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Linear Antenna Array Synthesis Using Taguchi's Method: A Novel Optimization Technique in Electromagnetics

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***Abstract*—We describe a new global electromagnetic optimization technique using Taguchi's method and apply it to linear antenna array design. Taguchi's method was developed on the basis of the orthogonal array (OA) concept, which offers systematic and efficient characteristics. This paper illustrates the implementation procedure of Taguchi's method in electromagnetic optimization problems. The optimization procedure is then used to design two linear antenna arrays with specific array factor requirements. Obtained results show that the desired null controlled pattern and sector beam pattern are successfully achieved. Compared to traditional optimization techniques, Taguchi's method is easy to implement and efficient to reach the optimum solutions.**

***Index Terms*—Array synthesis, linear array, optimization method, orthogonal array, Taguchi method.**

I. Introduction

In general, experiments are used to study the performance of systems or processes. According to the results of the current experiment, one may adjust the values of system parameters in the next experiment in order to achieve a better performance, which is called a *trial and error approach.* The drawback of this strategy arises when the obtained result is not the optimum or the system requirements cannot be satisfied after a large number of experiments. Alternatively, researchers may want to test all combinations of parameters in an experiment, which is called a *full factorial experiment.* This strategy can cover all possibilities in the experiment and determine the optimal result. However, it will run too many trials, costing too much time and money in practice.

In order to solve the above difficulties, Taguchi's method was developed based on the concept of the orthogonal array (OA), which can effectively reduce the number of tests required in a design procedure [1]. It provides an efficient way to choose the design parameters in an optimization problem. Although Taguchi's method has been successfully applied in many fields such as chemical engineering, mechanical engineering, integrated chip manufacture, and power electronics [2]–[5], it is not well known to the electromagnetic community, and only limited applications are available for the design of absorbers [6], [7], electrically conductive adhesives [8], diplexers [9], and statistical characterization of microwave circuit parameters [10]. It is the goal of this paper to introduce Taguchi's method to the electromagnetics community and demonstrate its great potential in electromagnetic optimizations.

Linear antenna array optimization has received a great attention in the electromagnetics community. Recently the genetic algorithm (GA) and particle swarm optimization (PSO) have been successfully applied in designing linear antenna arrays [11]–[17]. Besides GA and PSO methods, this paper uses a new global electromagnetic optimization technique, Taguchi's method, to design linear antenna arrays that produce a null controlled pattern and a sector beam pattern. A detailed implementation procedure is presented, and each step is illustrated by the array example. This paper shows that the proposed method is straightforward and easy to implement and can quickly converge to the optimum designs.

II. Orthogonal Arrays

Orthogonal arrays (OAs), which have a profound background in statistics [18], play an essential role in Taguchi's method. Orthogonal arrays were introduced in the 1940s and have been widely used in designing experiments. They provide an efficient and systematic way to determine control parameters so that the optimal result can be found with only a few experimental runs. This section briefly reviews the fundamental concepts of orthogonal arrays, such as their definition, construction, and important properties.

A. Definition of Orthogonal Arrays

Definition: Let S be a set of s symbols or levels. A matrix A, commonly called an array, of N rows and k columns with entries from S is said to be an *orthogonal array with s levels and strength* $t (0 \leq t \leq k)$ if in every $N \times t$ subarray of A, each t-tuple based on S appears exactly the same times as a row [18, Ch. 1].

The notation OA(N, k, s, t) is used to represent an orthogonal array. To help readers understand the OA definition, Table I shows an orthogonal array OA(27, 10, 3, 2), which has 27 rows and 10 columns. Each entry of the array is selected from a set $S = \{1, 2, 3\}$. Thus, this is a three-level orthogonal array. Pick any two $(t = 2)$ columns, and one may see nine possible combinations as a row: (1, 1), (1, 2), (1, 3), (2, 1), (2, 2), (2, 3), (3, 1), (3, 2), (3, 3). It can be easily proved that each combination appears exactly the same number of times as a row, i.e., three times.

When this OA is used to design experiments, ten columns represent ten parameters that need to be optimized. The entry levels

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TABLE I
THE OA(27, 10, 3, 2), FITNESS VALUES, AND S/N RATIOS IN THE FIRST ITERATION OF THE NULL CONTROLLED PATTERN OPTIMIZATION

