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Generation of Narrow Beams using differential Evolution Algorithm from Circular Arrays

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ABSTRACT

Concentric circular arrays are increasingly shown more interest in antenna design for generating low sidelobe patterns as they have radial symmetry and an invariant beam in the azimuthal plane. Such patterns are desirable in low EMI applications. In the present work, an attempt is made to generate low sidelobe patterns from concentric circular arrays by optimizing both ring radii and individual element excitations. The array is also subjected to thinning simultaneously. Thinning results in sidelobe reduction while keeping the number of active elements small. For each optimum configuration, the optimal ring radii and the amplitude excitation levels are obtained using Differential Evolution algorithm. Results are presented for 8, 10 concentric rings.

Keywords

Concentric Circular Array Antenna, Array Thinning, Optimization, Sidelobe Reduction, Differential Evolution.

1. INTRODUCTION

In many applications it becomes necessary to design antennas with directive radiation characteristics. Antenna arrays not only provide high gain but they also increase directivity. Careful design of antenna arrays results in patterns with desired radiation characteristics [1]. Planar arrays have better control than linear arrays over radiation characteristics.

A circular array is a planar array with elements arranged on a circle. A concentric circular array is an array of such circular arrays all sharing same center with different radii [2]. They are given more importance as they have attractive features like compact antenna structure, a beam pattern which remains constant in the azimuthal plane. As there are no edge elements, the directional pattern generated can be easily scanned in the array plane. These are used in various applications like radio direction finding, air and space navigation, mobile, radar and wireless communication applications [3-4].

A Uniform Concentric Circular Array (UCCA) is one where all the elements have an inter element spacing set to half wavelength and are given uniform excitation. Although this array exhibits high directivity, it suffers from high side lobes.

Reduction in side lobe level can be achieved by varying the ring radii, by non-uniformly exciting elements or by placing the elements unequally. A lot of research work was carried out for generating patterns with low side lobe levels. In [5], array factor for a concentric ring array with constant ring spacing was approximated as a truncated Fourier-Bessel-Series, from which the excitation weights for each ring were obtained to generate chebyshev like pattern. In [6], Goto and Cheng showed that the maximum inter element spacing should be less than 0.4λ for a taylor weighted ring array to avoid appearance of high side lobes. In [7], Biller and Friedman employed steepest descent method to obtain element weights and ring spacing that result in low side lobes as well as control over beamwidth. In [8], Huebner carried out optimization of small concentric ring arrays for low side lobe levels by finding proper ring spacings. Kumar and Branner [9] generated low side lobes from circular arrays by optimizing ring radius. Dessouky et al. [10] showed that low side lobes can be obtained by placing an active element at the centre of concentric array at the cost of small increase in the beamwidth.

Array thinning is another technique for generating low side lobe field patterns [11-12]. It results in reduction of cost and weight of the antenna array. Thinning is carried out by removing certain elements from the array without degrading the system performance. The elements which remain 'ON' (active) are given excitation levels necessary for side lobe reduction. Another advantage offered by thinning is that, the beamwidth can be maintained approximately same as for a fully filled array. Aperiodic array synthesis aims at reducing side lobes by strategically placing uniformly weighted elements. Thinning is simpler than aperiodic synthesis as a 'n' element array involves checking of 2^n possible combinations only. As 'n' becomes large, traditional methods won't work and one has to go for optimization techniques. Many global optimization techniques such as GA [13], PSO [14], BBO [15], Firefly Algorithm [16] etc were successfully applied for thinning of concentric ring arrays. Differential Evolution Algorithm [17] is used in the present work for optimization problem. It is an efficient search algorithm successfully applied for solving many optimization problems [18-20].

In the present work, Concentric Circular Arrays are thinned along with varying ring radii and non-uniformly exciting elements with an objective of side lobe reduction. The optimum array configurations are obtained by employing a Differential Evolution algorithm. The process is carried out in two steps. In the first step, a 'm' ring array is considered. Assuming all are isotropic elements, the array is first subjected to thinning only. Then in step two, ring radii and element excitations are also varied which resulted in reduced side lobes. The simulated results are presented for 8 and 10 rings. All results are simulated using Matlab software.

