Pattern Synthesis for a Conformal Array Antenna Mounted on a Paraboloid Reflector Using Genetic Algorithms

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Abstract **─** In this article a 12×1 conformal array antenna is designed for Identification Friend or Foe (IFF) applications. Using Genetic Algorithm (GA), the phase and amplitude weights of each element mounted on a paraboloid reflector surface is calculated. To have a broadband array with adjusted integrated balun, an optimized printed dipole is chosen as an array element. The effect of mutual coupling between the elements is taken into account through using the Multi-Level Fast Multipole Method (MLFMM). The gain of the antenna is about 15.4 dBi with a 3 dB beam width of 67° and 12° in the two principal planes. Also, the side lobe level of the H-plane pattern is below -25 dBi.

Index Terms **─** Conformal array antenna, Genetic Algorithm (GA), Identification Friend or Foe (IFF).

I. INTRODUCTION

Conformal array antennas are used in many different applications due to their advantages of volume saving, reduction of radar cross-section, reduction of aerodynamic drag, potential increase in available aperture, etc. [1], [2]. There are a wide variety of techniques that have been developed for their analysis and synthesis, which include matrix method using near-field data [3], Least-Mean-Squares methods (LMS) [4], projection methods [5], optimization methods [6]-[9], Volume-Surface Integral Equation (VSIE) formulation and pre-corrected-Fast Fourier Transform method (p-FFT) fast solver [10]. Another approach for the fast analysis of irregular arrays is based on the use of p-series expansion and NUFFT routines [11]. Also, adaptive array methods have been successfully applied to synthesizing pattern of conformal antenna array [12].

Iterative methods based on optimization techniques are very powerful tools for pattern synthesis [2]. Particle Swarm Optimization (PSO) [13] and Differential Evolution Algorithm [14], were used in the array pattern synthesis.

One possible optimization method is Genetic Algorithm (GA) technique, which using to select the excitation magnitudes and phasing that would synthesis best array radiation pattern. Genetic algorithm techniques have been used to optimize array characteristics; for example, in [15] for the reduction of side lobes.

In [16], a hexagonal configuration of an array is placed on a paraboloidal surface and is compared with a planar array of the same projected aperture. In this paper, we synthesize a twelve-element array antenna to conform to a parabolic reflector surface for volume saving. The parabolic reflector is a common surface for radar application. In portable vehicles, the available space for antennas is limited. The proposed structure designed for IFF frequency band and the parabolic surface can be used for an antenna at X-band as a reflector at the same time. However, this method can be applied on the other kinds of surfaces. Therefore, the projection method is used to select element excitations for conformal arrays. This method is not respondent alone, but the achieved values would be useful for characterizing the range of optimization parameters to reduce the time of calculations by genetic algorithm.

For synthesis of the conformal array, we will use genetic algorithm and take the amplitude and phase weights as optimization parameters to give an antenna pattern with low side lobe level, low

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HPBW in elevation plane and maximum gain to satisfy the pattern characteristic required to IFF systems. The proposed array structure is modeled through the software package CST Microwave Studio 2011, using the integral equation solver which is of special interest for electrically large models. In [17], an approximated method is proposed to solve the time consuming issue of a large array modeled with MOM which it neglects the coupling. For calculation efficiency, the equation system is solved by the Multi-Level Fast Multipole Method (MLFMM) for electrically large models. The system matrix is dense because every element couples to all other elements. The single level Fast Multipole Method (FMM) uses boxes to combine the couplings. A recursive scheme is used for the MLFMM to increase the efficiency.

II. ANTENNA ELEMENT DESIGN

We select the printed dipole with adjusted integrated balun proposed in [18] as array element which features a broadband performance. Since the position of feed point (illustrated in Fig. 1) is an adjustable parameter, the adjusted integrated balun match to different impedance values, which is useful for antenna arrays because the mutual coupling between array elements change the input impedance of each antenna element.

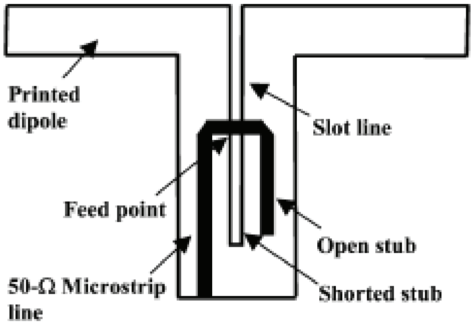

Fig. 1. Printed dipole with a modified integrated balun [18].