Experiment \ Element	1	2	3	4	5	6	7	8	9	10	Fitness	S/N Ratio (dB)
1	1	1	1	1	1	1	1	1	1	1	5.153	-14.240
2	2	1	2	2	2	3	3	1	2	3	9.076	-19.157
3	3	1	3	3	3	2	2	1	3	2	9.578	-19.625
4	1	2	1	2	2	2	3	3	1	2	9.847	-19.866
5	2	2	2	3	3	1	2	3	2	1	6.821	-16.676
6	3	2	3	1	1	3	1	3	3	3	14.233	-23.066
7	1	3	1	3	3	3	2	2	1	3	12.898	-22.210
8	2	3	2	1	1	2	1	2	2	2	9.911	-19.922
9	3	3	3	2	2	1	3	2	3	1	9.073	-19.155
10	1	1	2	1	2	2	2	3	3	1	9.245	-19.319
11	2	1	3	2	3	1	1	3	1	3	14.696	-23.344
12	3	1	1	3	1	3	3	3	2	2	11.785	-21.427
13	1	2	2	2	3	3	1	2	3	2	7.690	-17.719
14	2	2	3	3	1	2	3	2	1	1	7.220	-17.171
15	3	2	1	1	2	1	2	2	2	3	11.447	-21.174
16	1	3	2	3	1	1	3	1	3	3	12.176	-21.710
17	2	3	3	1	2	3	2	1	1	2	7.716	-17.748
18	3	3	1	2	3	2	1	1	2	1	7.553	-17.563
19	1	1	3	1	3	3	3	2	2	1	10.495	-20.419
20	2	1	1	2	1	2	2	2	3	3	11.054	-20.871
21	3	1	2	3	2	1	1	2	1	2	12.142	-21.686
22	1	2	3	2	1	1	2	1	2	2	10.197	-20.169
23	2	2	1	3	2	3	1	1	3	1	11.646	-21.324
24	3	2	2	1	3	2	3	1	1	3	11.940	-21.540
25	1	3	3	3	2	2	1	3	2	3	11.702	-21.365
26	2	3	1	1	3	1	3	3	3	2	11.695	-21.360
27	3	3	2	2	1	3	2	3	1	1	9.354	-19.420

1, 2, and 3 denote three possible options for each parameter. Each row describes a possible combination of the level values for these ten parameters. For example, the second row means that parameters 2 and 8 take level 1, parameters 1, 3, 4, 5, and 9 take level 2, and parameters 6, 7, and 10 take level 3. Once each parameter is assigned a specific level value, one could conduct the experiment and find the corresponding output. This OA has 27 rows, which means 27 experiments need to be carried out.

B. Important Properties of Orthogonal Arrays

The first important property of the orthogonal array is the fractional factorial characteristic. Using the above example that includes ten parameters, where each has three levels, one notices that a full factorial strategy needs to conduct $3^{10} = 59\,049$ experiments. In contrast, if one uses the orthogonal array to design such experiments, only 27 experiments are needed. After a simple analysis and processing of the output results from the 27 experiments, an optimum combination of the parameter values can be obtained [1, Ch. 15]. It is demonstrated in statistics that although the number of experiments is dramatically reduced, the optimum result obtained from the orthogonal array usage is close to that obtained from the full factorial approach.

The second fundamental property of the orthogonal array is that all possible combinations of up to t parameters occur equally, which ensures a balanced and fair comparison during experiments. A quick examination of Table I reveals that for each parameter (column), levels 1, 2, and 3 have the same times of occurrence. A similar property applies for the combinations of any two parameters. Therefore, the orthogonal array approach investigates not only the effects of the individual parameters on the experiment outcome but also the interactions of any two parameters. In general, one could increase the strength t of the orthogonal array to consider the interactions of more parameters. However, the larger the strength t is, the more rows the orthogonal array has. The orthogonal arrays used in this paper have a strength of two, which is found to be efficient for the problems considered.

Another useful property of orthogonal arrays is that any $N \times k'$ subarray of an $\mathrm{OA}(N, k, s, t)$ is still an $\mathrm{OA}(N, k', s, t')$, where $t' = \min\{k', t\}$. In other words, if one or more columns are deleted from an OA, the resulting array is still an OA but with a smaller number of parameters. This property is especially useful when selecting an orthogonal array with a specific number of parameters from an existing OA database. More orthogonal array properties can be found in [18, Ch. 1].

C. Existence and Construction of Orthogonal Arrays

Two fundamental questions concerning orthogonal arrays, namely, existence and construction, are discussed in this section. A simple statement of the existence question is: for given values of k, s, and t, determine the minimum number of rows N so that an $\mathrm{OA}(N, k, s, t)$ exists. The reason one would like to find the minimum N is that a small number of experiments is preferred in practice. Rao's inequalities are established to answer the existence question [19]. The parameters of $\mathrm{OA}(N, k, s, t)$ must satisfy the following inequalities:

$$N \geq \sum_{i=0}^{u} \binom{k}{i} (s-1)^i, \text{ if } t = 2u, \quad u > 0 \tag{1a}$$

$$N \geq \sum_{i=0}^{u} \binom{k}{i} (s-1)^i + \binom{k-1}{u} (s-1)^{u+1}$$
$$\text{if } t = 2u+1, \quad u \geq 0. \tag{1b}$$

Further improvements on Rao's bound can be found in [18] for orthogonal arrays with strength two or three and for two-levels orthogonal arrays.

