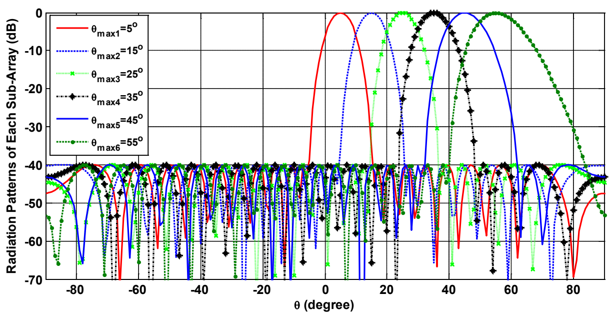

Fig. 3. The far field patterns of each sub-array of the 6x20 rectangular planar antenna using the Dolph-Chebyshev amplitudes given in Table 3.

In Fig. 4, the Dolph-Chebyshev and the optimized far field patterns of the 4x10 planar array are given together to see the effect of the optimization process on the main beam characteristic. It is clear from the Fig. 4 that a lower ripple level, which is crucial in target strength measurements, is achieved by a compromise between the ripple level and the *MSLL*. Furthermore, the far field patterns resulted from the CST full-wave simulations of both the 4x10 and 6x20 planar antennas with their optimized excitation amplitudes and phases are also given in the same figure. From these graphs, one can derive the following results: (i) the proposed synthesis method is a simple, easy and successful method since it is fast and easy to implement and results agree with the full-wave simulations; (ii) optimization process reduces the ripple factor of the top characteristic for the rectangular array of a fixed elements; (iii) increase in the number of elements results in reduce the ripple factor, thus one can obtain flatter main beam characteristic with sharper falling rate; and (iv) full-wave simulations indicate that the upper limit of the flat top region is expected to be smaller in comparison to the value computed while synthesizing the array.

Furthermore, synthesized excitation amplitudes and phases of the 4x10 and 6x20 planar antenna are applied to the planar array with the rectangular patch type element (Fig. 5). In these antennas, a substrate (RT/duroid 5880) with dielectric constant of 2.2, h=1.58 mm is used and W, L dimensions of the patch antennas are 10.136 mm and 8.18, respectively, so as to resonate at 11.7 GHz. The CST simulation software is utilized to obtain results of the total radiation patterns of the sub-arrays having 40 and 120 microstrip elements as given in Fig. 6.

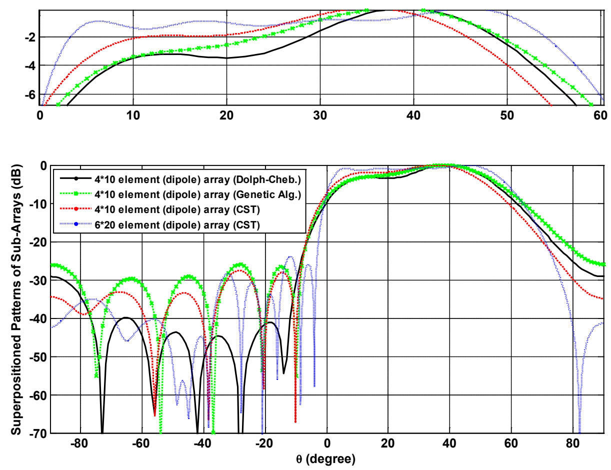

Fig. 4. The Dolph-Chebyshev and optimized far field patterns of the 4x10 element planar array, and the CST simulations of the 4x10 element and 6x20 element planar arrays.

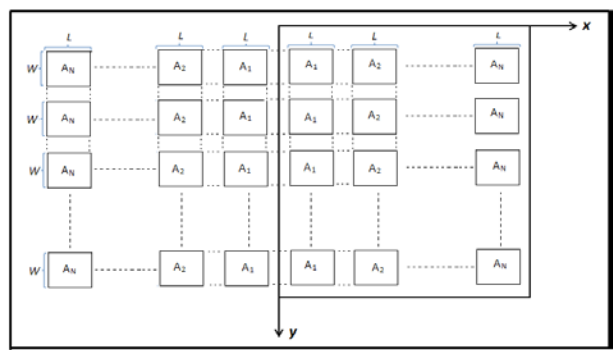

Fig. 5. A rectangular planar patch antenna array.

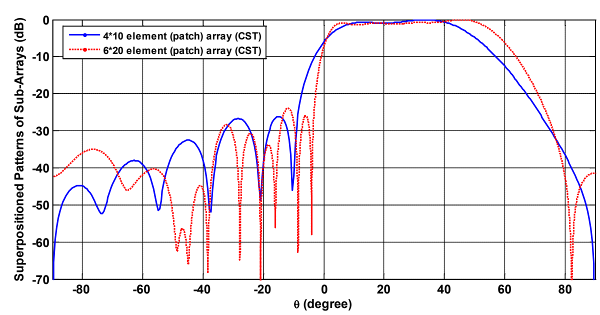

Fig. 6. The simulated radiation patterns of the 4x10 element and 6x20 element planar arrays including microstrip patch antennas.

The desired 60^o main width radiation pattern in $\theta = 90^o$ principal plane is also achieved using the microstrip antennas as the elementary antenna as seen from Fig. 6. It is illustrated that the *MSLL* of the total radiation pattern is restricted with -25 dB. It is obvious that the coverage of 6x20 element rectangular microstrip array in the 60^o width region is better than the coverage of 4x10 element array pattern.

V. CONCLUSION

In this work, a simple method is presented to synthesize a rectangular planar array antenna with a flat top characteristic within the given $0^o \le \phi \le \phi_{\max}$ region in the $\theta = 90^o$ principal plane to be used in the volume scanning radars. In the synthesis process, linear sub-arrays are taken as the units so that each of which main beam is collimated to the pre-determined direction with a permissible beam width so as to cover the overall main beam flat characteristics.

The synthesis process can be shortened with a suitable geometry. In our worked examples, the linear sub-arrays are placed along the *x*-axis symmetrically with respect to the y-axis. Thus the number of the unknowns is reduced half of the original number. All the elementary antennas in the array are excited with Dolph-Chebyshev amplitudes to provide the required beamwidth for the linear sub-array units. Thus, the resulted far field patterns of each sub-array are collimated to the determined directions, rather than collimating the array elements to the different directions [11]. Thus, the desired overall far field pattern characteristic is synthesized as superposition of contribution of each linear sub-array.

The effects of the number of sub-arrays and the number of antennas in each sub-array on the coverage region are investigated by synthesizing the planar array with different number of antennas. Moreover, the excitation amplitudes are optimized by genetic algorithm to obtain more compatible pattern with the desired pattern. Half-wave dipoles and microstrip patches are utilized as the elementary antenna and the simulation results are obtained using CST. The simulation results verify that the proposed simple method can be used successfully in volume scanning arrays.

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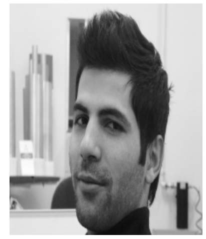

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