This antenna is designed for IFF applications at the L-band and is simulated on a substrate of RO4003 with a dielectric constant of ε_r=3.55 and a loss tangent of 0.0027. The dipole and a slot line are printed on the back side and microstrip line of integrated balun printed on the front side of the substrate. The printed dipole with adjusted integrated balun fed by a coaxial line underneath the ground plane as illustrated in Fig. 2.

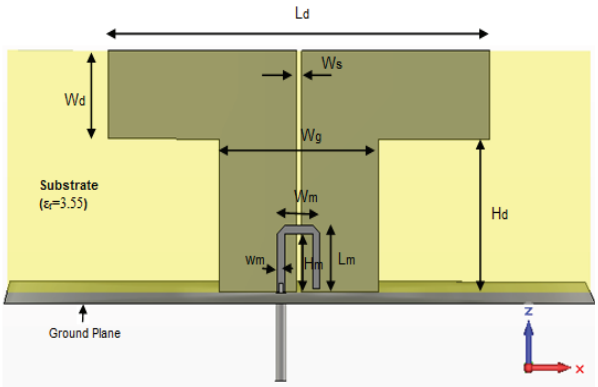

Fig. 2. Geometry of the printed dipole with adjusted integrated balun.

The geometric parameters of the antenna element are listed in Table 1. Figure 3 shows the CST simulated S11 of the printed dipole antenna. The simulated S11-10 dB bandwidth is from 0.86 to 1.22 GHz, which means the impedance bandwidth is ~34%. The simulated E- and H-plane radiation patterns of the printed dipole at the center frequency of 1.06 GHz are shown in Fig. 4.

Table 1: Geometric parameters of the printed dipole with adjusted integrated balun

L_d	144 mm	W_m	16 mm
W_d	30 mm	H_m	20 mm
H_d	52 mm	W_s	1.8 mm
W_g	60 mm	w_m	1.8 mm
L_m	23 mm	t (thickness of substrate)	0.81 mm

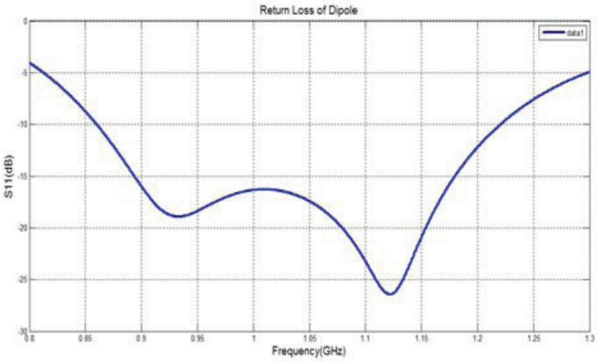

Fig. 3. Input reflection coefficient of the dipole.

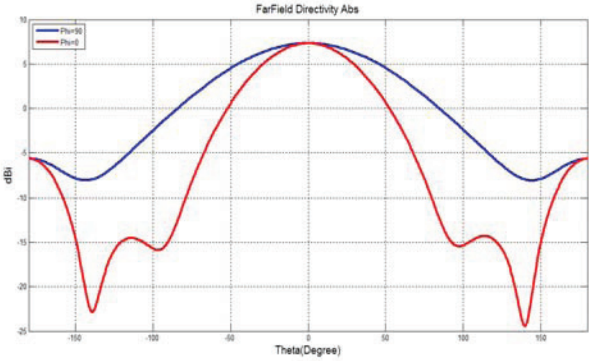

Fig. 4. Radiation pattern of the dipole.

III. CONFORMAL ARRAY SYNTHESIS

A. Theory

We consider a conformal array composes N elements which are mounted on a parabolic reflector surface, as shown in Fig. 5. The equation for a paraboloid of revolution can be written as:

$$4f(z-h)=-(x^2+y^2), \tag{1}$$

where f is the focal distance. We consider an array of antenna elements uniformly spaced in a straight line along the surface of a parabolic platform of finite length according to above equation.