The second question is how to construct an $\mathrm{OA}(N, k, s, t)$. Numerous techniques are known for constructing orthogonal arrays. Galois fields [18, Ch. 3] turn out to be a powerful tool for the construction of orthogonal arrays, and several methods are proposed using such fields and finite geometries. In addition, it has been noticed that there is a close relation between orthogonal arrays and coding theory. Thus, many constructions for orthogonal arrays are presented based on error-correcting codes. Furthermore, the difference scheme is also known as one of the earliest methods to construct certain orthogonal arrays. Nowadays, many orthogonal arrays with different numbers of parameters, levels, and strengths have been developed and archived in OA databases or libraries, which can be found in books related to orthogonal arrays or Taguchi's method. The orthogonal arrays used in this paper are listed in [20].

III. IMPLEMENTATION PROCEDURE OF TAGUCHI'S METHOD

This paper presents a novel iterative implementation of Taguchi's method, as shown in Fig. 1. To illustrate the implementation procedure, a linear antenna array optimization is used as an example. Fig. 2 depicts the antenna array geometry,

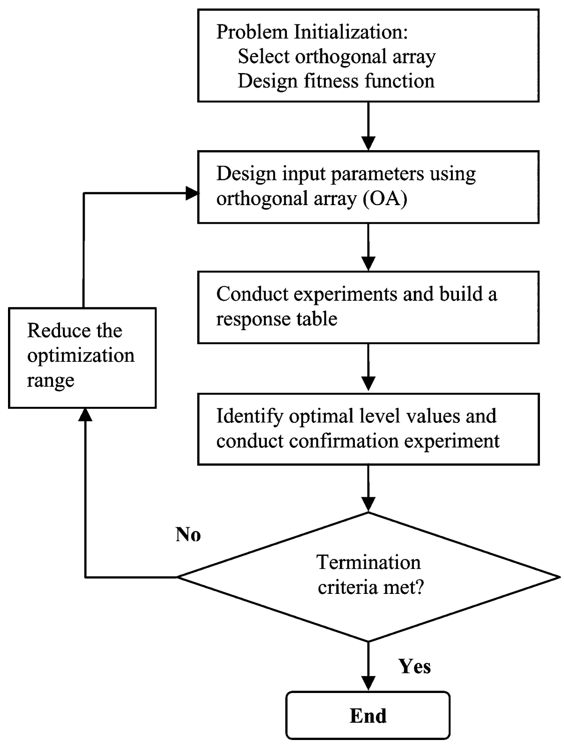

Fig. 1. Flow chart of Taguchi's method.

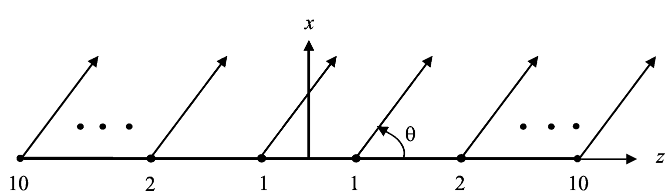

Fig. 2. Geometry of a 20-element equally spaced linear array.

which has 20 equally spaced elements along the z axis. The element spacing is half-wavelength and the excitations of array elements are symmetric with respect to the x axis. The excitation magnitudes of the ten elements will be optimized in the range of [0, 1] to obtain an array factor with prescribed nulls. The procedure of the first iteration is explained in detail, and the procedures of the remaining iterations are the same as those of the first one.

A. Problem Initialization

The optimization procedure starts with the problem initialization, which includes the selection of a proper OA and design of a suitable fitness function. The selection of an OA mainly depends on the number of input parameters. For the antenna array shown in Fig. 2, there are ten excitation magnitudes that should be optimized. Thus, the orthogonal array to be selected should have ten columns to represent these parameters. In order to characterize the nonlinear effect, three levels are necessary for each input parameter. After searching [20], an OA(27, 10, 3, 2) is adopted for this problem, as shown in Table I.

The fitness function is devised according to the optimization goal. For a 20-element symmetrical array, the array factor (AF) can be written as

$$\mathrm{AF}(\theta) = 2\sum_{n=1}^{10} a(n)e^{j\varphi(n)}\cos[\beta d(n)\cos\theta] \tag{2}$$

where β is the wave number and $a(n)$, $\varphi(n)$, and $d(n)$ are the excitation magnitude, phase, and location of the nth element, respectively. Since the phase of each element is equal to zero for this problem, the array factor can be simplified as

$$\mathrm{AF}(\theta) = 2\sum_{n=1}^{10} a(n)\cos[\beta d(n)\cos\theta]. \tag{3}$$

The following fitness function can be used in the optimization:

$$\mathrm{Fitness} = \int_{0^\circ}^{180^\circ} |\mathrm{AF}_d(\theta) - \mathrm{AF}(\theta)|d\theta \tag{4}$$

where $\mathrm{AF}_d(\theta)$ is the desired null controlled pattern and $\mathrm{AF}(\theta)$ is the pattern obtained from (3). Basically, the fitness can be seen as the difference area between the desired pattern and obtained pattern. The smaller the fitness value, the better the match between the obtained pattern and the desired one.