The paper is organized as follows. Section 2 gives a brief description of DE algorithm. Problem formulation is given in section 3. In section 4, results are presented. Conclusions are discussed in section 5.

2. DIFFERENTIAL EVOLUTION ALGORITHM

DE is a simple population based stochastic search algorithm. It was first proposed by Storn and Price [21]. It is another evolutionary algorithm which paved way for solving complex optimization problems. It is a powerful search technique which is successfully applied in many fields like communications, pattern recognition etc. The algorithm offers following advantages:

- It can easily handle non-linear, non-differentiable complex cost functions
- It has few easy to choose control parameters which influence the convergence of the algorithm
- Good convergence speed in finding optimum value

The main steps involved in the algorithm are described as below:

Step 1: Initialization: The algorithm starts with 'N' (at least equal to 4) population vectors. The individuals are called target vectors. The total number of these parameter vectors remains same throughout the algorithm. Let '$x_{i,G}$' represent the i^{th} parameter vector where i=1, 2… N. 'G' is the generation number. The parameter vectors are randomly initialized in step 1.

Step 2: Cost Evaluation: The initial $x_{i,G}$ parameter vectors are evaluated for their cost using the objective function.

Step 3: Mutation: In this step, new parameter vectors are generated by adding weighted difference between two target vectors to a third target vector, i.e. for a given target vector '$x_{i,G}$' , select three target vectors $x_{r1,G}$, $x_{r2,G}$, $x_{r3,G}$ such that i, r1, r2, r3 are distinct to form mutant vectors called 'donor vectors'.

$$V_{ji,G+1} = x_{r1,G} + F\left(x_{r2,G} - x_{r3,G}\right)$$

here r1, r2, r3 ∈ {1, 2…, N}

Mutation expands the solution space. The factor 'F' is called mutation factor. Usually it is a real constant chosen in the range 0 to 2.

Step 4: Crossover: It increases the diversity of parameter vectors by including good solutions or vectors from previous generations. It forms the new so called 'trail vectors ($u_{i,G+1}$)' by mixing elements of target vector '$x_{i,G}$', and donor vector '$v_{i,G+1}$'.

$$\begin{aligned} u_{ji,G+1} &= v_{ji,G+1} \; if \; rand \le CR \; or \; j = I_{rand} \\ &= x_{ji,G+1} \; if \; rand > CR \; and \; j \ne I_{rand} \end{aligned}$$

Here i=1,2…N; j=1,2…,D. D is the number of parameters in one vector. I_{rand} is a randomly number chosen in the range 1 to D which ensures that $u_{i,G+1}$ gets at least one parameter from $v_{i,G+1}$. CR is the crossover constant to be taken in the range (0,1).

Step 5: Selection: It imitates survival-of-the-fittest. It follows greedy scheme and selects vectors for next generation. The process is as follows:

$$\begin{aligned} x_{i,G+1} &= u_{i,G+1} \; if \; cost\left(u_{i,G+1}\right) \le cost\left(x_{i,G}\right) \\ &= x_{i,G} \quad otherwise \end{aligned}$$

That means, the newly generated trial vectors replace parent target vectors if they yield lower cost otherwise the parent target vectors are passed on to next generation.

Step 6: Stopping criteria: Steps 2 to 5 are repeated until some stopping criteria is met. Stopping criteria in general may be fixed number of generations or predetermined cost.

There are different schemes in DE suggested by Storn and Price [21]. In the present work, a DE/rand/1/binary scheme is used.

3. FORMULATION

The geometry of a 'm' ring concentric circular array with a single element at centre is as shown in figure 1. Assume all elements are isotropic elements. Let r_m represent the radius of m^{th} ring and let the number of elements present in m^{th} ring be N_m where m=1,2,..,M. Let d_m be the inter element spacing.