Since the desired polarization of the reflector is horizontal, the printed dipoles lying in x-z plane orthogonally in order to obviate the mutual coupling effects between the reflector and the array antenna.

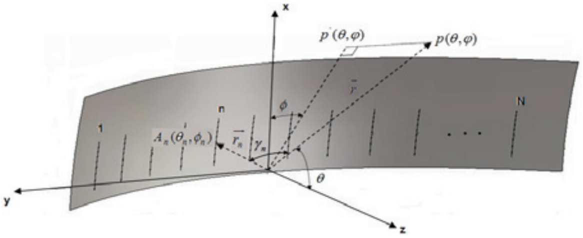

Fig. 5. The conformal antenna array element mounted on a parabolic reflector surface.

The total far-field radiation pattern of the array contains N elements can be expressed as:

$$E(\theta,\phi)=\sum_{n=1}^{N}I_n f_n(\theta,\phi)e^{j(kR_n\cos\gamma_n+\varphi_n)}, \tag{2}$$

where I_n is the element excitation current amplitude, φ_n is the excitation current phase, and $f_n(\theta,\phi)$ characterizes the individual element pattern for A_n. R_n is the distance between A_n and the coordinate origin o. γ_n is the angle between reference direction vector $\vec{r}$ and element position vector $\vec{r_n}$, and k is the free-space wave-number. Moreover, there are the following parameters in the array of Fig. 5 which expressed as:

$$\hat{r}=\hat{x}\sin\theta\cos\phi+\hat{y}\sin\theta\sin\phi+\hat{z}\cos\theta, \tag{3}$$

$$\hat{r}_n=\hat{x}\sin\theta_n\cos\phi_n+\hat{y}\sin\theta_n\sin\phi_n+\hat{z}\cos\theta_n, \tag{4}$$

$$\begin{aligned}\cos\gamma_n &= \hat{r}\hat{r}_n=\sin\theta\sin\theta_n\cos\phi\cos\phi_n\\ &+\sin\theta\sin\theta_n\sin\phi\sin\phi_n+\cos\theta\cos\theta_n\\ &=\cos^2[(\phi-\phi_n)/2]\cos(\theta-\theta_n)\\ &+\sin^2[(\phi-\phi_n)/2]\cos(\theta+\theta_n),\end{aligned} \tag{5}$$

$$\vec{r}_n=\hat{x}A_n(x)+\hat{y}A_n(y)+\hat{z}A_n(z), \tag{6}$$

$$\begin{aligned}R_n\cos\gamma_n &= \vec{\gamma}_n\hat{\gamma}=A_n(x)\sin\theta\cos\phi\\ &+A_n(y)\sin\theta\sin\phi+A_n(z)\cos\theta.\end{aligned} \tag{7}$$

The phasing parameter φ_n may be used to steer the main beam of the array radiation pattern by selecting its value according to:

$$\begin{aligned}\varphi_n &= -k[A_n(x)\sin\theta_0\cos\phi_0\\ &+A_n(y)\sin\theta_0\sin\phi_0+A_n(z)\cos\theta_0],\end{aligned} \tag{8}$$

where (θ_0,φ_0) is the desired steering angle.

With above conditions, Eq. (2) may be written as:

$$\begin{aligned}E(\theta,\phi) &= \sum_{n=1}^{N}I_n f_n(\theta,\phi)\exp\{j[k(A_n(x)\sin\theta\cos\phi\\ &+A_n(y)\sin\theta\sin\phi+A_n(z)\cos\theta)+\varphi_n]\}.\end{aligned} \tag{9}$$

B. MLFMM

The radiation pattern of the individual array element that mounted on the parabolic surface is influenced by their location on the platform. Thus, each individual array element pattern is different. This subject makes the radiation pattern synthesis procedure complicated. The radiation pattern of the elements with considering the effect of the mutual coupling between the elements achieve by calculating the antenna array using the Multi-Level Fast Multipole Method (MLFMM). Here, we use genetic algorithm as a synthesis technique for determining the optimal set of excitation amplitudes and phases required to make desired pattern by the actual radiation patterns of each element in presence of other elements and platform determined by MLFM method.