B. Design Input Parameters Using OA

Next, the corresponding numerical values for the three levels of each input parameter should be determined in order to conduct the experiments. In the first iteration, the value for level 2 is selected at the center of the optimization range. Values of levels 1 and 3 are calculated by subtracting/adding the value of level 2 with a parameter called level difference (LD). The level difference in the first iteration (LD_1) is determined by the following equation:

$$\mathrm{LD}_1 = \frac{\max - \min}{\text{number of levels} + 1} = \frac{1-0}{3+1} = 0.25 \tag{5}$$

where $\max$ is the upper bound of optimization range and $\min$ is the lower bound of optimization range. Thus, each entry of the OA in Table I can be converted into a corresponding level value for the antenna excitation magnitude $a(n)_1^m$, where n indicates the nth antenna element, the subscript 1 indicates the first iteration, and the superscript m indicates level 1, 2, or 3.

C. Conduct Experiments and Build a Response Table

After determining the input parameters, the fitness function for each experiment can be calculated. For example, the fitness value for experiment 1 with all parameters' level being 1 is computed using (4) and the result is 5.153. Next, the fitness value is converted to the signal-to-noise (S/N) ratio (η) in Taguchi's method [1, Ch. 12] using the following formula:

$$\eta = -20\log(\mathrm{Fitness})\ (\mathrm{dB}). \tag{6}$$

TABLE II
RESPONSE TABLE IN THE FIRST ITERATION OF NULL CONTROLLED PATTERN OPTIMIZATION

(dB)

Level \ Element	1	2	3	4	5	6	7	8	9	10
1	-19.67	-20.01	-20.00	-19.87	-19.78	-19.95	-20.03	-19.23	-19.69	-18.37
2	-19.73	-19.86	-19.68	-19.70	-20.09	-19.69	-19.69	-20.04	-19.76	-19.95
3	-20.52	-20.05	-20.23	-20.36	-20.05	-20.28	-20.20	-20.65	-20.46	-21.60

Hence, a small fitness value results in a large S/N ratio. After conducting all experiments in the first iteration, the fitness values and corresponding S/N ratios are obtained, listed in Table I. These results are used to build a response table for the first iteration by averaging the S/N ratios for each parameter n and each level m using the following:

$$\overline{\eta}(m,n) = \frac{s}{N} \sum_{i,OA(i,n)=m} \eta_i.$$

For example, the average S/N ratio for $a(7)_1^2$ is shown in (7) at the bottom of the page. Therefore, the response table is created, as shown in Table II.

D. Identify Optimal Level Values and Conduct Confirmation Experiment

Finding the largest S/N ratio in each column of Table II can identify the optimal level for that parameter. For example, the optimum values for the first iteration are $a(1)_1^1$, $a(2)_1^2$, $a(3)_1^2$, $a(4)_1^2$, $a(5)_1^1$, $a(6)_1^2$, $a(7)_1^2$, $a(8)_1^1$, $a(9)_1^1$ and $a(10)_1^1$, as indicated by the gray background in Table II.

Next, a confirmation experiment is performed using the combination of the optimal levels identified in the response table. This confirmation test is necessary since the OA-based experiment is a fractional factorial experiment, and the optimal combination may not be included in Table I. The fitness value obtained from the optimal combination is regarded as the fitness value of the current iteration.

E. Reduce the Optimization Range

If the results of the current iteration do not meet the termination criteria, which are discussed in Section III-F, the process is repeated in the next iteration. The optimal level values of the current iteration are used as central values (values of level 2) for the next iteration

$$a(n)_{i+1}^2 = a(n)_i^{\text{opt}}. \tag{8}$$

To reduce the optimization range, the LD_i is multiplied with a reduced rate (RR) to obtain LD_{i+1} for the $(i+1)$th iteration

$$\text{LD}_{i+1} = \text{RR} \cdot \text{LD}_i. \tag{9}$$

The RR can be set between 0.5 and 1 depending on the problems. The larger the RR is, the slower the convergence.

If the LD is a large value, while the central level value is located near the upper bound or lower bound of the optimization range, the value of level 1 or 3 may reside outside the optimization range. Therefore, a process of checking the level values is necessary in order to guarantee that all level values are located within the optimization range. If the excessive situation happens, reassigning the level value for the parameter will be performed. For example, if $a(n)_i^1$ is smaller than $\min$, the $a(n)_i^1$ is then set to $\min$.

F. Check the Termination Criteria

When the number of iterations is large, the level difference of each element becomes small. Hence, the level values are close to each other and the fitness value of the next iteration is close to the fitness value of the current iteration. The following equation may be used as a termination criterion for the optimization procedure:

$$\frac{\text{LD}_i}{\text{LD}_1} < \text{converged value}. \tag{10}$$

Usually, the *converged value* can be set between 0.001 and 0.01 depending on the problem's nature. The iterative optimization process will be ended if the design goals are achieved or (10) is satisfied.