The array factor for the array [22] is given by

$$E(\theta) = 1 + \sum_{m=1}^{M} \sum_{n=1}^{N_m} I_{mn} \, A_{mn} \exp(jkr_m \sin\theta \cos(\emptyset - \emptyset_{mn})) \tag{1}$$

where M=number of rings

N_m=Number of elements in ring 'm'

I_{mn}=excitation of n^{th} element in m^{th} ring= '1' for ON

= '0' for OFF

r_m= radius of ring 'm'

A_{mn}= Amplitude excitation of n^{th} element in m^{th} ring

$\emptyset_{mn}$ = angular position of n^{th} element of m^{th} ring

$$= \frac{2\pi(m-1)}{N_m} \tag{2}$$

k=2π/λ

θ= elevation angle

∅=azimuthal angle=constant in the present work

In 'u' domain

$$E(u) = 1 + \sum_{m=1}^{M} \sum_{n=1}^{N_m} I_{mn} \, \mathrm{A_{mn}} \exp(jkr_m u \cos(\emptyset - \emptyset_{mn}))$$

where u=sinθ

The radius of m^{th} ring is given by $r_m=m\lambda/2$ (3)

The inter element spacing is assumed to be approximately λ/2 i.e. $d_m=\lambda/2$

The number of equally spaced elements present in ring 'm' is given by $N_m = \frac{2\pi r_m}{d_m}$ (4)

Since the number of elements must be an integer, the values in eq. (4) must be rounded up or down. To maintain $d_m \ge \lambda/2$, the digits present on right of the decimal point were dropped. All the elements have uniform excitation phase of zero degrees.

Present work is divided into two cases. In the first case, an 8 ring concentric array of isotropic sources is considered. The array is excited uniformly and the interelement spacing is set to half wavelength. The number of elements in each ring is calculated using eq. (4). The ring radii are calculated using eq. (3). The resulting far field pattern yields a peak SLL of -17.39dB. Now the array is subjected to thinning. The results show a reduction in peak SLL.

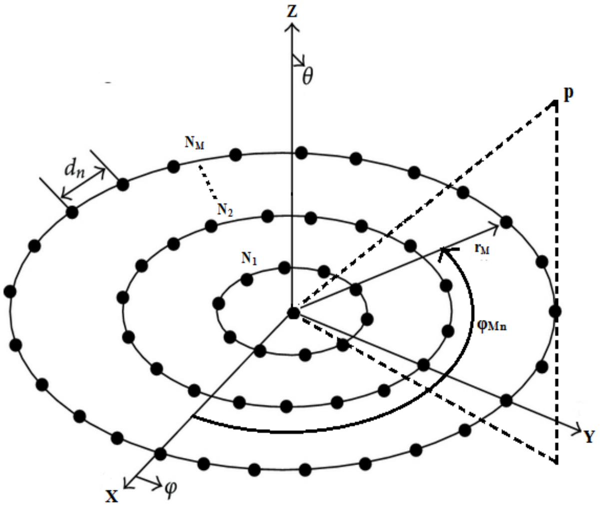

Figure 1. Concentric Circular array of isotropic antennas

In the second case, both ring radii and amplitude excitations of elements in each ring are optimized. The array is also thinned simultaneously. This resulted in further reduction of side lobes. Results are also presented for 10 rings following the same above mentioned procedure. All the optimum array configurations are acquired by employing a DE algorithm.

The objective function used for calculating the fitness of candidate solutions is as follows:

$$Fit = PSLL_o - SLL_d$$

where $PSLL_o = Max\left[20\log\left|\frac{E(u,)}{E_{Max}\,(u)}\right|\right]$ u ∈ side lobe region.

SLL_d =Desired Sidelobe level

$E_{max}(u)$=Main beam peak value

4. RESULTS

This section presents a brief description of results obtained for concentric circular arrays. An eight ring concentric array of isotropic sources with central element feeding is considered. An interelement spacing of half wavelength is maintained throughout for all optimum array configurations. The ring radii and number of elements in each ring are presented in Table 1. A DE algorithm is used for array thinning. Table 2 shows the corresponding ON/OFF status of the elements.

The resulting far field pattern after thinning is as shown in figure 2. A peak SLL of -31.08dB is obtained after thinning. An improvement of 13.7dB can be observed compared to -17.39dB obtained from a fully filled array.