The MLFMM is an alternative formulation of the technology behind the MoM and is applicable to much larger structures than the MoM, making full-wave current-based solutions of electrically large structures a possibility. This fact implies that it can be applied to most large models that were previously treated with the MoM without having to change the mesh.

The effects of parabolic reflector and dipole placement on the radiation patterns of the individual array elements are considered in Fig. 6.

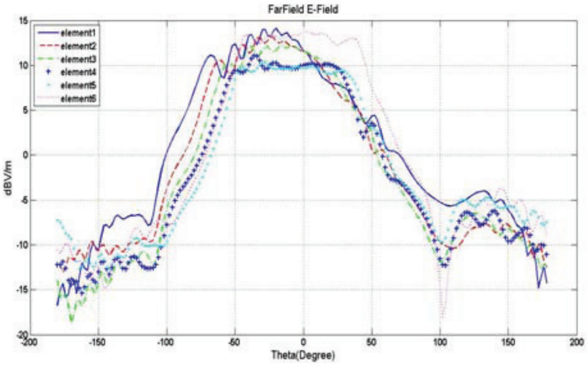

Fig. 6. Element patterns for the array elements mounted on the parabolic reflector illustrated in Fig. 5. Because of symmetry, the radiation patterns of other elements are identical.

The MLFMM is used to calculate the radiation pattern associated with each of the twelve printed dipole antennas for the configuration shown in Fig. 5. Because of the mutual couplings of all elements, the system matrix is considerably dense. Therefore, MLFMM is used because it is suitable for electrically large models. The plots of Fig. 6 clearly show that the radiation pattern produced by an individual printed dipole antenna element is strongly dependent upon the location at which it is placed on the doubly curved parabolic reflector platform. These plots specify that the closer to the end of the reflector the element is placed, the pattern will become more distorted. The far field radiation pattern for this parabolic reflector-mounted array must be calculated using (9).

C. Genetic algorithm

Genetic algorithms are a family of computational models inspired by evolution. These algorithms encode a potential solution to a specific problem on a simple chromosome-like data structure and apply recombination operators to these structures as to preserve critical information. Genetic algorithms are often viewed as function optimizer; although, the ranges of problems to which genetic algorithms have been applied are quite broad. An implementation of genetic algorithm begins with a population of (typically random) chromosomes. One then evaluates these structures and allocated reproductive opportunities in such a way that these chromosomes which represent a better solution to the target problem are given more chances to 'reproduce' than those chromosomes which are poorer solutions. The 'goodness' of a solution is typically defined with respect to the current population. To illustrate the working principles of GA, an unconstrained optimization problem is considered. We consider following minimization problem:

$$\mathit{Minimize} f(x), x_i^l \le x_i \le x_i^u, i = 1, 2, \ldots, N, \tag{10}$$

where x_i^l and x_i^u are the lower and upper bound the variable x_i can take.

The advantage of the GA approach is the ease with which it can handle arbitrary kinds of constraints and objectives; all such things can be handled as weighted components of the fitness function, making it easy to adapt the GA scheduler to the particular requirements of a very wide range of possible overall objectives.

In this paper, the GA will be used to choose the optimal excitation amplitude and phase parameters for each element. The main tasks of the optimization are to minimize the side-lobes, HPBW to a certain level, and achieve the maximum gain. Thus, the fitness function can be written as:

$$\begin{aligned} \mathit{Fitness}(\overline{X}) = {} & w_1 \left| 20\log\left(\frac{1}{\theta_{SLL}} \sum_{\theta\in\theta_{SLL}} E(\overline{X},\theta,\phi_0) \right) - SLL_d \right| \\ & + w_2 \left| 20\log\left(\frac{1}{\theta_G} \sum_{\theta\in\theta_G} E(\overline{X},\theta,\phi_0) \right) - G_d \right| \\ & + w_3 \left| 20\log\left(\frac{1}{\theta_{HPBW}} \sum_{\theta\in\theta_{HPBW}} E(\overline{X},\theta,\phi_0) \right) - HPBW_d \right|, \end{aligned} \tag{11}$$

where $E(\overline{X},\theta,\phi_0)$ is the far-field values calculated from (9). SLL_d and G_d represent desired Side

Lobe Level and Gain, respectively, and $HPBW_d$ is target 3 dB beam width at angle of $\phi_0 = 90^\circ$. w_1, w_2, w_3 are the weight coefficients in the fitness function.