IV. DESIGN OF LINEAR ANTENNA ARRAYS

Antenna pattern synthesis can be classified into several categories or groups [21, Ch. 7]. One of these groups requires that the antenna patterns possess nulls in desired directions, which

$$\overline{\eta}(2,7) = \frac{1}{9} \cdot \sum_{i,OA(i,7)=2} \eta_i = \frac{1}{9}\Big[(-19.625) + (-16.676) + (-22.21) + (-19.319) + (-21.174) + (-17.748) + (-20.871) + (-20.169) + (-19.42)\Big] = 19.69\,(\text{dB}). \tag{7}$$

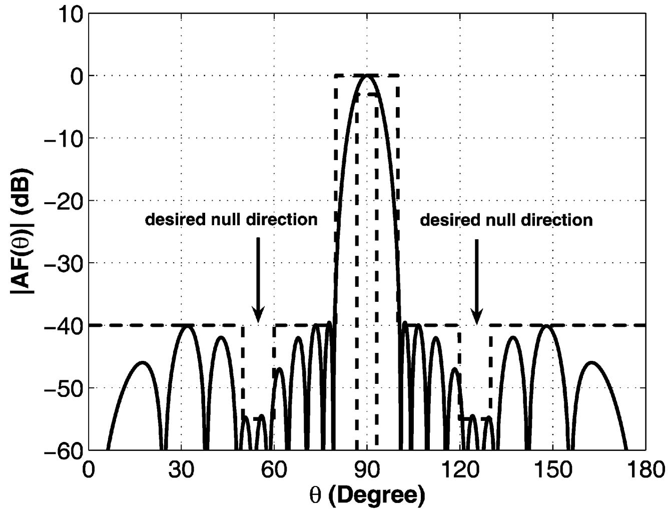

Fig. 3. Null controlled pattern of an optimized 20-element linear array. The dashed lines are the desired pattern, which has prescribed nulls at [50°,60°] and [120°,130°] with level of −55 dB and has a 3 dB beamwidth of 7.4°.

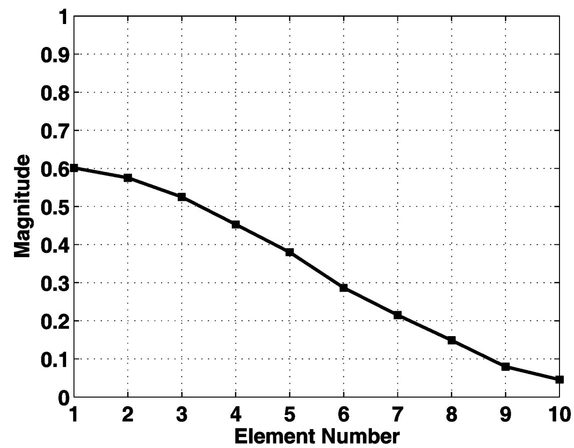

Fig. 4. Optimized excitation magnitudes of the linear antenna array with a null controlled pattern shown in Fig. 3.

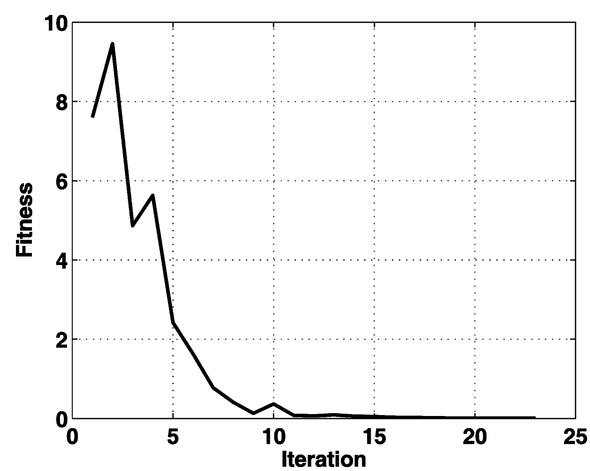

Fig. 5. Convergence curve of the fitness value of the 20-element equally spaced linear array for the null controlled pattern design.

are widely used in smart antenna systems to eliminate the interference from specific noise directions. The Schelkunoff polynomial method is an effective approach to synthesize the null controlled patterns. Another group requires that the antenna patterns exhibit a desired distribution in the entire visible region, which is also referred to as beam shaping. A typical example is the design of a sector beam pattern, which allows that the antenna array has a wider coverage. They are usually accomplished using the Fourier transform and the Woodward–Lawson methods. In this section, Taguchi's method is used to design two linear antenna arrays, and each array belongs to one of the groups mentioned above. Although they have different pattern requirements, the design process for the two arrays follows the same implementation procedure, which demonstrates the versatility and robustness of Taguchi's method.