Table 1. Ring radii for M=8 rings

Ring number	Radius	Number of elements in each ring
1	0.5	6
2	1.0	12
3	1.5	18
4	2.0	25
5	2.5	31
6	3.0	37
7	3.5	43
8	4.0	50

Table 2. Element status for M=8 rings

Ring number	Number of elements in each ring	Thinning weights (1=ON, 0=OFF)
1	6	1,1,1,1,1,0
2	12	0,0,0,0,0,1,1,0,1,1,1,1
3	18	0,1,1,1,1,1,1,1,1,1,0,0, 1,1,1,1,1,1
4	25	1,1,1,1,1,0,1,1,1,1,1,1, 0,1,0,1,0,1,0,1,1,1,1,1,1
5	31	1,0,1,1,1,0,0,1,1,1,0,1, 0,0,1,1,0,1,1,0,1,1,1,0, 1,0,1,0,0,1,1
6	37	0,1,1,0,1,0,0,1,1,1,1,1, 1,1,1,0,0,0,0,1,0,0,1,1, 1,0,0,1,1,1,1,1,1,0,0,0,0
7	43	1,0,0,1,1,1,0,1,0,1,1,1, 1,1,0,0,1,1,0,1,0,0,0,1, 0,1,1,0,0,0,0,1,0,0,1,1, 1,0,0,1,0,0,1
8	50	0,1,0,0,1,0,0,1,1,0,1,1, 1,1,1,1,0,0,0,0,1,0,0,1, 0,0,1,0,0,0,0,0,0,0,1,1, 0,0,1,1,1,0,1,0,1,0,1,0, 1,1

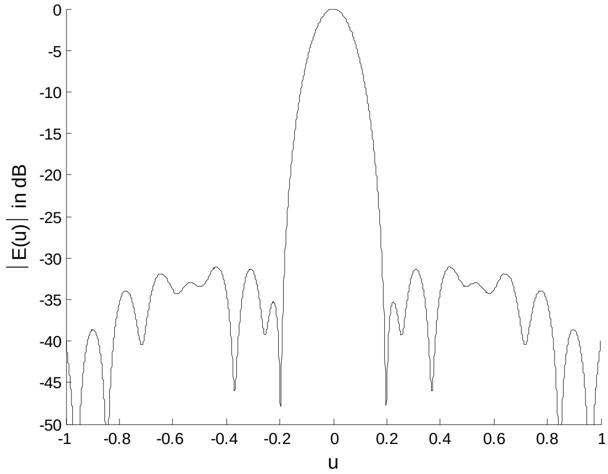

Figure 2. Radiation pattern for M=8 rings

The parameter selection plays an important role in convergence of the algorithm. The control parameter setting for a DE algorithm with DE/rand/1/binary strategy is as given in Table 3.

Table 3. Parameter selection

Parameters for DE	
Population size	30
Mutation	0.7
Crossover ratio	0.8
Number of generations	100

Now ring radii, element amplitude excitations are also optimized in addition to thinning. Table 4 shows the optimum radii and Table 5 shows the ON/OFF status for the 8 ring concentric array. The optimized element excitations in each ring are presented in Table 6.

Table 4. Optimum Ring radii for M=8 rings

Ring number	Radius	Number of elements in each ring
1	0.6629	8
2	1.3441	16
3	1.8695	23
4	2.5521	32
5	3.1786	39
6	3.6981	46
7	4.2538	53
8	4.8632	61

Table 5. Element status for M=8 rings

Ring number	Number of elements in each ring	Thinning weights (1=ON. 0=OFF)
1	8	1,1,0,1,0,0,0,0,
2	16	0,1,1,1,1,0,0,0,1,0,1,1, 0,0,0,1,
3	23	1,0,0,1,1,1,1,1,0,1,1,1, 0,1,1,0,1,1,1,1,0,1,0,
4	32	1,1,0,0,1,1,1,0,0,1,1,0, 1,1,0,0,0,0,1,0,1,1,1,0, 1,1,0,1,0,1,0,0,
5	39	1,0,0,0,0,1,1,1,0,1,0,0, 1,0,1,1,1,1,1,1,0,1,0,1, 1,1,0,1,1,0,1,1,1,0,1,0, 0,1,1,
6	46	0,1,1,0,0,1,1,1,1,1,0,1, 1,1,1,1,0,1,0,1,0,1,0,1, 0,1,0,1,1,1,0,0,0,1,1,1, 1,1,1,0,0,0,1,0,0,1,
7	53	1,0,0,0,0,0,0,1,0,0,1,1, 1,1,1,0,1,0,1,0,0,0,0,0, 0,0,1,0,0,1,1,1,0,1,1,0, 0,1,1,1,0,1,1,0,1,1,0,1, 0,1,1,0,1,
8	61	1,0,1,0,1,1,0,0,1,0,1,0, 1,0,0,1,1,0,0,0,1,0,1,1, 0,0,1,0,0,1,1,1,1,1,0,1, 0,1,1,0,0,1,1,1,1,1,0,0, 1,0,1,1,0,1,0,1,1,1,0,0,1