IV. RESULTS

A twelve-element conformal antenna array mounted on a parabolic reflector was modeled via CST to yield radiation pattern of each element in presence of others. The simulated conformal array antenna is shown in Fig. 7.

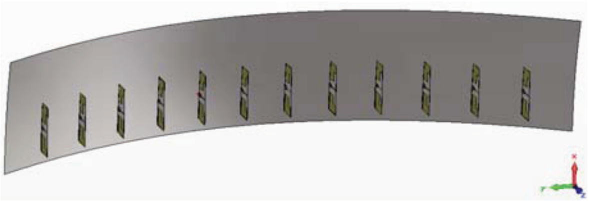

Fig. 7. Twelve-element conformal array of the printed dipole with adjusted integrated balun.

When the inter-element spacing is more than 1λ, the grating lobes are formed, because of the periodicity of the array factor. Also, we should consider mutual coupling effects on array design. Thus, with aspect to this consideration, the element spacing is chosen 18.5 cm. The parabolic reflector under consideration has a length of 240 cm and a focal distance of 90 cm. Analysis and optimization together with CST is a time- and memory-consuming method. For optimization, first the pattern of each element was obtained by MLFMM in CST MWS solver and then was transformed to MATLAB for optimization by GA. The excitation distribution is optimized using genetic algorithm to achieve a minimum Side Lobe Level (SLL) of -25 dB and a 3 dB beam width of 67° and 12° in E-plane and H-plane, respectively, and the gain of 15 dBi at the center frequency.

The population size durig process and the maximum of generations are 140 and 85, respectively. Figure 8 represents the fitness function value in the iterations of genetic algorithm. The optimization parameters SLL=-25 dB, Gain=15 dB and HPBW of 12° obtained in the operational plane (YZ-plane). Figure 9 shows some selected radiation patterns in relative iterations during optmization. The optimization time was about 1 hour on a core-i5 CPU PC. The resulting radiation pattern of the conformal array antenna achieved by optimization using genetic algorithm shows in Fig. 10.

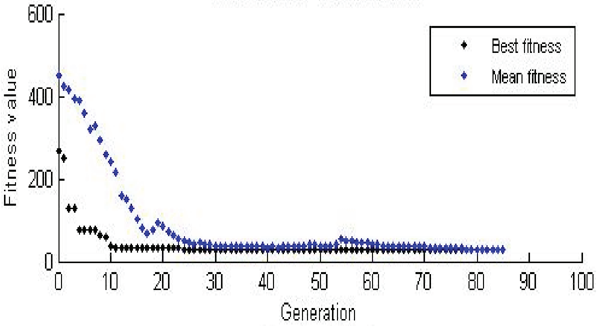

Fig. 8. The objective function value of the best point in the population for GA runs.

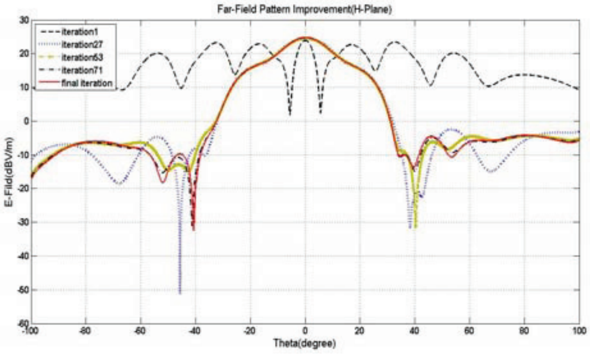

Fig. 9. Far-Field E-Field pattern improvement in some selected iterations during genetic algorithm optimization.

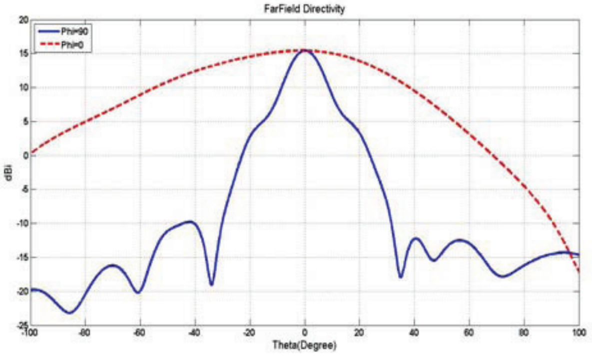

Fig. 10. Optimized E and H-plane radiation patterns of the conformal array antenna at center frequency.