A. Null Controlled Pattern Design

The design objective is to optimize the excitation magnitudes of array elements so that the corresponding array factor has nulls at specified directions [11]–[14]. A 20-element equally spaced linear array structure is shown in Fig. 2, and the desired antenna pattern is marked in Fig. 3 by the dashed lines. Two nulls are desired to exist between 50° and 60° and between 120° and 130°, and their magnitude should be lower than −55 dB.

Most settings of this optimization case, such as the selections of the orthogonal array and fitness function, design of the input parameters, and construction of the response table, have been discussed in the previous section. In addition, the *converged value* is set to 0.002 and the RR is set to 0.75 in this optimization case.

When this optimization process has been executed for 23 iterations, an optimal null control pattern is obtained and presented in Fig. 3. The result shows that the beam width at −40 dB sidelobe level is 20.9°, the half-power beam width (HPBW) is 7.4°, and nulls are below −55 dB in the angle ranges of [50°, 60°] and [120°, 130°] as desired. The optimized excitation magnitudes of elements from number one to number ten are: [0.603, 0.577, 0.530, 0.459, 0.379, 0.294, 0.214, 0.155, 0.082, 0.046], as shown in Fig. 4. To appreciate the efficiency of Taguchi's method, the convergence curve of fitness value is plotted in Fig. 5. It is observed that the fitness value converges to the optimum result quickly.

B. Sector Beam Pattern Design

To further demonstrate the validity of Taguchi's method, a relatively complex case, a sector beam pattern design, is attempted here. In this design, the same 20-element array in Fig. 2 is used, but both excitation magnitudes and phases of the array elements are to be optimized to shape the antenna pattern [15], [22, Ch. 3]. Thus, an OA(81, 20, 3, 2) [20], which offers ten columns for magnitudes and ten columns for phases, is adopted in this sector beam pattern synthesis.

The requirements for the sector beam pattern are shown in Fig. 6 using dashed lines. To define the sector beam, there are two specific angular regions. Region I ranges from 78° to 102°, where ripples should be smaller than 0.5 dB. Region II controls the sidelobe levels, which are all below −25 dB between 0° and 70° and between 110° and 180°.

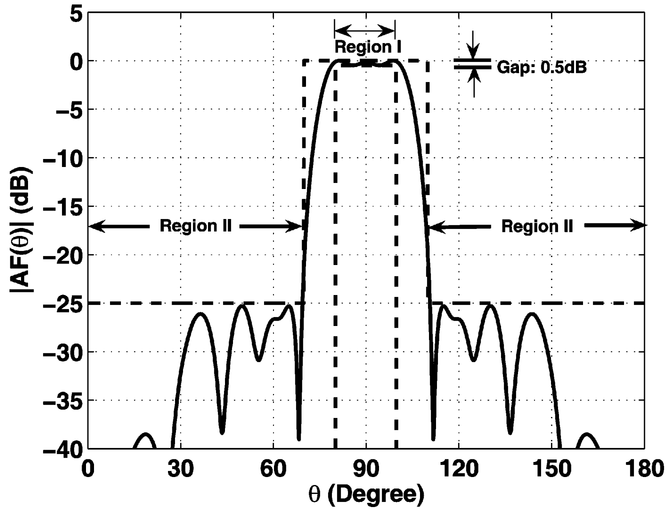

Fig. 6. Sector beam pattern of an optimized 20-element linear array. The dashed lines are the desired pattern, which requires ripples in Region I smaller than 0.5 dB and sidelobe levels in Region II lower than −25 dB.

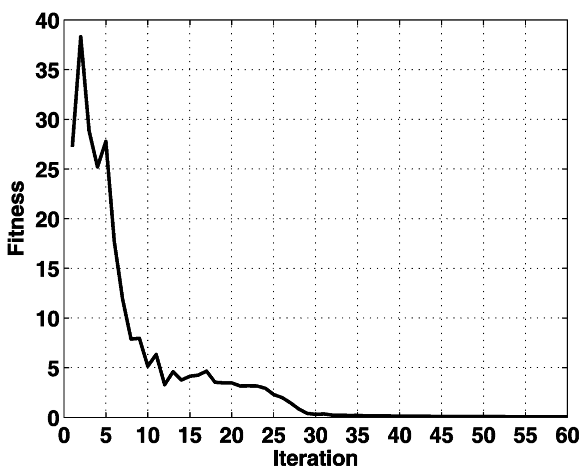

Fig. 7. Convergence curve of the fitness value of the 20-element equally spaced linear array for the sector beam pattern design.

The optimization ranges of the excitation magnitude and phase of each element are from zero to one and from $-\pi$ to π, respectively. Equation (4) is used for evaluating the fitness value during the optimization process. The *converged value* is set to 0.002 and the RR is set to 0.9.