Table 6. Amplitude excitations for M=8 rings

Ring number	Number of elements in each ring	Element excitations
1	8	0.774,0.697,0.504,0.853,0.815, 0.802,0.610,0.900
2	16	0.873,0.289,0.628,0.824,0.383, 0.239,0.722,0.610,0.863,0.641,

		0.884,0.354,0.713,0.845,0.869, 0.641
3	23	0.174,0.446,0.190,0.103,0.437, 0.222,0.383,0.495,0.733,0.340, 0.621,0.395,0.475,0.565,0.721, 0.137,0.378,0.762,0.900,0.302, 0.900,0.547,0.261
4	32	0.887,0.900,0.447,0.186,0.720, 0.104,0.533,0.513,0.549,0.431, 0.389,0.707,0.573,0.675,0.893, 0.655,0.101,0.706,0.171,0.100, 0.349,0.802,0.399,0.348,0.888, 0.347,0.767,0.323,0.601,0.574, 0.900,0.494
5	39	0.736,0.160,0.871,0.900,0.735, 0.254,0.705,0.484,0.873,0.192, 0.280,0.768,0.872,0.100,0.843, 0.387,0.634,0.755,0.152,0.420, 0.834,0.899,0.862,0.452,0.309, 0.899,0.466,0.900,0.411,0.418, 0.495,0.631,0.900,0.159,0.758, 0.546,0.898,0.758,0.638
6	46	0.457,0.878,0.415,0.753,0.876, 0.365,0.296,0.883,0.524,0.809, 0.798,0.888,0.188,0.212,0.477, 0.349,0.283,0.217,0.834,0.266, 0.355,0.243,0.523,0.375,0.668, 0.556,0.240,0.549,0.134,0.219, 0.483,0.850,0.624,0.863,0.880, 0.606,0.831,0.100,0.460,0.642, 0.900,0.107,0.403,0.543,0.714, 0.186
7	53	0.418,0.895,0.616,0.900,0.131, 0.149,0.482,0.469,0.299,0.882, 0.826,0.670,0.784,0.794,0.869, 0.218,0.384,0.100,0.412,0.465, 0.443,0.380,0.740,0.785,0.857, 0.100,0.642,0.889,0.377,0.234, 0.461,0.306,0.770,0.107,0.900, 0.900,0.717,0.119,0.888,0.865, 0.842,0.401,0.424,0.330,0.495, 0.629,0.236,0.443,0.169,0.199, 0.492,0.891,0.253
8	61	0.109,0.753,0.100,0.677,0.262, 0.153,0.509,0.332,0.134,0.519, 0.100,0.201,0.734,0.276,0.262, 0.222,0.107,0.284,0.892,0.406, 0.863,0.900,0.139,0.525,0.381, 0.329,0.500,0.102,0.510,0.191, 0.526,0.154,0.100,0.108,0.120, 0.136,0.547,0.252,0.123,0.359, 0.301,0.640,0.337,0.820,0.721, 0.878,0.460,0.630,0.365,0.354, 0.498,0.793,0.755,0.145,0.736, 0.327,0.397,0.105,0.372,0.766, 0.9

The resulting radiation pattern is as shown in figure 3. In this case, a peak SLL of -34.56dB is obtained which shows a further improvement of around 3.5dB compared to previous case.