Amplitude and phase weights of the 6 elements of the conformal array which optimized by genetic algorithm are shown in Table 2. Because of the symmetrically of the structure, weights of other 6 elements are identical. In optimization, we consider the location of the elements 6th and 7th as reference points, and other phase weights are based on their distances of these elements.

Table 2: Optimized amplitude and phase weights of the conformal array by GA

Element	Amplitude	Phase (degree)
1	0.03183	-351.038
2	0.22667	-243.916
3	0.0532	-136.87
4	0.4948	-50.713
5	0.9997	-25.4
6	0.97015	0

The sum radiation patterns in the two principal planes are shown in Fig. 11 and Fig. 12 at both frequencies of 1030 MHz and 1090 MHz. Figure 13 shows the difference pattern of the array which is obtained by 180° phase shifting in the half of elements phase weights.

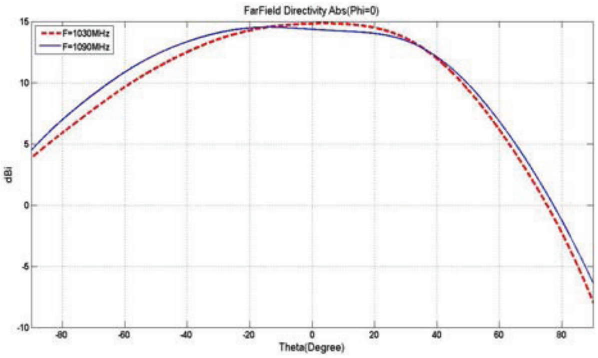

Fig. 11. Sum radiation pattern (E plane).

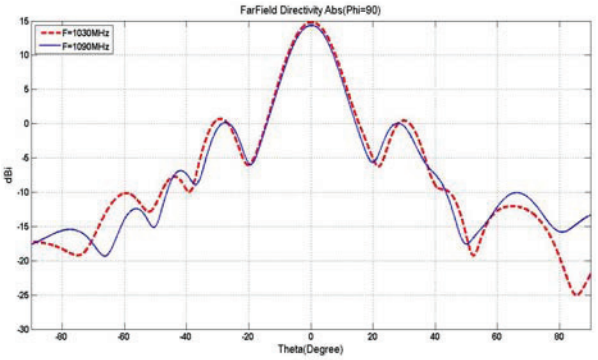

Fig. 12. Sum radiation pattern (H plane).

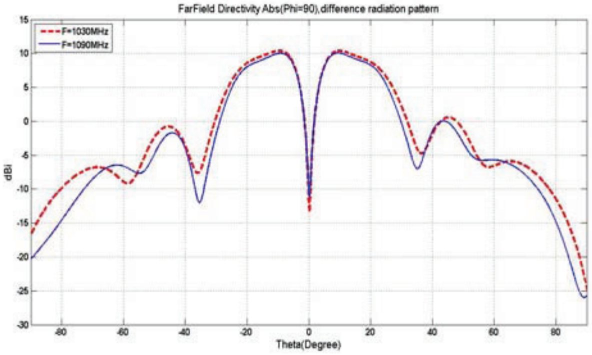

Fig. 13. Delta radiation pattern (H plane).

V. CONCLUSION

A 12x1 conformal antenna array mounted on a parabolic reflector surface is proposed for serving L band (1025-1095 MHz) IFF systems. The basic array element is an optimized printed dipole with adjusted integrated balun. In this array structure, all elements of the array have not identical element pattern, so the synthesis of the conformal array is difficult. In this paper, we used genetic algorithm to synthesize the radiation pattern of the conformal array antenna. This synthesis technique yields the optimal set of excitation current amplitudes and phases required to compensate as much as possible for platform effects and mutual coupling effects on the individual array element patterns. The coupling of antennas and their platform can be taken into account by using of the Multi-Level Fast Multipole Method.

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