The convergence curve of fitness value is presented in Fig. 7. After 60 iterations, an optimum sector beam pattern is obtained, as plotted in Fig. 6. It has a ripple of 0.48 dB in Region I, the beam width at −25 dB sidelobe level is 41.2°, and the HPBW is 28.1°. The optimized excitation magnitudes of the elements from number one to number ten are [0.437, 0.321, 0.188, 0.122, 0.132, 0.130, 0.079, 0, 0, 0], as shown in Fig. 8(a). The optimized excitation phases (degree) of the elements are [9.03, 2.51, −16.74, −77.72, −119.81, −112.63, −111.57, −111.27, −170.14, −175.43], as shown in Fig. 8(b). The optimized result indicates that a 14-element symmetrical linear array is capable of realizing the same design goal but with less antenna elements.

The same sector beam problem was optimized in [15] using PSO method. The desired pattern was obtained by using 20

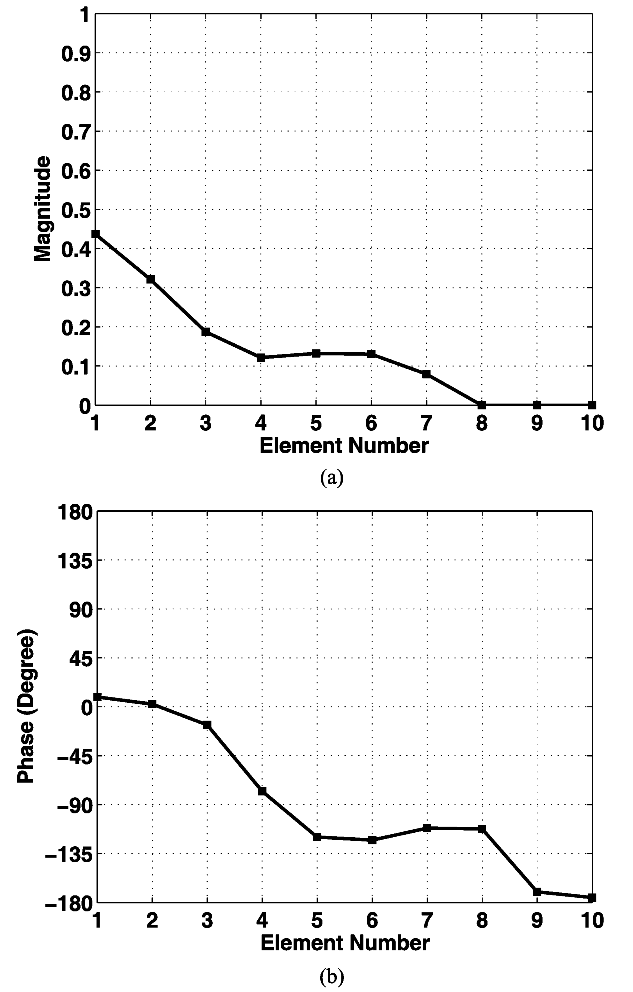

Fig. 8. Optimized element excitations of the linear antenna array with a sector beam pattern shown in Fig. 6. (a) The magnitudes of elements and (b) the phases of elements.

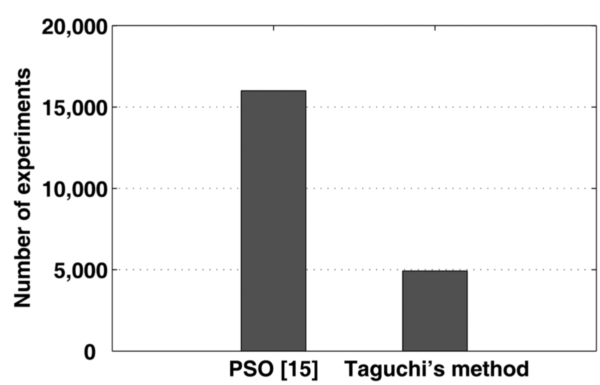

Fig. 9. Comparison of total experiment numbers required in PSO [15] and Taguchi's method for the sector beam pattern optimization problem.

particles and running around 800 iterations. Thus, the total experiments needed were 16 000. However, only 4920 experiments (82 experiments by 60 iterations) are required to achieve the same goal by Taguchi's method. A comparison plot is shown in Fig. 9. The number of experiment reduction is around 70%, which shows that Taguchi's method is quicker than PSO to achieve the same optimization goal for this problem.

V. Conclusion

In this paper, a global optimization technique based on Taguchi's method is introduced for electromagnetic applications. The implementation procedure is described in detail, and two linear antenna array examples are discussed to demonstrate its validity. Optimized results show that the desired array factors, a null controlled pattern and a sector beam pattern, are successfully obtained. It is found that Taguchi's method is a good candidate for optimizing various electromagnetics applications, as it is easy to implement and converges to the desired patterns quickly.

References

[1] G. Taguchi, S. Chowdhury, and Y. Wu, *Taguchi's Quality Engineering Handbook*. New York: Wiley, 2005.

[2] H. Nagano, K. Miyano, T. Yamada, and I. Mizushima, "Robust selective-epitaxial-growth process for hybrid SOI wafer," in *Proc. IEEE Int. Symp. Semicond. Manuf.*, San Jose, CA, Oct. 2003, pp. 187–190.