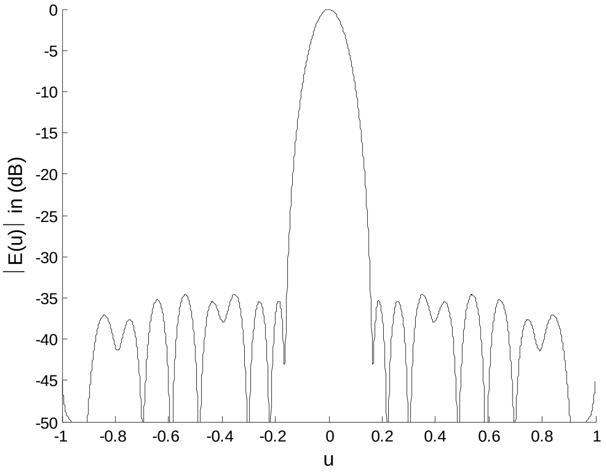

Figure 3. Radiation pattern for M=8 rings (both radii and element amplitudes optimized)

Similarly for 10 ring concentric circular array, Table 7 shows the ring radii and the organization of ON elements is shown in figure 4.

Table 7. Ring radii for M=10 rings

Ring number	Radius	Number of elements in each ring
1	0.5	6
2	1.0	12
3	1.5	18

4	2.0	25
5	2.5	31
6	3.0	37
7	3.5	43
8	4.0	50
9	4.5	56
10	5.0	62

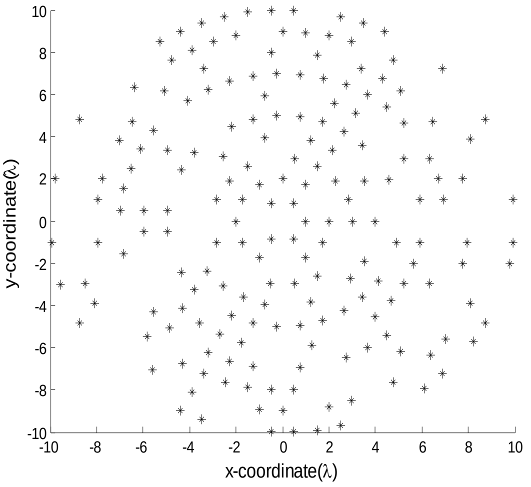

Figure 4. Element Status for M=10 rings

The far field pattern is shown in figure 5. A PSLL of -33.39dB is obtained for only thinning case.

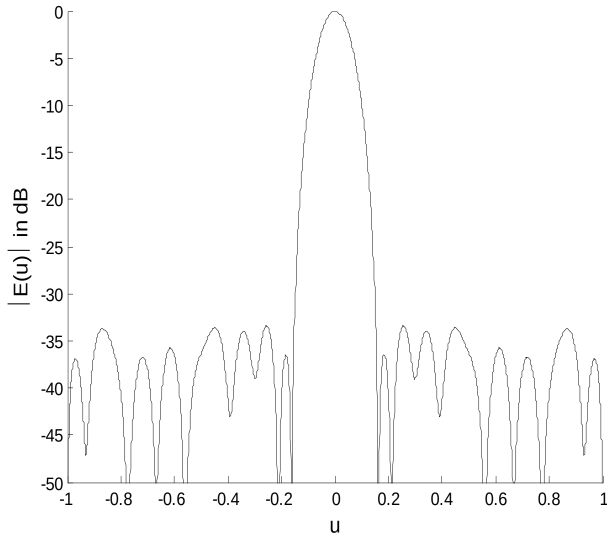

Figure 5. Radiation pattern for M=10 rings

Optimum ring radii for case two are listed in Table 8 and figure 6 shows the layout of ON elements. Figure 7 depicts the element excitations.