[3] G. Y. Hwang, S. M. Hwang, H. J. Lee, J. H. Kim, K. S. Hong, and W. Y. Lee, "Application of Taguchi method to robust design of acoustic performance in IMT-2000 mobile phones," *IEEE Tran. Magn.*, vol. 41, pp. 1900–1903, May 2005.

[4] T. Y. Chou, "Applications of the Taguchi method for optimized package design," in *Proc. IEEE 5th Topical Meeting Electr. Performance Electron. Packag.*, Napa, CA, Oct. 1996, pp. 14–17.

[5] H. T. Wang, Z. J. Liu, S. X. Chen, and J. P. Yang, "Application of Taguchi method to robust design of BLDC motor performance," *IEEE Trans. Magn.*, vol. 35, no. 5, pt. 2, pp. 3700–3702, Sep. 1999.

[6] A. D. MacDonald, "A modified Taguchi method for the design of broadband spiral cavity absorbers," in *Proc. Int. Symp. Antennas Propag. Soc.*, Dallas, TX, May 1990, vol. 3, pp. 1180–1183.

[7] A. Charles, M. S. Towers, and A. McCowen, "Sensitivity analysis of Jaumann absorbers," *Proc. Inst. Elect. Eng. Microw., Antennas Propag.*, vol. 146, no. 4, pp. 257–262, Aug. 1999.

[8] J. Felba, K. P. Friedel, and A. Moscicki, "Characterization and performance of electrically conductive adhesives for microwave applications," in *Proc. 4th Int. Conf. Adhesive Joining Coating Technol. Electron. Manuf. 2000*, Espoo, Finland, Jun. 2000, pp. 232–239.

[9] P. Gouget, G. Duchamp, and J. Pistre, "Optimisation and comparison of three diplexers based on a new slot to microstrip junction," in *2003 IEEE MTT-S Int. Microw. Symp. Dig.*, Philadelphia, PA, Jun. 2003, vol. 2, pp. 1231–1234.

[10] K. L. Virga and R. J. Engelhardt, Jr, "Efficient statistical analysis of microwave circuit performance using design of experiments," in *1993 IEEE MTT-S Int. Microw. Symp. Dig.*, Atlanta, GA, Jun. 1993, vol. 1, pp. 123–126.

[11] M. M. Khodier and C. G. Christodoulou, "Linear array geometry synthesis with minimum sidelobe level and null control using particle swarm optimization," *IEEE Trans. Antennas Propag.*, vol. 53, pp. 2674–2679, Aug. 2005.

[12] D. W. Boeringer and D. H. Werner, "Particle swarm optimization versus genetic algorithms for phased array synthesis," *IEEE Trans. Antennas Propag.*, vol. 52, pp. 771–779, Mar. 2004.

[13] D. W. Boeringer, D. H. Werner, and D. W. Machuga, "A simultaneous parameter adaptation scheme for genetic algorithms with application to phased array synthesis," *IEEE Trans. Antennas Propag.*, vol. 53, pp. 356–371, Jan. 2005.

[14] F. J. Ares-Pena, A. Rodriguez-Gonzalez, E. Villanueva-Lopez, and S. R. Rengarajan, "Genetic algorithms in the design and optimization of antenna array patterns," *IEEE Trans. Antennas Propag.*, vol. 47, pp. 506–510, Mar. 1999.

[15] D. Gies and Y. Rahmat-Samii, "Particle swarm optimization for reconfigurable phased-differentiated array design," *Microw. Opt. Technol. Lett.*, vol. 38, no. 3, pp. 168–175, Aug. 2003.

[16] Y. B. Tian and J. Qian, "Improve the performance of a linear array by changing the spaces among array elements in terms of genetic algorithm," *IEEE Trans. Antennas Propag.*, vol. 53, pp. 2226–2230, Jul. 2005.

[17] N. Jin and Y. Rahmat-Samii, "A novel design methodology for aperiodic arrays using particle swarm optimization," in *2006 Nat. Radio Sci. Meeting Dig.*, Boulder, CO, Jan. 2006, pp. 69–69.

[18] A. S. Hedayat, N. J. A. Sloane, and J. Stufken, *Orthogonal Arrays:Theory and Applications*. New York: Springer-Verlag, 1999.

[19] C. R. Rao, "Factorial experiments derivable from combinatorial arrangements of arrays," *J. Roy. Statist. Soc.*, vol. 9, no. 1, pp. 128–139, 1947.

[20] N. J. A. Sloane, A library of orthogonal array [Online]. Available: http://www.research.att.com~njas/oadir/

[21] C. A. Balanis, *Antenna Theory: Analysis and Design*, 3rd ed. New York: Wiley, 2005.

[22] R. J. Mailloux, *Phase Array Antenna Handbook*, 2nd ed. Norwood, MA: Artech House, 2005.

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