Table 8. Optimum ring radii for M=10 rings

Ring number	Radius	Number of elements in each ring
1	0.581	7
2	1.172	14
3	1.684	21
4	2.276	28
5	2.839	35
6	3.349	42
7	3.876	48
8	4.431	55
9	5.027	63
10	5.623	70

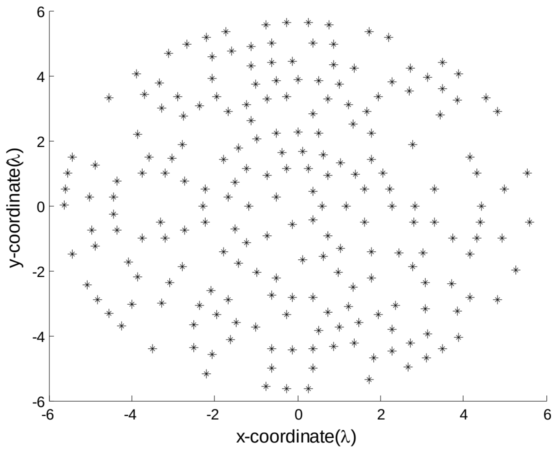

Figure 6. Element Status for M=10 rings

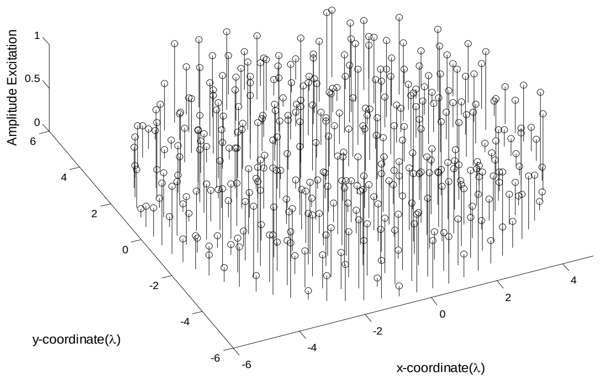

Figure 7. Amplitude excitations for M=10 rings

Figure 8 shows the corresponding radiation pattern. A PSLL of -35.75dB is obtained in this case. An improvement of around 2.36dB can be observed.

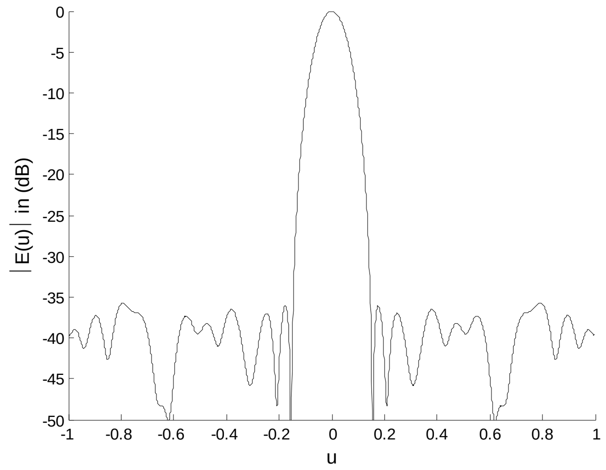

Figure 8. Radiation pattern for M=10 rings (both radii and element amplitudes optimized)

The comparison of Peak SLLs obtained for 8 and 10 rings for both considered cases using DE is presented in Table 9 for the sake of convenience.

Table 9. Comparison of PSLL obtained using DE and GA

Case1: Thinning only	M=8	M=10
	-31.0793dB 59.009%	-33.3970dB 55.2941%
Case 2: Thinning and Variable Element Amplitudes and variable radii	M=8	M=10
	-34.5645dB 56.1151%	-35.7562dB 55.0914%

The table also lists the percentage of thinning values for both ring configurations for the considered two cases. Percentage of thinning is defined as follows:

% of thinning= (Number of ON elements/ Total number of elements)*100

From the results, it can be seen that the second method where ring radii and element excitations are both optimized in addition to thinning, resulted not only in low side lobe levels but also a reduction in percentage of thinning. That means better PSLL values are achieved even after removal of certain elements through second method. The programming is done in Matlab Language and the algorithm is run for 100 generations in each run.

5. CONCLUSIONS

The paper presents the synthesis of low sidelobe patterns from concentric circular arrays. Two cases are considered. In the first case, the arrays are only thinned. In the second case, the ring radii and element amplitudes are also optimized in addition to array thinning. Results are presented for 8, 10 ring concentric arrays. Results clearly show that the second case resulted in lower sidelobe levels while keeping the number of active elements minimum. The percentage of thinning is maintained well below 60% for the second case. All the optimal solutions are derived by employing a Differential Evolution Algorithm. All results are simulated using Matlab software. The work can be extended to non-isotropic elements and to different geometries.

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